Development of new generation sCMOS based imaging devices with edge computing capabilities at Creotech Instruments

Paweł Zienkiewicz(1), Katarzyna Karpińska(2), Bartłomiej Juszczyk(3), Dmytro Pochapskyi(4)

(1) Creotech Instruments S.A., Okulickiego 7/9, 05-500 Piaseczno, Poland, Email: pawel.zienkiewicz@creotech.pl,
(2) Creotech Instruments S.A., Okulickiego 7/9, 05-500 Piaseczno, Poland, Email: katarzyna.karpinska@creotech.pl,
(3) Creotech Instruments S.A., Okulickiego 7/9, 05-500 Piaseczno, Poland, Email: bartlomiej.juszczyk@creotech.pl,
(4) Creotech Instruments S.A., Okulickiego 7/9, 05-500 Piaseczno, Poland, Email: dmytro.pochapskyi@creotech.pl

ABSTRACT

Creotech Instruments is currently developing a new generation of innovative sCMOS-based cameras. The Engineering Model of the astronomical camera intended for Space Surveillance and Tracking (SST) applications is under verification. The device is designed to meet not only the SST requirements but can also be utilized for NEO and debris detection. The overall camera platform can be easily adapted to implement other sensors optimized for applications in quantum technologies, microscopy for biology and others. The novelty of the camera solution resides in the capability of edge computing. The device takes advantage of modern FPGA-based SoC enabling usage of both hard real time processing inside the programmable logic and Linux-based pre-processing. The camera can operate in autonomous mode without dedicated workstation or server. Machine Learning algorithms can be implemented directly on the camera, which can open a novel approach to astronomical applications. The data pre-processing, even simple frame stacking, can significantly reduce the amount of processed, transferred and stored data.

In this paper, the camera concept and architecture are introduced. First results of engineering model (EM) characterization and testing are presented and discussed, especially in the context of specific camera use cases and future further development of the new product line.

1 INTRODUCTION

Creotech Instruments has a long-standing experience in control and measurement systems design, including camera solutions. The new camera development project discussed in this paper stems from the experience gained during, among others, the Pi of the Sky project (cameras for Las Palmas Observatory in Chile), ASOPEK (cameras for Air Force Institute of Technology’s SST telescope), Neostel and PIAP military robotic cameras project. The company has also experience in design of control and measurement systems for High Energy Physics for partners such as CERN, GSI, CCFE, LNLS and others. In recent years, the company has observed two interesting trends in technologies used on the scientific instrumentation market where the company is constantly active:

1. The fast and very promising development and maturation of sCMOS sensors, which have reached performance parameters similar to cutting edge CCD sensors while having much lower cooling requirements and energy consumption levels.
2. Successful development and broad implementation of edge computing or distributed computing technologies, with advantages in many scientific and industrial applications.

The development of high-sensitivity and high-resolution sCMOS sensors with a large frame rate per second (FPS) is attractive for advanced astronomical and SST applications, which makes it interesting to develop a new product able to take full advantage of such sensor parameters. However, such sensors become a source of a very significant stream of data, which leads to high demands on interfaces and infrastructure - data servers and computing resources. On the other hand, in many applications, users are interested only in very specific features or very low-volume information that can be inferred directly from the image. This makes it natural to consider combining the two before-mentioned technological trends and embark on a new approach to camera architecture design, combining high-performance sensors with local computing power of advanced FPGA SoC-based electronics integrated with the sensor. This approach allows for data pre-processing directly on the camera, lowering the outgoing data volume. Moreover, in applications requiring fast feedback and control, the camera can become a trigger source for the control system, allowing for significantly cutting down response times. In distributed systems, a significant level of autonomous operation of the camera can be implemented. Such features are very attractive for SST applications, but also for numerous other scientific or industrial systems.

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2 CAMERA CONCEPT

To address the needs of advanced astronomical applications, the decision to design a new camera, CreoSky 6000, was made.

