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Authors	SANGIORGI, Pierluca, CAPALBI, Milvia, CATALANO, OSVALDO, GIARRUSSO, SALVATORE, Gimenes, R., IMPIOMBATO, Domenico, LA ROSA, GIOVANNI, RUSSO, FRANCESCO, SEGRETO, ALBERTO, SOTTILE, Giuseppe, GRILLO, ALESSANDRO, BONANNO, Giovanni, MARANO, DAVIDE, GAROZZO, Salvatore, ROMEO, Giuseppe, CONFORTI, Vito, GIANOTTI, FULVIO, TRIFOGLIO, MASSIMO
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The ASTRI Camera control software of the ASTRI SST-2M prototype for the Cherenkov Telescope Array

P. Sangiorgi^{a,*}, M. Capalbi^a, O. Catalano^a, S. Giarrusso^a, R. Gimenes^{a,d}, D. Impiombato^a, G. La Rosa^a, F. Russo^a, A. Segreto^a, G. Sottile^a, A. Grillo^b, G. Bonanno^b, D. Marano^b, S. Garozzo^b, G. Romeo^b, V. Conforti^c, F. Gianotti^c, M. Trifoglio^c, for the CTA ASTRI Project

^aINAF - Istituto di Astrofisica Spaziale e Fisica Cosmica di Palermo, Via U. La Malfa 153, 90146, Palermo, Italy

^bINAF - Osservatorio Astrofisico di Catania, Via S. Sofia 78, 95123 Catania, Italy

^cINAF - Osservatorio di Astrofisica e Scienza dello Spazio di Bologna, Via Pietro Gobetti 93/3, 40129, Bologna, Italy

^dInstituto de Astronomia, Geofísica e Ciências Atmosféricas, Universidade de São Paulo-IAG/USP, Rua do Matão 1226, 05508-090 São Paulo, SP, Brazil

Abstract

Within the framework of the Cherenkov Telescope Array (CTA) observatory, the Italian National Institute for Astrophysics (INAF) is leading the "Astrofisica con Specchi a Tecnologia Replicante Italiana" (ASTRI) Project mainly devoted to the definition and development of a set of small-size class telescopes with dual-mirror optical design (SST-2M) for the CTA southern site. The prototype of such telescopes, named ASTRI SST-2M, is installed in Italy at the INAF "M.C. Fracastoro" observing station located in Serra La Nave, Mount Etna, Sicily. In addition to the dual-mirror optical design based on the Schwarzschild-Couder configuration, the ASTRI SST-2M telescope adopts a focal plane camera formed by an array of monolithic silicon photomultiplier sensors coupled with a specifically designed front-end electronics and back-end electronics that represent a further innovative solution for the detection of atmospheric Cherenkov light. The ASTRI SST-2M prototype is currently under completion of the overall commissioning phase: structure, mirrors, camera, control software, data archiving and analysis pipeline. This contribution focuses the attention on the software devoted to the control and monitoring operations of the ASTRI camera. We will provide a brief description of the electronic assemblies and of the software architecture designed, according to software engineering modularization, in terms of functional blocks and how they are deployed in the back-end electronics. Then, we will show how all these functionalities are accessible by the user through the graphical user interface developed and currently used for the engineering tests performed on site.

Keywords: Cherenkov Telescope Array, CTA, ASTRI, SiPM, Software Design, GUI

1. Introduction

The CTA project has the purpose of designing, building and operating a ground-based observatory for very high energy gamma-ray astronomy. CTA [1] will be composed of more than one hundred telescopes located in the Northern and Southern Hemisphere, and will improve the performance of the current generation of

Imaging Atmospheric Cherenkov Telescopes. Three classes of telescopes of different sizes are foreseen, in order to extend the energy range of sensitivity from some tens of GeV up to hundreds of TeV. Italy joined the CTA Consortium with the ASTRI [2] project, led by INAF, which aims at realizing a set of Small-Size Telescopes fully compliant with the CTA specifications. The first step of the ASTRI project has been the development of an end-to-end prototype [3], named ASTRI SST-2M, which is currently concluding the commissioning and

