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# An innovative sCMOS based autonomous astronomical camera dedicated to universal use for SST and other fields of optical astronomy

Paweł Zienkiewicz, Katarzyna Karpińska, Mikołaj Jamroży, Bartłomiej Juszczyk, Dmytro Pochapskyi, Tomasz Przedpełski, Jerzy Łukasiewicz, Natalia Czortek, and Grzegorz Brona

***Abstract*—Creotech Instruments is advancing a game-changing sCMOS camera series. The Final Prototype Model of an astronomical camera for Space Surveillance and Tracking (SST) is in the test campaign phase. Designed for SST, NEO, and debris detection, its adaptable platform suits quantum tech and biological microscopy. Edge computing sets it apart, leveraging FPGA-based SoC for real-time processing and Linux-based pre-processing. Operating autonomously, it supports on-camera ML algorithms, revolutionizing astronomy. Data pre-processing, like frame stacking, reduces data load. This paper introduces the camera's concept, architecture, and prototype test results, emphasizing specific use cases and future product line development.**

***Keywords*—sCMOS camera series; astronomical camera; Space Surveillance and Tracking (SST)**

## I. Introduction

CREOTECH Instruments brings extensive experience in designing control and measurement systems, including camera solutions. Our involvement in various projects, such as the Pi of the Sky project for the Las Palmas Observatory, ASOPEK for the Air Force Institute of Technology's SST telescope, Neostel for ESA, and the PIAP military robotic cameras project, underscores our commitment to innovation. Collaborating with partners like CERN, GSI, CCFE, LNLS, among others, we have developed control and measurement systems for High Energy Physics.

In recent years, we've observed two significant trends in scientific instrumentation technology. Firstly, the rapid advancement of sCMOS sensors offers performance akin to cutting-edge CCD sensors with reduced cooling requirements and energy consumption. Secondly, the successful proliferation of edge computing or distributed computing technologies offers benefits across various scientific and industrial applications.

The development of high-sensitivity, high-resolution sCMOS sensors with a high frame rate per second (FPS) holds promise for advanced astronomical and SST applications. However, these sensors generate substantial data streams, necessitating robust infrastructure. To address this challenge, we've explored a novel camera architecture, integrating high-performance sensors with the local computing power of advanced FPGA SoC-based electronics. This approach enables on-camera data pre-processing, reducing outgoing data volume and enhancing efficiency. Moreover, in applications requiring rapid feedback and control, the camera can act as a trigger source, significantly reducing response times. This autonomy is particularly advantageous in distributed systems, making our solution appealing for SST applications and beyond.

## II. Camera Concept

To address the needs of advanced astronomical applications, we embarked on the development of a new camera, the CreoSky 6000, with specific requirements in mind:

- Integration of a modern, low-noise, high-framerate sCMOS sensor with a 60mm x 60mm active area and high Quantum Efficiency, allowing for sensor alteration with minimal design changes if needed.
- Compact size of approximately 200mm x 200mm to minimize light obstruction on telescopes, with a target mass of around 5kg without accessories to minimize impact on telescope load.
- Active sensor cooling with reliable temperature stabilization to minimize dark noise effects, potentially utilizing air cooling for standalone usage without external heat exchange systems.
- Flexible, configurable I/O set including general-purpose pins for hardware trigger inputs and outputs, shutter operation, and connectivity to external devices via digital buses.
- Standard and scalable communication ports such as USB3, Copper gigabit ethernet, and Fibre Optic 10Gb ethernet, eliminating the need for custom accessories for camera workstation setup.
- Standalone operation with a built-in general-purpose operating system for customizable device operation modes and data acquisition and processing pipelines.
- Multiple frame buffer with runtime reconfigurable real-time data processing capabilities in FPGA and Linux.
- Ability to implement custom data processing paths with

The camera project receives co-financing from the Polish National Centre for Research and Development as part of the 'Path for Mazovia' competition, under Project No. MAZOWSZE/0183/19 titled 'Innovative autonomous camera for monitoring near-Earth objects.' The research outcomes from this project will also be utilized in The NImSoQ project – "New Imaging and Control Solutions for Quantum processors and metrology," supported by the Quantera call 2021 and co-financed by the Polish National Centre for Research and Development.