The key requirements established for the newly created camera platform were:

- Usage of modern low noise, high FPS, 60mm x 60mm active area, high Quantum Efficiency sCMOS sensor with the option of altering the sensor with the smallest possible design changes if needed for the application.
- Maximum size of about 200mm x 200mm for the minimum light obstruction on telescopes with a mass target of about 5kg without accessories aimed for the lowest possible load on the telescope.
- Active sensor cooling with reliable temperature stabilization to reduce the dark noise impact on observations, possibly with air cooling for usage without external heat exchange systems.
- Flexible, configurable I/O set including the general-purpose pins for example for hardware trigger inputs and outputs, shutter operation, external device connectivity through digital buses etc.
- Usage of standard and scalable communication ports such as USB3, Copper gigabit ethernet, Fibre Optic 10Gb ethernet without the need for custom accessories for the camera workstation
- Reliable, standalone operation with a built-in general-purpose operating system enabling customization of the device operation mode and data acquisition and processing pipelines.
- Multiple frame buffer with runtime reconfigurable real-time data processing in the FPGA and Linux
- Possibility to implement custom data processing path with user algorithms in FPGA, Linux and future-proof machine learning capabilities.
- ASCOM and SDK libraries available for easy and rapid user software development
- Time synchronization at the level of at most 1us using the Ethernet medium or GPS.

In order to meet these requirements, the new device was designed, the engineering model was built and is now under characterization. The architecture of the camera, its software and preliminary characterization outcome are presented in the next chapters of this article.

3 CAMERA ARCHITECTURE

To meet the previously presented expectations, a camera architecture design was created to achieve the parameters described in Table 1.

Table 1: 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 (for high FWC mode):	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:	~5kg without external shutter and adapters
Size:	Fi ~202x180 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 in modular fashion so the future modifications such as sensor upgrade, SoC/FPGA change, cooling method alteration or any other need making this platform future-proof and to be able to meet the requirements of applications other than astronomy. The enclosure of the camera was designed to endure harsh environment and is sealed from water and dust. The fan cooling assembly has dust filters and is easily replaceable even in the field. Every connector is prepared to endure not only the humidity but also possible mechanical damage during operation.

The outcome of the mechanical design process is presented in the 3D visualization with the optional iris shutter enclosure mounted is presented in Figure 1, Figure 2 and Figure 3 present the mechanical drawing with external dimensions without the accessories.

Figure 1: 3D visualization of the camera from the backside view with visible basic cabling and shutter adapter.

The mechanical interfacing with accessories such as shutters, focusers, etc. is possible using the multiple threaded hole front plate interface. The accessories can be electrically connected with general purpose Input/Output interfaces and an example of such connection with external is presented in Figure 1.

The camera is able to autonomously operate the shutter during normal operation without any external drivers. The multiple external electrical interfaces alongside the embedded Linux Operating System provide the possibility to achieve a truly standalone system with short control loop and thus supply reliable timestamping of the events and deterministic latency for real-time operation of a complete telescope setup. The time synchronization with the PTPv2 or GPS can provide the accuracy of at most 1us and can be further tuned with added timing signals, for example, precise PPS or 10MHz or triggers, which can be provided to the camera through the signal inputs or be controlled by the camera as outputs. This unique architecture enables the easy creation of a tight coupled camera array which can supply new opportunities for astronomical observations and debris detection. This functionality is further enhanced by the embedded processing capabilities described in the next chapter of this article.

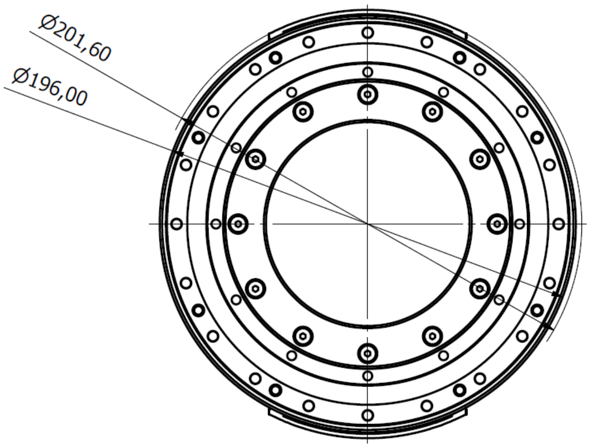

Figure 2: CAD mechanical drawing presenting the camera dimensions, front view.

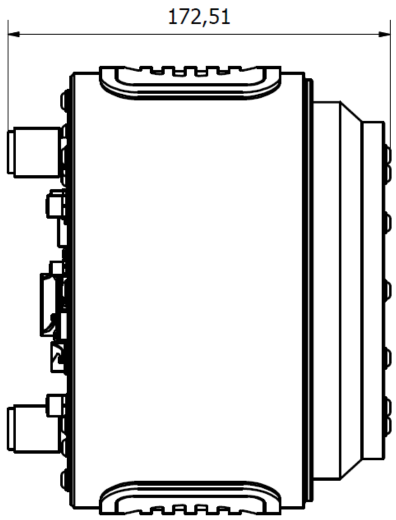

Figure 3: CAD mechanical drawing presenting camera dimensions, side view.