*pierluca.sangiorgi@inaf.it, +39 091 68 09 566

starting the science verification phase. It is installed in Italy, at the INAF observing station in Serra La Nave, located at 1735 m a.s.l. on the Etna Mountain in Sicily. The prototype realization includes the development of mechanical structure, mirrors, camera and calibration system, archive system, software for hardware control [4] and for data analysis. ASTRI SST-2M is characterized by an optical design based on a dual-mirror Schwarzschild-Couder configuration [5] with two mirrors of 4.3 m and 1.8 m diameter respectively. This configuration allows a good angular resolution over the whole field of view of about 10 degree and the use of a compact and lightweight (about 73 kg) Cherenkov camera. The focal surface of the camera is composed of a set of Photon Detection Modules (PDMs), which integrate Silicon Photo-Multiplier (SiPM) sensors coupled with a specifically designed front-end electronics. The sensors are structured as an array of 8x8 pixels, each one having an angular size of 0.19 degree matching the angular resolution of the optical system.

In order to manage the electronic assembly of the ASTRI SST-2M camera, a dedicated control and monitoring software has been designed and developed. In the following, after a short overview of the camera hardware components, we will describe the software architecture, its functionalities and how they can be accessed through Graphical User Interfaces (GUIs).

2. Camera Hardware description

The camera of the ASTRI SST-2M prototype is composed of several components belonging to four hardware main block assemblies: Mechanical, Power Supply, Electronics and Thermal System. Since the camera is controlled and operated by dedicated and customized software and firmware, we provide a brief description of some of the components that are involved in software management. For a more detailed description of the camera and its electronics, refer to [6, 7]. A logical representation of the hardware components of the camera and how they are interconnected is provided in Figure 1.

2.1. Photon Detection Module

The focal plane of the camera is composed of a set of PDMs, shown in Figure 2, which are the electro-mechanical unit containing the SiPMs board, Front End Electronics (FEE) and Artix-7 FPGA Printed Circuit Boards (PCBs). SiPM PCB is formed of one SiPM unit of 8x8 pixels of 7x7 mm and nine precision analog

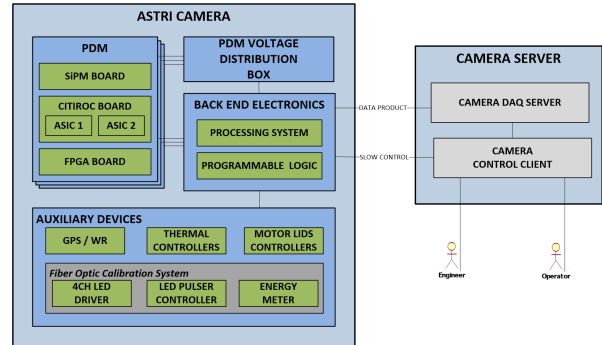


Figure 1: ASTRI SST-2M Camera logical view

temperature sensors used for SiPMs temperature monitoring. The FEE is designed to acquire electrical signals from the SiPMs and it is based on the CITIROC chip and two dual channel 12-bit ADCs that convert low-gain and high-gain sampled values to digital outputs. In order to process the 64 pixels of the PDM, two CITIROC ASICs [8, 9] are connected in a daisy chain. Each ASIC is configured to undertake the desired functions by loading the configuration registers serially (slow control mode). This operation is managed by the Artix-7 FPGA under the control of the Back End Electronics (BEE). The Artix-7 FPGA governs and controls all the operations of the PDM front-end. It is interfaced to the BEE through bidirectional serial lines for slow control operations, housekeeping (HK) information and scientific data transfer. It receives commands from the BEE that are interpreted and dispatched to the CITIROC PCB via a serial line. Once the data are acquired by the FEE, they are returned to the FPGA and dispatched to the BEE.