Authors (without seventh) are with Creotech Instruments S.A., Poland (e-mail: {pawel.zienkiewicz, katarzyna.karpinska, mikolaj.jamrozy, bartlomiej.juszczyk, dmytro.pochapskyi, tomasz.przedpelski, natalia.czortek, grzegorz.brona} @creotech.pl).
The seventh Author is with Air Force Institute of Technology (ITWL), Poland (e-mail: jerzy.lukasiewicz@itwl.pl).

user algorithms in FPGA, Linux, and future machine learning capabilities.

- Availability of ASCOM and SDK libraries for simplified user software development.
- Time synchronization with precision of at most 1us using Ethernet or GPS.

To meet these requirements, we designed the new device, built the engineering model, and it is currently undergoing characterization. The architecture, software, and preliminary characterization results of the camera are detailed in subsequent sections of this article.

## III. CAMERA ARCHITECTURE

To fulfill the expectations outlined earlier, a camera architecture was devised to meet the parameters outlined in Table I.

TABLE I
TARGET SPECIFICATION FOR THE CAMERA

| | |
|---|---|
| **SENSOR:** | Gpixel sCMOS, GSENSE6060 (6k x 6k, 10um pixel) Front Side or Back Side Illuminated |
| **QUANTUM EFFICIENCY:** | 71,6%@550nm for FSI, 95%@580nm for BSI |
| **FULL WELL CAPACITY:** | 128ke for FSI, 102ke for BSI |
| **TEMPORAL NOISE (LOW NOISE MODE):** | 4,6e for FSI, 3e for BSI |
| **DARK CURRENT:** | < 0,5e/pix/sec @ -10ºC |
| **READOUT MODES:** | 12bit, 14bit and HDR |
| **MAX FPS:** | 22fps full frame max speed @ 12bit for ROI with row skip can be higher, for example, 6k x 3k can be about 44fps, for 6k x 1k can be up to about 132 fps, etc. |
| **SENSOR COOLING:** | TEC with fan air exchange enhanced with custom vibration limiting solution by default can be customized for TEC and water/glycol coolant |
| **WEIGHT:** | ~5,5kg without external shutter and adapters |
| **SIZE:** | Fi ~208x172 mm, can be modified with an external shutter and other additional mechanical adapters |
| **DATA TRANSFER INTERFACES:** | 10Gb (Fibre Optic), 1Gb (Copper) Ethernet with PTPv2 support and USB 3.0 device mode |
| **SOFTWARE INTERFACES:** | ASCOM-based, SDK library, REST API, self-hosted Web interface, embedded Linux libraries for custom software |
| **OTHER I/O PORTS:** | USB 2.0 Host (for external devices, such as GPS and other external devices), Trigger and general I/O pins (customizable) including shutter interface, CAN or RS485 lines with optional customization |
| **OTHER FUNCTIONALITY** | Sensor control implemented in FPGA accompanied by Cortex processor running Linux with flexible data and processing path, multi-frame buffer, Machine Learning and OpenCV capabilities |

The camera was designed with modularity in mind, allowing for easy future modifications such as sensor upgrades, SoC/FPGA changes, or alterations in cooling methods. This ensures the platform's longevity and adaptability to applications beyond astronomy. Its robust enclosure is built to withstand harsh environments and is sealed against water and dust ingress. The fan cooling assembly includes dust filters and can be easily replaced, even in the field. Each connector is engineered to withstand both humidity and potential mechanical damage during operation.

The outcome of the mechanical design process is presented in 3D visualization, featuring the optional iris shutter enclosure, as depicted in Figure 1. Figures 2 Figures 3 and 4 illustrate the mechanical drawings, showcasing external dimensions without accessories.