4 CAMERA COMPUTING RESOURCES AND IMAGE PROCESSING

The camera operation is controlled by embedded Linux in autonomous manner. Any disturbance in the Camera to Workstation or Server connection does not affect the camera operation if the storage host is able to receive data from the camera. The multiple frames buffer gives added safety mechanism in case of emergencies. If the buffer is not full, the image data won't be lost.

The usage of embedded Linux supplies the flexibility of the camera operation. The software is implemented in a fault-tolerant manner.

The main components running on Linux handle sensor readout control, data capture, data processing and data output to external systems. The software architecture enables the user to make on-the-fly reconfigurations during the camera operation such as changing the sensor operation mode, selection of the region of interest, data processing pipeline and data output path including, if needed, fits file generation and FTP upload. The software is made in a modular manner so the configuration of the runtime can be adjusted to the user's need. The Linux software suite is actively communicating with FPGA to control the data capture and processing path. This enables rapid path modification.

The camera provides multiple methods of control, such as:

- ASCOM (AStronomy Common Object Model) compatible driver for operation under Microsoft Windows
- REST API - uniform interface for easy interfacing using popular web application manner.
- C++/Python SDK for application development under Windows or Linux
- WWW configuration page that provides the full functionality for ad-hoc camera operation
- Linux Secure Shell with the possibility to operate directly from a shell with an option to write custom runtime applications for both, camera operation and data processing.

The camera architecture is based also on the Xilinx FPGA. The IP block for data processing implemented in the FPGA section provides the user with the ability to perform operations on the collected photos in real-time. Although the module is under development, it provides, among other things, the ability to stack photos or subtract frames from each other. The algorithm is fully configurable from the Linux application via configuration registers. An example of the data processing path is shown in Figure 4. The presented algorithm enables the automatic stacking of up to 16 frames in the FPGA on the fly without any significant performance or latency penalties.

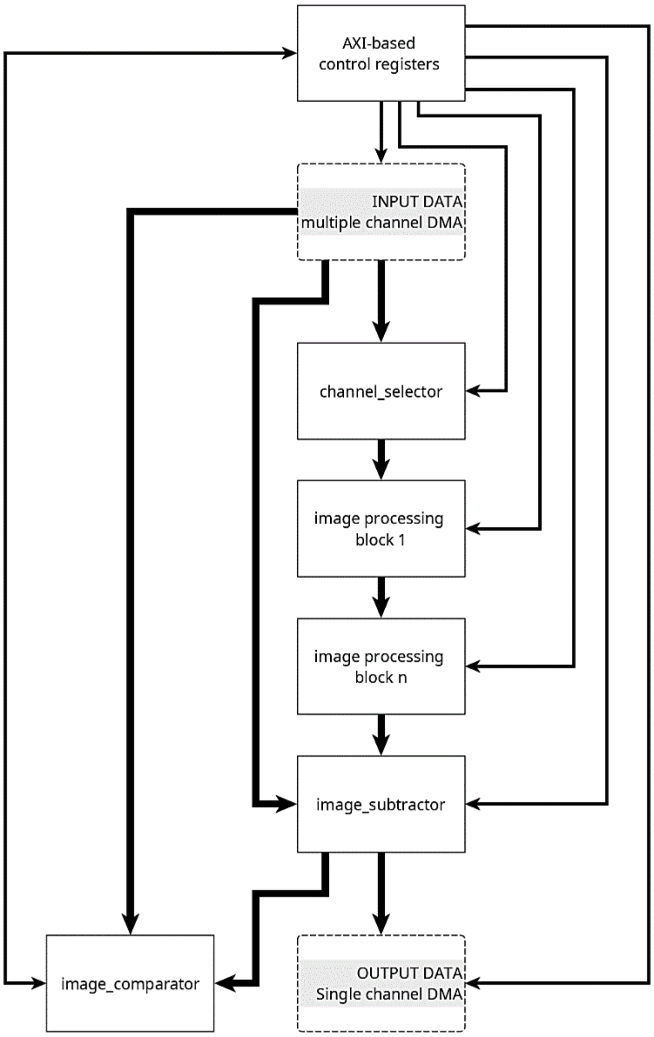

Figure 4: Example of the data processing with simple stacking path implemented in the FPGA.