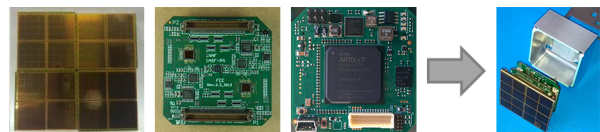


Figure 2: Components of the Photo Detection Module unit and its assembly

2.2. Voltage Distribution Box

All the voltages needed for the PDMs are provided by a Voltage Distribution Box (VDB) that consists of two main boards that can host up to 38 daughter boards, one for each PDM. The VDB converts one low-voltage supply (24V) input to a total of five regulated output

voltages, four low voltages for the power supply of the boards and one high voltage for the SiPM. Moreover, every mainboard provides three additional voltage output and some of them are used for some auxiliary devices. A custom firmware provides control and HK functions which can be accessed by an SPI communication interface.

2.3. Back End Electronics

The BEE is hosted on a custom built electronic board based on the Xilinx Zynq-7000 All Programmable SoCs which is composed of two main parts: a Processing System (PS) formed around a dual-core ARM Cortex-A9 processor, and a Programmable Logic (PL), which is equivalent to that of an FPGA. It also features integrated memory, a variety of peripherals, and high-speed communication interfaces. The PL section is ideal for implementing high-speed logic, arithmetic and data flow subsystems, while the PS supports software routines and/or operating systems, meaning that the overall functionality of any designed system can be appropriately partitioned between hardware and software. Figure 3 shows a sample of our BEE board. We designed it around the Xilinx chip adding two additional Xilinx FPGA Artix-7 in order to manage all the communication with the PDMs and some logic related to them, a set of serial ports for the auxiliary devices and the set of connectors for PDMs and additional sensors of humidity and temperature.

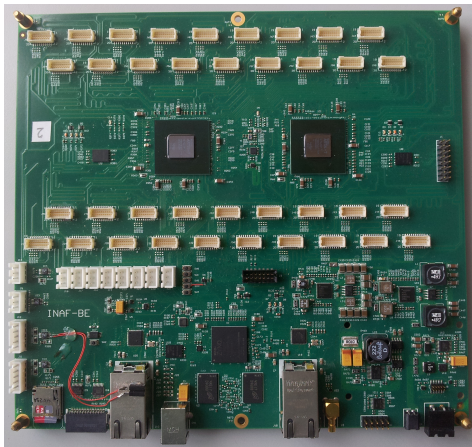


Figure 3: The BEE board with a customized Xilinx Zynq architecture

The BEE represents the elaboration unit of the camera software and is the heart of the electronics, since it is in charge of the complete data and command management of the instrument and it interfaces the detector

to the external world. It performs the following main functions:

- receive commands from the Camera Control Client and perform the related procedures;
- receive data from the front-end in real-time;
- deliver results to the Camera Server System in the required ASTRI packet format;
- perform control and monitoring operations of the auxiliary devices;
- perform a limited number of additional processes upon user request.

2.4. Auxiliary Devices

The camera is equipped with a set of additional devices which are described below.

A compact and lightweight GPS receiver with a precise pulse per second (PPS) output is used for time synchronization and time-tagging of the triggered events. In addition, the BEE provides the required 10 ns precision processing, with a proper circuit embedded in the FPGA part.

The camera is thermally controlled through a thermoelectric system based on 4 Peltier cells controlled by 4 thermal controllers that are connected to the BEE through a RS485 port. The controllers can operate in both heating and cooling modes to maintain the temperature near to the desired value and provide temperature monitoring and functions for the control of the thermoelectric system.

Opening and closing operations of the telescope lids are performed by means of two motor controllers connected through RS485 port to the BEE.

The relative gain calibration of the camera is performed by means of a fiber optic calibration system which includes an I2C 4 channel LED driver to activate the LED of the desired color, an RS232 led pulser to perform full control of pulse width, pulse current and repetition rate. An USB power and energy meter controls the stability of the LED.