Fig.1. 3D visualization of the camera from the backside view with visible shutter and dedicated cabling

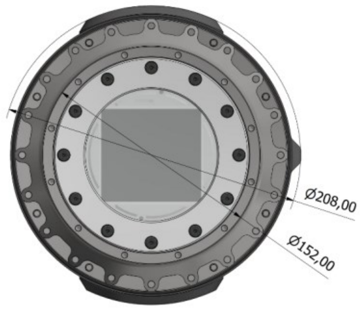


Fig.3. CAD mechanical drawing presenting the dimensions, front view

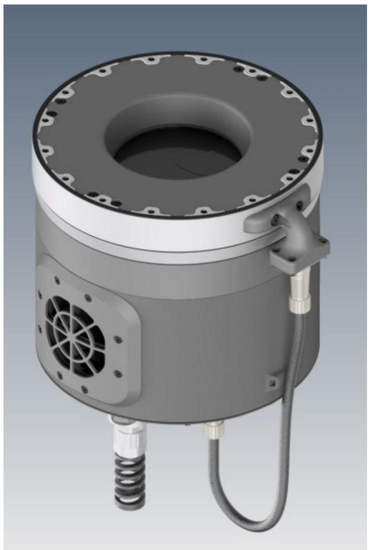

Fig.2. 3D visualization of the camera from the frontside view with visible basic cabling and shutter adapter

The mechanical interface allows for the integration of accessories like shutters and focuses via the multiple threaded hole front plate interface. These accessories can be electrically connected using general-purpose Input/Output interfaces, as depicted in Figure 1.

During normal operation, the camera autonomously controls the shutter without the need for external drivers. Multiple external electrical interfaces, along with the embedded Linux Operating System, enable the creation of a standalone system with a short control loop. This ensures reliable timestamping of events and deterministic latency for real-time telescope operation.

Time synchronization with PTPv2 or GPS guarantees accuracy of up to 1us and can be fine-tuned with additional timing signals, such as precise PPS or 10MHz, which can be inputted to or outputted from the camera. This unique architecture facilitates the seamless formation of a tightly coupled camera array, introducing new possibilities for astronomical observations and debris detection. Furthermore, this functionality is bolstered by the embedded processing capabilities outlined in the subsequent chapter of this article.


Fig.4. CAD mechanical drawing presenting camera dimensions, side view

## IV. CAMERA COMPUTING RESOURCES AND IMAGE PROCESSING

The camera operates autonomously via embedded Linux, ensuring continuous functionality even in case of a disrupted connection to the Workstation or Server, as long as the storage host can receive data. Multiple frame buffers offer added security by preventing data loss during emergencies, provided the buffer isn't full.

Embedded Linux provides flexibility in camera operation, implemented with fault tolerance. Key components managed by Linux control sensor readout, data capture, processing, and output to external systems. This architecture enables on-the-fly reconfigurations during operation, such as changing sensor modes, selecting regions of interest, adjusting data processing pipelines, and configuring data output paths, including fits file generation and FTP upload. The modular software suite allows for runtime configuration adjustments to meet user needs, with active communication between Linux and FPGA for rapid path modifications.

The camera supports multiple control methods:

- ASCOM-compatible driver for Microsoft Windows operation
- REST API for easy interfacing with web applications
- C++/Python SDK for application development on Windows or Linux
- WWW configuration page for full functionality in ad-hoc camera operation
- Linux Secure Shell for direct operation and custom runtime applications development.

The camera architecture is based on Xilinx FPGA, with an IP block for real-time data processing, enabling operations on collected photos such as stacking or frame subtraction. The algorithm is configurable from the Linux application. An example of data processing that can be easily implemented is the automatic stacking of up to 16 frames in FPGA without significant performance or latency penalties.

The architecture based on modern, advanced SoC containing the application processor and FPGA in one chip enables the low latency, in situ data processing and future-proof possibility of implementing machine learning in both, software and IP Core, hard real-time data processing or easy prototyping the algorithms in Linux user space.

The characterization of the camera running software architecture with simple frame stacking is presented in the next chapter.

## V. EM CHARACTERIZATION

As of December 2023, the Final Prototype Model of the camera was undergoing characterization and initial observations indicated that it either meets or closely aligns with the specified requirements. The previous, Engineering Model of the camera was already verified, and the changes that needed to be introduced were minor.

Verification of the Engineering Model was conducted using the Gigahertz-Optik ISS-30VA reference light source, covering the spectrum from 300nm to 1100nm. This source is based on an integrating sphere with a 100mm output port, a halogen lamp, and a photometric monitor with a control unit. Tests were performed following the procedures outlined in the EMVA1288 revision 4 standards.

The camera under test is depicted in Figures 5 and 6. The final prototype model, of which the EM model under test was a reference, is shown in Figures 5, 6, and 7.