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 userspace.

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

5 EM CHARACTERIZATION

Currently (January 2023) the camera's EM is still in the process of characterization, but it can be seen that it meets or is close to meet the assumed requirements.

The verification of the Engineering Model was performed using Gigahertz-Optik ISS-30VA reference light source for 300nm to 1100nm spectrum based on integrating sphere with 100mm output port, halogen lamp and photometric monitor with control unit. The tests were performed according to EMVA1288 revision 4 standard procedures. The device under test is shown in Figure 5 and Figure 6.

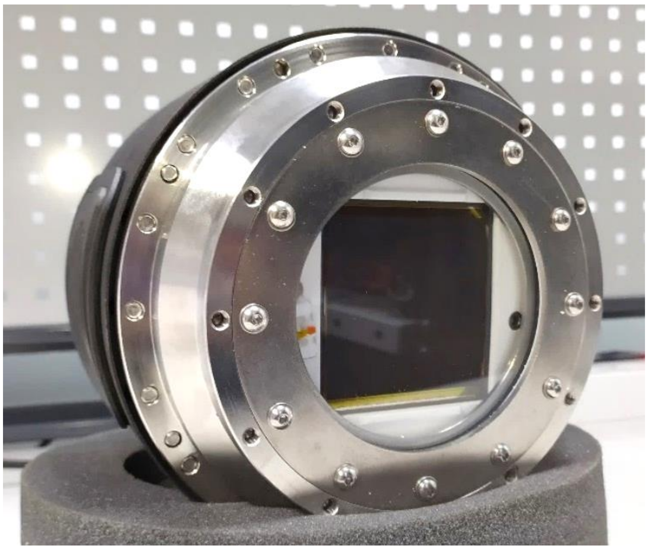

Figure 5: Engineering Model, front view photo

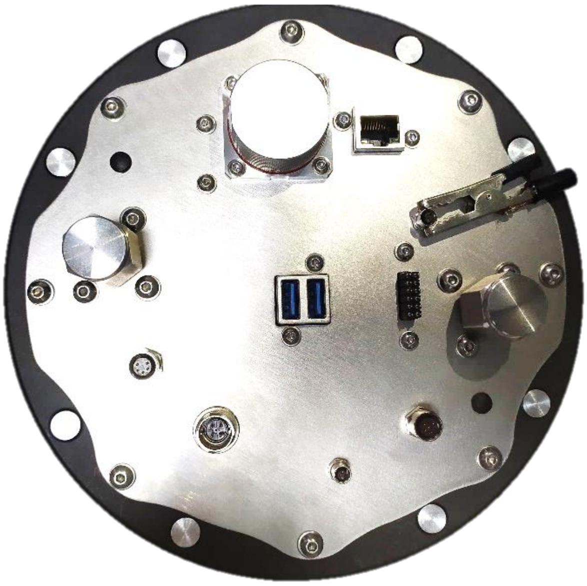

Figure 6: Engineering Model, back view photo, with visible grounding cabling for laboratory usage

For the testing purpose, the sensor was cooled down to 10 degrees Celsius, and the ambient temperature was at about 28 degrees Celsius. The sensor was not cooled down below 10 degrees to represent the worst-case scenario with a very dry environment at about 50 degrees Celsius, where the sensor would be stabilized at about this temperature. The deeper cooling can provide better results in the case of the dark current generation but does not significantly affect other parameters of the readout. The cooling stack with TEC to air heat exchange was verified to achieve continuously at least a 40K difference between the ambient and the sensor temperature. The concept of TEC to water-glycol coolant exchange was also designed and tested. Such a camera could cool down the sensor down to -50 degrees Celsius, depending on the temperature of the coolant and the need of an application. The operating temperature of the sensor should be chosen as a compromise between the parameters and the power drawn from the power supply and emitted to the environment during the sensor operation.

The sensor used in the Engineering Model was Engineering Sample grade – equivalent to a grade 5 sensor. The ES cosmetics do not have any constraints regarding to the amount and character of defects. The computations were based on the 300x300 pixel central region of the sensor. The region contained multiple PRNUs and DSNUs. Further characterization will be performed with at least grade 2 sensor and is expected to be happening in the forthcoming weeks. The 14-bit and HDR modes as well as lower gain, providing higher Full Well Capacity are also implemented and are now under (January 2023) characterization. The highest gain with the lowest noise and fastest readout was verified as the overall performance benchmark assumed as the most valuable for faint object detection and space debris tracking.