2.5. Camera Control Client

The Control Client is represented by a personal computer where the high-level slow-control software is executed. This client represents the entry point for the final user (engineer or operator) who interacts with the camera using GUIs in order to access monitoring and control functionality. The external commands are sent to the BEE and all errors, warning, performance and other reports from the BEE are received by the Control Client.

2.6. Camera DAQ Server

The Camera DAQ Server represents the Data Acquisition (DAQ) Workstation responsible for receiving and storing the different data packets (Housekeeping, Calibration and Scientific) produced by the camera [10, 11].

3. Camera Software description

3.1. Overview

The ASTRI Camera Control Software is organized as a client-server system. The server component runs on the BEE on board of the camera and the client component is deployed on a dedicated computer in the control room. The user interacts directly with the client component through dedicated GUIs and all the requested operations are dispatched to the server component and translated into commands for the camera instrumentations. The communication stack between these two components is managed by the industrial standard protocol OPC-UA and it is totally transparent for the user.

3.2. Architecture

During the requirement elicitation phase we identified the functionalities of the camera to be implemented. We grouped these functionalities in terms of functional blocks according to the technique of modularization and modules decoupling of the software engineering. Once the functionalities were defined, due to requirements related to the elaboration speed and the particular hardware platform adopted for the BEE, we identified two main classes of software components: Slow and Fast. Slow software components are implemented in the PS of the BEE and run over ARM processors under Linux and Java Runtime environment installed on it. Fast software components do not implement particularly complex logic but they are responsible for tasks that require high speed in their execution and for this reason they are realized in the PL side of the BEE. At the end of these processes we defined the architecture [12] depicted in Figure 4 where the functional blocks, their deployment and how they interact each other are represented.

The *Port Handlers* modules manage all the communication ports of the BEE like TTL, RS232, RS485, SPI, I2C and USB. They are responsible of: port reservation and initialization, by specifying the right parameters for communication like baud rate, databit, stopbit, parity bit and flow control; transmission over the port, by sending strings or byte array of data; receiving strings or byte array of data, by using a port event listener which notifies

upcoming port activities. In addition to the functionalities of send and receive data, they also manage communication protocol of request-response type implementing, on received data, exit conditions like prefixed size or token identification and timeout in order to provide replies from interconnected devices as soon as possible. Every interaction with hardware devices connected to the BEE is managed by these modules which represent the low level abstraction layer of the software, responsible to manage the physical layer of the communication. These modules are used by those related to the management of devices equipped with the relative physical port. The use of the object oriented programming allows the reuse of the same module for all those devices which share the use of the same port type.

The *Auxiliary Managers* are a set of components for each auxiliary device which allow to manage the desired functionalities to be performed by the integrated devices. They basically represent a wrapper between the desired high level commands like "open lids", "pulse fiber", "set desired temperature", etc, and proper data in terms of strings or byte array to be sent to the devices in order to perform its configuration. By managing the specific communication protocol, which is defined by the vendors of the devices, they configure the device, monitor a set of attributes and perform actions.

The *VDB Manager* is very similar as concept and internal architecture to the auxiliary managers, but it is responsible of the monitoring and control of the power supply management of the PDM. Since the VDB is not a board provided off-the-shelf by a vendor, the module implements our custom built communication protocol of the VDB in order to switch on and off low and high voltages of the PDMs, and keep track of some parameters to ensure that the PDMs work always in the proper range of voltages. It also provides commands to allow to turn on and off some auxiliary voltage outputs where some auxiliary devices are connected. In this way we can turn on devices like motor lids controllers and fiber pulser for a limited time only when they are really needed, increasing their lifetime.