For testing, the sensor was cooled to 10 degrees Celsius while the ambient temperature was around 28 degrees Celsius. We deliberately avoided cooling below 10 degrees to mimic a worst-case scenario, simulating a dry environment reaching approximately 50 degrees Celsius, stabilizing the sensor at this temperature. Deeper cooling may enhance dark current generation but has minimal impact on other readout parameters. The cooling system, employing Thermoelectric Cooling (TEC) with air heat exchange, was validated to maintain a minimum 40K temperature difference between ambient and sensor. Additionally, a concept employing TEC for water-glycol coolant exchange was designed and tested, potentially cooling the sensor to -50 degrees Celsius depending on coolant temperature and application requirements. Selecting the sensor's operating temperature involves balancing various parameters and power consumption emitted during operation.

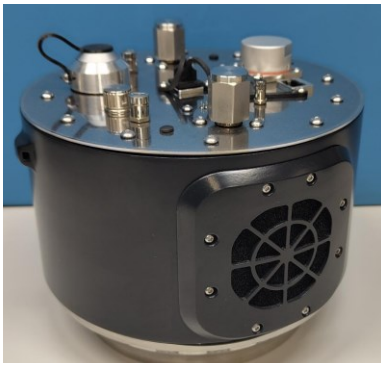

Fig.5. Final Prototype Model

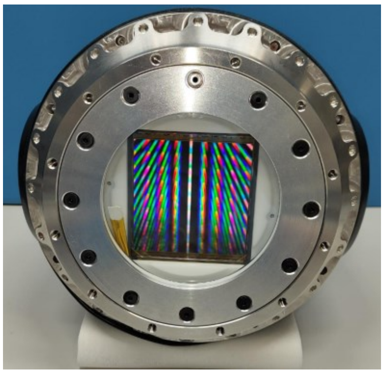

Fig.6. Final Prototype Model, front view photo

*Fig.7. Final Prototype Model, back view photo*

The Final Prototype Model used an Engineering Sample grade sensor, equivalent to grade 2, with some amount of cosmetic defects. Calculations focused on the 500x500 central region of the sensor, containing some PRNUs and DSNUs. As of December 2023, the 14-bit and HDR modes, along with lower gain for increased Full Well Capacity, are implemented, and undergoing characterization. The highest gain with the lowest noise and fastest readout serves as the performance benchmark, prioritizing faint object detection and space debris tracking.

EMVA 1288 test results characterizing the 12-bit, low noise (high gain) mode are presented in Table 2 and the following figures:

- Linearity plot in Figure 8
- Photon Transfer plot in Figure 9
- Sensitivity plot in Figure 10
- Signal to Noise Ratio in Figure 11