The EMVA 1288 test procedure result plots characterizing the 12bit, low noise (high gain) mode are presented in Table 2 and figures:

- Linearity plot in Figure 7
- Photon Transfer plot in Figure 8
- Sensitivity plot in Figure 9
- Signal to Noise Ratio in Figure 10
- Signal to Noise Ratio using stacking algorithm for pair of 2 frames presented previously in Figure 11
- Signal to Noise Ratio using stacking algorithm for pair of 4 frames presented previously in Figure 12

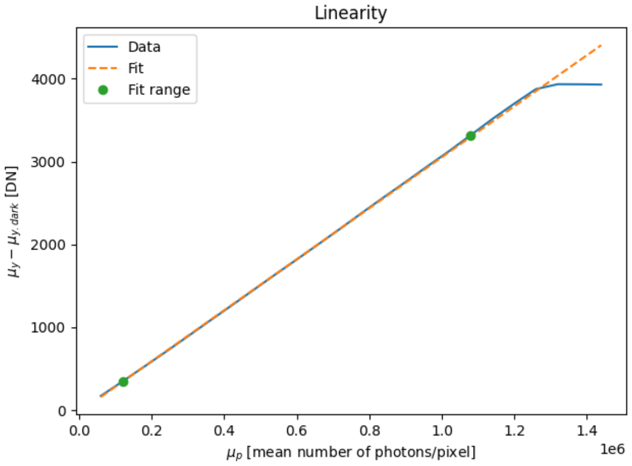

Figure 7: 12bit LN mode Linearity plot

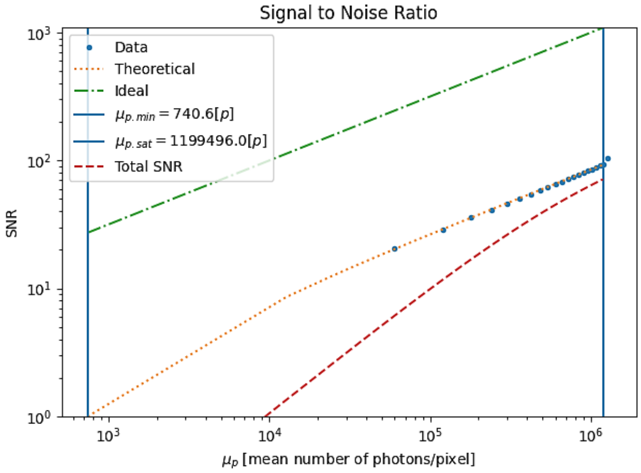

Figure 10: 12bit LN mode SNR plot

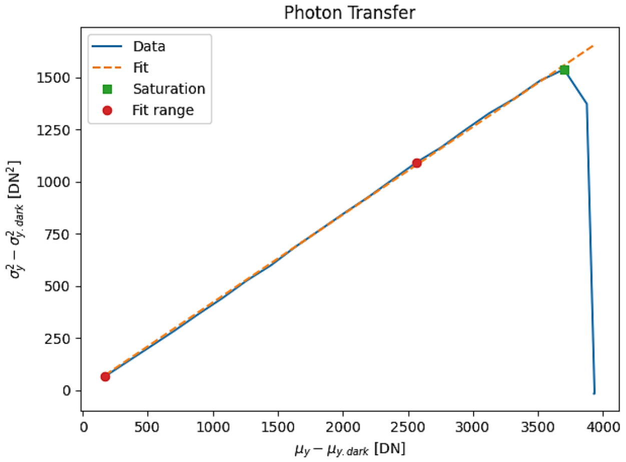

Figure 8: 12bit LN mode Photon Transfer plot

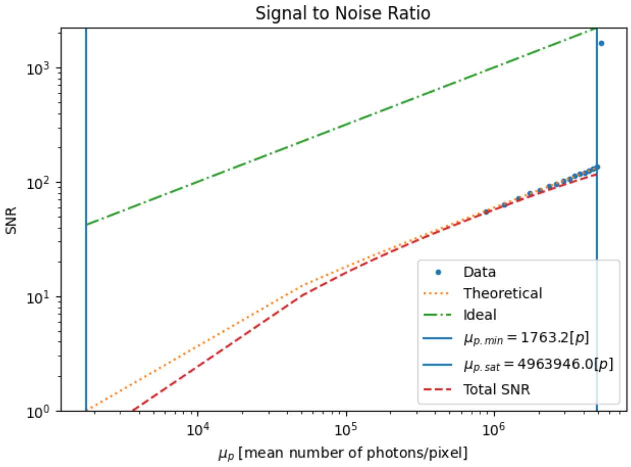

Figure 11: 12bit LN mode SNR plot for two image stack

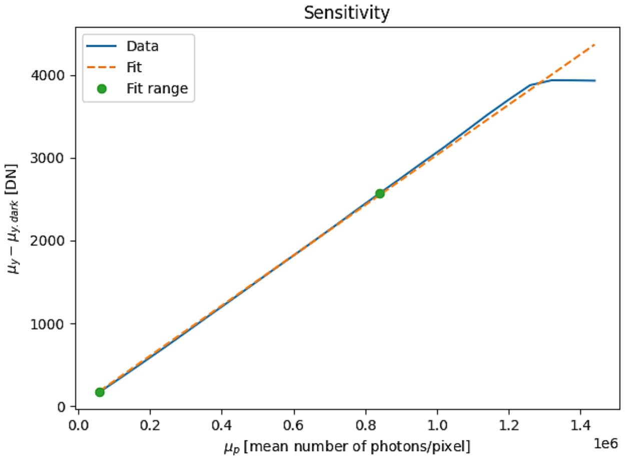

Figure 9: 12bit LN mode Sensitivity plot

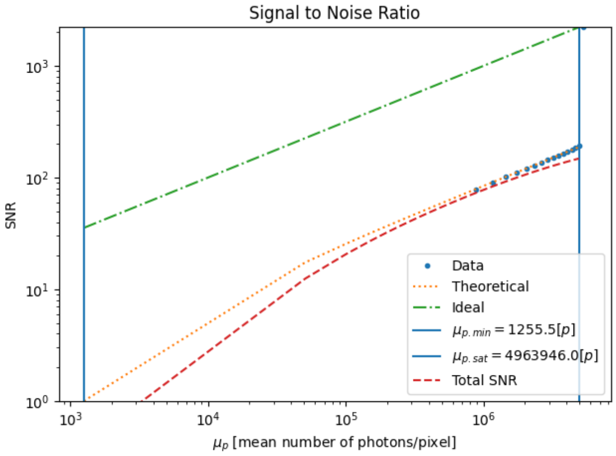

Figure 12: 12bit LN mode SNR plot for four image stack

Table 2: Measured EM parameters for High Gain, Low Noise 12bit mode using grade 5 (ES) FSI sensor @ 10 ºC.

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@17ºC	6.03 e^-/pix/s
Dark Noise sensor@-30ºC	0.37 e^-/pix/s
Dark Noise sensor@-40ºC	0.24 e^-/pix/s

As can be seen the parameters meet or come close to meeting the requirements. In the case of linearity, the results can deviate from the expected because of the cosmetics of the Engineering Sample sensor. The better grade sensor will be characterized in upcoming weeks.

The further development of software and FPGA data processing will be performed to offer rich feature set for the user. The field tests of the CreoSky 6000 are expected to be performed in the forthcoming months and are expected to supply valuable feedback on the further product line development.

6 CONCLUSIONS AND OUTLOOK

The camera design presented in this paper is still under development at the Engineering Model stage. Despite this fact, the initial characterization results indicate the correctness both in terms of the assumed architecture as well as the design and execution. Further product development will be carried out over the next few months and the final product is expected to be ready shortly.

The CreoSky 6000 camera presented in this paper has been designed in a flexible and modular manner, allowing for simple adoption of other types of sensors, opening the possibility of new applications. One such new use case is already pursued in a QuantEra project “New Imaging and control Solutions for Quantum processors and metrology” conducted with partners from Max-Planck-Institut für Quantenoptik and the Institute of Physics, Zagreb. As part of the project, a camera tailored to the requirements of quantum technologies is designed and presented in two specific use cases: a) increasing the efficiency and shortening the time of qubit state readout for quantum computers (crucial for the implementation of error correction); b) increasing the short-term stability of hybrid atomic clocks. Other use cases of the new camera have already been specified in microscopy and spectroscopy applications for biology and chemistry.

7 ACKNOWLEDGMENTS

We thank the entire team working at Creotech Instruments S.A. for their significant contribution to the project without which the creation of this device would not have been possible.

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