The *PDM Manager* is responsible of the control of the PDMs. It implements our custom built communication protocol of the PDM in order to initialize the PDM, send, write and execute the configuration tables for the ASICs and the FPGA, reset the FPGA modules and request data relative to different acquisition modes and purpose (calibration, housekeeping, variance, scientific). Commands and data sent through the slow serial interface of the BEE are firstly routed by a dispatcher to the desired PDM according to the protocol message. Messages are received by the FPGA of the

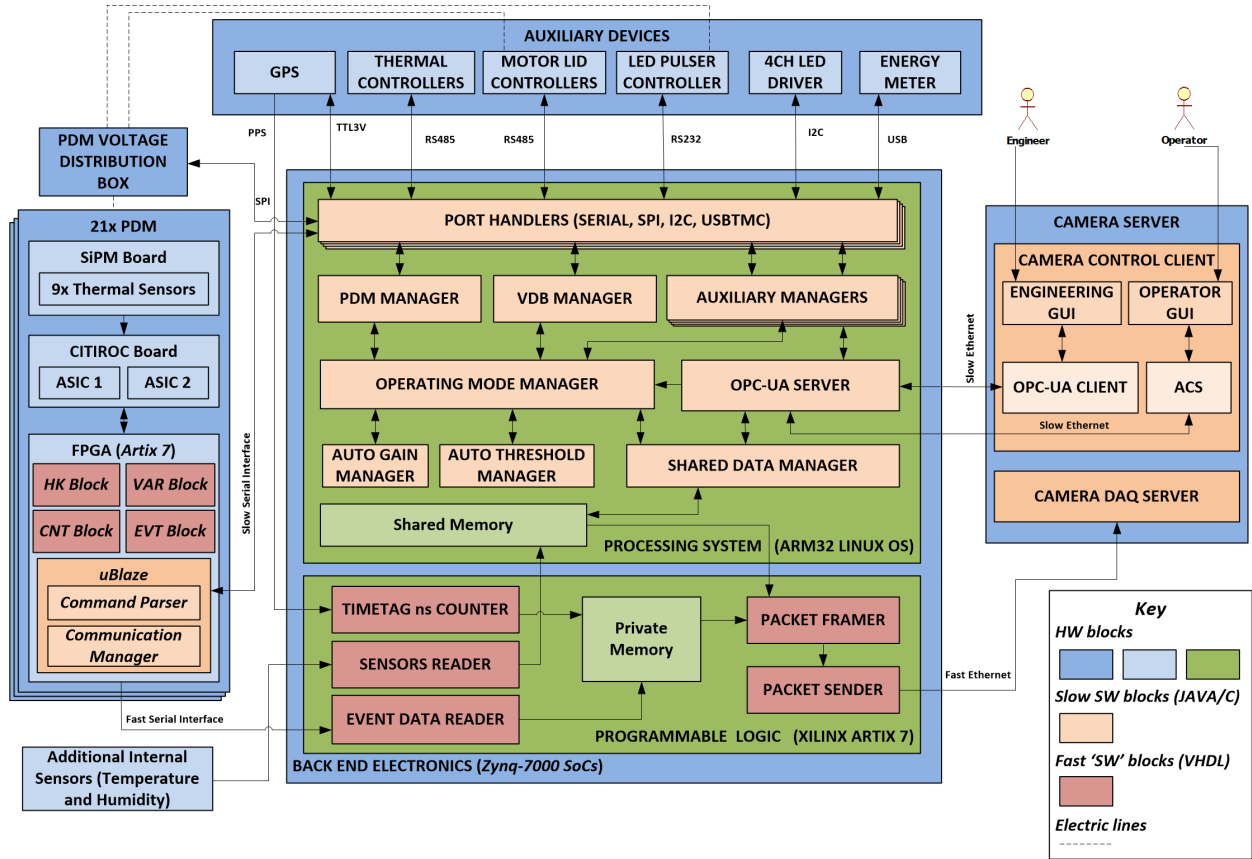


Figure 4: Camera Software Architecture

PDM which implements, in a firmware deployed in a MicroBlaze soft processor, the communication protocol manager and the command parser. Once a command is correctly received and recognized, the firmware sends requested data or activates the proper lines of the hardware modules, realized in VHDL, to perform the corresponding functionalities of housekeeping, variance, calibration and scientific acquisition.