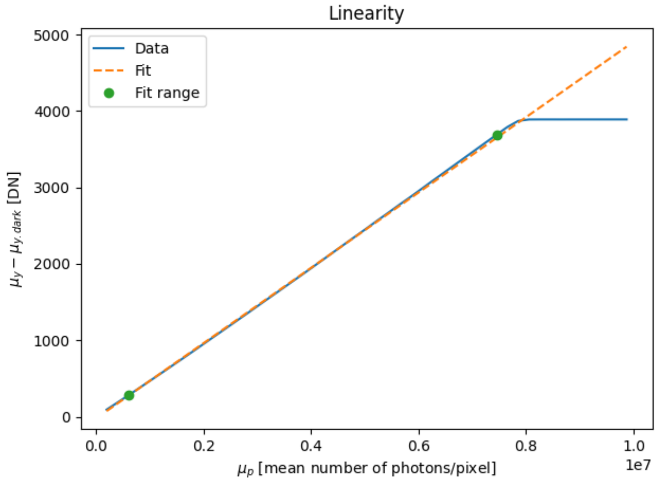


Fig.8. 12bit LN mode Linearity plot

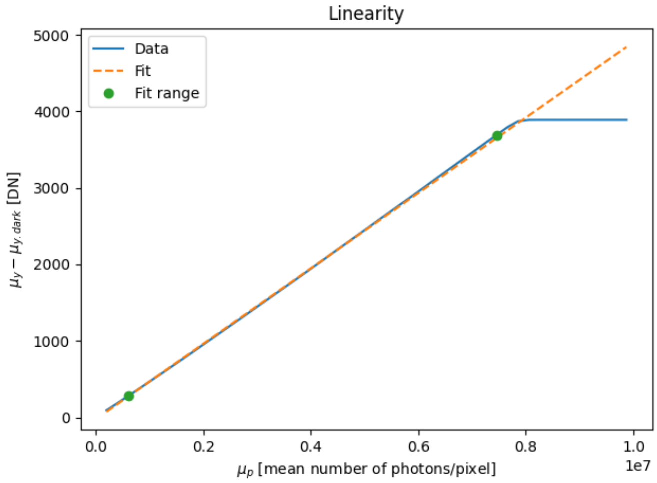


Fig.9. 12bit LN mode Photon Transfer plot

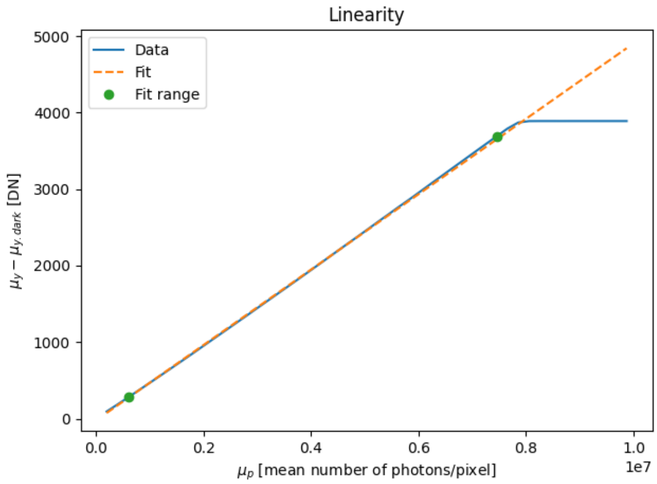


Fig.10. 12bit LN mode Sensitivity plot

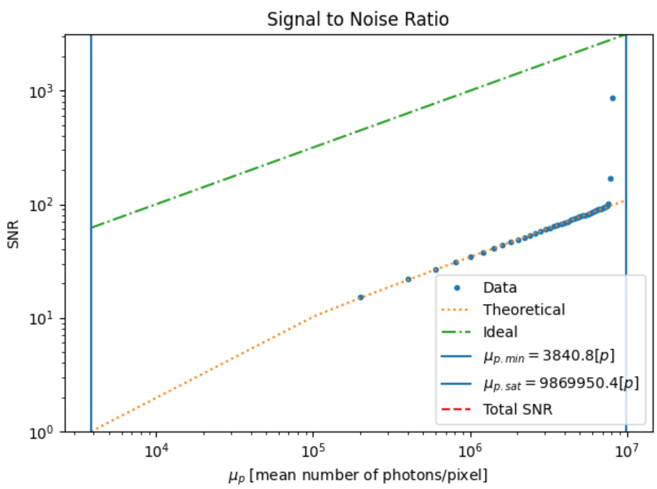


Fig.11. 12bit LN mode SNR plot

TABLE II
MEASURED EM PARAMETERS FOR HIGH GAIN, LOW NOISE 12BIT MODE USING GRADE 2 FSI SENSOR @ 10 °C

| PARAMETER | MEASURED VALUE |
|---|---|
| LINEARITY (0 TO FWC) | Better than 1% |
| DYNAMIC RANGE | 64dB |
| DYNAMIC RANGE (STACK OF 2) | 67dB |
| DYNAMIC RANGE (STACK OF 4) | 69dB |
| SIGNAL TO NOISE RATIO | 39,4dB |
| FULL WELL CAPACITY | 8,7 ke- |
| TEMPORAL READOUT NOISE | 4,8 e- |
| DARK NOISE SENSOR@17°C | 6.03 e-/pix/s |
| DARK NOISE SENSOR@-30°C | 0.37 e-/pix/s |
| DARK NOISE SENSOR@-40°C | 0.24 e-/pix/s |

As observed, the parameters either meet or closely approach the specified requirements. Deviations in linearity results may arise due to the sensor's cosmetics.

In addition, the engineering model was subjected to a number of tests. In particular, the following were performed:

- measurement of the mechanical dimensions;
- leakage measurement of the sensor chamber using vacuum gauges and a helium leakage detector;
- vibration test, also for extreme telescope movement scenarios;
- mass spectrometry testing of the sensor chamber outgassing for long operation without any need for servicing.