The *Operating Mode Manager* handles all the operations of the subsystems of the camera needed for the specific operational mode (Idle, Scientific, Calibration). It receives the command corresponding to the operation requested by the user and the related parameters and prepares the proper CITIROC and FPGA configurations for the FEE to be dispatched by the PDM Manager. Simultaneously, it schedules all the needed operations requested for that particular mode using functions provided by the other modules with which it is interconnected. As an example, in a relative calibration operational mode it provides the high voltage to the PDM

through the VDB Manager, closes the lids through the motor lid manager, starts the pulsing of the fiber optic calibration system, sends the proper configurations to the PDMs defining the trigger threshold, the topological trigger, the acquisition time, and so on. Once all the requested procedures are accomplished, the manager applies the configurations to all the PDMs, the operating mode starts and the readout data are acquired and stored in the camera server. During the scientific operation mode, this module also performs continuous monitoring of SiPM temperatures of the PDMs and the trigger rate of the focal plane and passes these data to the *Auto Gain Manager* and *Auto Threshold Manager* modules. These two modules make the camera a dynamic control system able, through specific algorithms, to dynamically evaluate the ideal PDM configurations for the runtime context [13, 14].

In the PL side of the BEE we have mainly the modules that require major priorities in terms of speed and then are not suitable to run under an operating system. The *Sensor Reader* is used for continuous monitoring of

additional temperature and humidity sensors installed in several points of the camera. While the auxiliary manager related to GPS device in the PS side is responsible of the continuous read of the time with a precision of one second, the *Timetag ns Counter* provides high precision time information for the timetag of the events with a precision of 10 nanoseconds. This is done by using a simple counter, clocked at 100 Mhz, controlled by the signal of the PPS responsible of the reset of the counter and the camera trigger signal responsible for reading of the value every time a scientific event occurs. During the scientific mode the PDM works as master device and the data related to events, which are not predictable, are automatically sent to the BEE. These data are collected from all the PDMs by the *Event Data Reader* module which passes them to the *Packet Framer* module. This is in charge to organize these data, plus additional information, according to the current operating mode in a packet data format compliant with the ASTRI telemetry specification. This additional information is provided by the BEE PS side through a shared memory accessible from the user space and managed by the *Shared Data Manager* module. This implies that the entire process of scientific data acquisition and sending, which is the crucial activity for the camera, is totally managed in parallel with the operating system. In this way it is managed with higher priority and without affecting or being affected by computational complexity. All described modules implement the functionalities requested for the camera. But as the BEE is installed in the camera itself on board the telescope, we developed the *OPC-UA Server* and *OPC-UA Client* modules in order to implement the client-server architecture and provide to the users all the functionalities of the camera from the camera control client through graphical user interfaces. Functionalities provided to the Operator GUI are managed by an additional level of software implemented in the module. This module makes use of the Alma Common Software (ACS) framework [15] to implement the ACS Camera Component that communicates with the Camera OPC-UA Server and implements two main functions: Camera parameters monitoring and Camera control commands.

3.3. Engineering Graphical User Interface

For the performance verification phase of the ASTRI project, an engineering GUI [16] has been developed, allowing to manage the instrument in order to execute the normal operations and also for specific test and recovery operations. Several commands for expert users together with a lot of information and tools for the system monitoring are available in the engineering GUI.

Information and controls are coupled in a way that the software can be used by engineering users with strong knowledge of the instrument from the point of view of the electronics providing an high level of granularity to hardware devices control, as well as users performing science acquisition during observation night. It is designed, in fact, in a user friendly way providing a Main GUI (Figure 5) containing only the more important monitoring data and the set of commands more frequently used. Additional information and configurations are accessible for particular operations through a number of sub-GUI. Information and controls in the main GUI are grouped according to their context in different sections of the screen.

In the top bar there are status monitor of the connection between the camera on the telescope and the control client where the software is running, buttons for the access to tools of real time visualization of acquired data and a set of buttons for the management of every hardware subsystems of the camera.

In the left part of the screen is located the section *Focal Plane Monitoring* which offers monitoring information of data related to the focal plane of the camera, like values of temperature and humidity sensors, current dead time, trigger rate of the camera, identifier of the current acquisition process of the Camera Server and the current number of telemetry packets sent to the Camera Server for the acquisition processes of housekeeping, variance, calibration or scientific data.

The other information, specifically related to the PDMs, are displayed in a specific graphic component that visually represents the focal surface of the camera. For each PDM the component displays three values in a vertical raw related to different quantities that the user can choose from a list. The choice to limit the number of quantities simultaneously visualized is due to the graphical space available on the screen as well as to the readability aspect, but if the user is interested to monitor at the same time all the information of a PDM, he can simply perform a click over the interested PDM in the graphic component and a new window will appear with all the details.

In the center of the screen is located the *Operating Mode* section which displays the current state of the camera and allows the control operations of the camera, related to the operating mode management for the acquisition processes of housekeeping, variance, relative calibration and scientific data.

The *Thermal Control* section displays monitoring information about the thermal control system of the camera. Here the user can basically check the status of the system, the temperatures reached compared to the de-

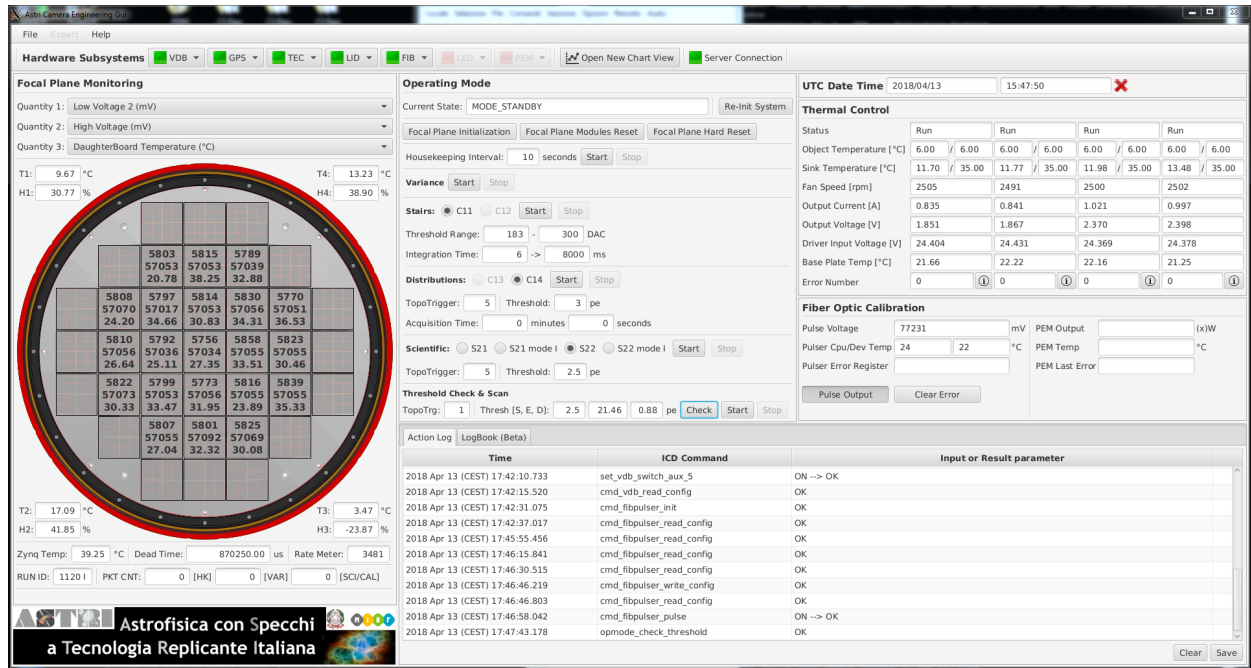


Figure 5: Camera software main engineering gui

sired temperatures, the speed of the fans and so on. This group of information is very important for the commissioning phase because all the possible weather conditions of the site can not be reproduced in laboratory and the response of the SiPM have a strong dependency from the temperature.