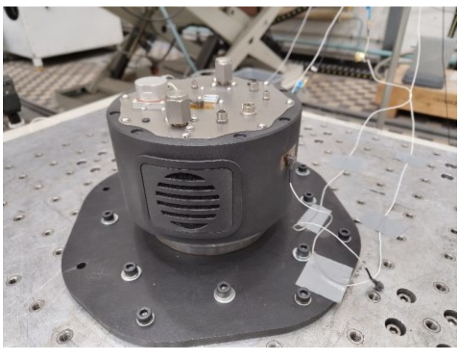

Fig.13. Engineering Model prepared for vibration test

All tests resulted in extremely high-quality results. During the vibration tests, there was also no visible fixed deformation or destruction of the structural components.

Special attention should be paid to the measurement of the tightness and outgassing of the sensor chamber. During the mass spectrometry testing of the sensor chamber, the chamber was pumped down to a vacuum of ~$10^{-5}$ mbar using a set of scroll and turbomolecular pumps, while spectra were measured using a quadrupole mass spectrometer. The recorded spectrum was mainly characterized by the content of gases commonly found in HV vacuum systems: hydrogen, carbon, nitrogen, water vapor, and its derivatives, oxygen, and carbon dioxide. Thanks to the use of suitable materials and special processes, we have achieved results that are close to those of equipment that operates in a very high vacuum, which confirms that the designed device will be able to operate for several years without service. This is a feature unique to this type of equipment.

The Engineering Model prepared to test, is shown in Figures 13, Figures 14. The result of mass spectrometry testing of the sensor chamber.is shown in Figures 15.

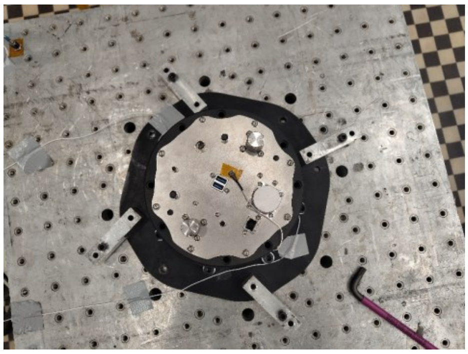

Fig.14. Engineering Model prepared for vibration test

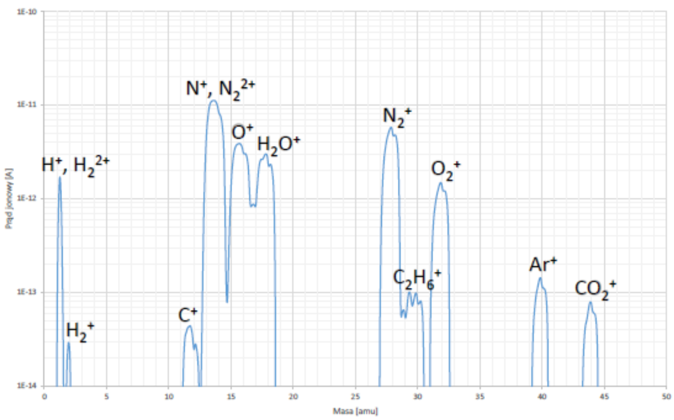


Fig.15. The result of mass spectrometry testing of the sensor chamber

## VI. CONCLUSION

The innovative camera design discussed in this paper is currently in the Final Prototype Model phase of development. Initial characterization results indicate the correctness of the assumed architecture and design. Currently, there are advanced discussions with prospective clients interested in the product.

The CreoSky 6000 camera, outlined in this paper, is designed for flexibility and modularity, allowing for seamless integration of various sensor types, and enabling novel applications. One such application is being explored in the QuantEra project "New Imaging and Control Solutions for Quantum Processors and Metrology," conducted in collaboration with partners from Max-Planck-Institut für Quantenoptik and the Institute of Physics, Zagreb. This project focuses on developing a camera tailored to the requirements of quantum technologies, applied in specific use cases such as improving efficiency and reducing qubit state readout time in quantum computers (critical for error correction) and enhancing the short-term stability of hybrid atomic clocks. Moreover, the camera is slated for use in microscopy and spectroscopy applications in biology and chemistry.

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