The *Fiber Optic Calibration* section displays monitoring information about the fiber pulser device and provides controls to turn on and off the fiber in order to perform relative calibrations. While the fiber is pulsing, a graphical feedback is given to the user by a pulsing yellow ring around the focal plane graphic component in the Focal Plane Monitoring section.

The *Action Log* section displays in a table every action performed by the user. The information is composed of three values: the time when the operation is performed, the operation requested identified by a unique id and the result of this operation returned by the system. In this way the user can check if his actions have been successfully executed as well as have a summary of what he did.

3.4. Embedded tools

The ASTRI Camera software, in addition to its control and monitoring functionalities, provides integrated tools for several functionalities like quick look visualization of some type of data acquired that are displayed

in real time in parallel to their storage in the Camera Server, management of expert configurations of the system, calibration procedures and operations to speed up the normal acquisition operation. Some of this tools are described below.

3.4.1. Quick look of Housekeeping data

During a session of HK acquisition, user can see graphical representation of housekeeping data by opening the proper window shown in Figure 6. The tool provides five different charts where it is possible to display quantities selected by the user. Four of them are line chart and are useful to show trend over time of data, the last one is a bar chart where display same data related to all the PDMs and evaluate the distribution of that quantity on the focal plane.

3.4.2. Quick look of Variance data

The variance acquisition is a particular operating mode of the ASTRI camera that measures the statistical fluctuation of the SiPMs signals and allows the evaluation of the night sky background [17]. During this kind of acquisition, the user can see graphical representation of variance data by opening the proper window shown in Figure 7. Data will be automatically plot in the graphic component that represents the focal plane. It is possible

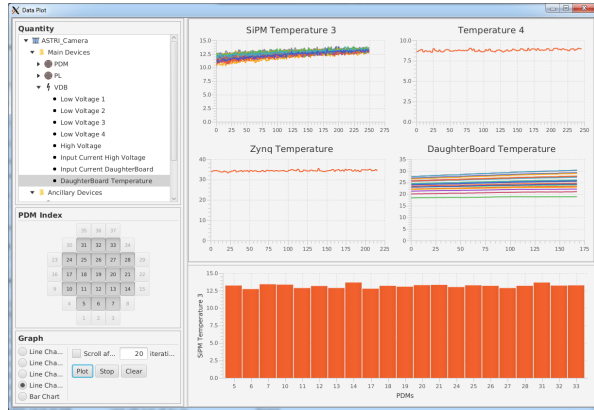


Figure 6: Quick look visualization of HK data

to choose whether display data in a color scale automatically calculated for each event or in a manual color scale with minimum and maximum values specified by the the user. Additional radio buttons allow to select the coordinate system (camera-view or sky-view) to represent the data on the focal plane.

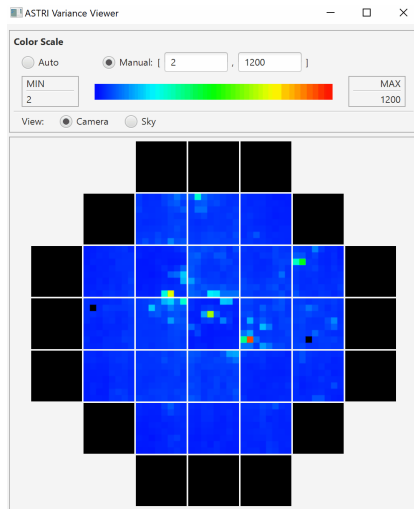


Figure 7: Quick look visualization of Variance data

3.4.3. Threshold scanning

This function was implemented to provide to the user a tool to evaluate the trigger rate of the camera at different values of the trigger threshold. It does not produce any data storage on the Camera Server in order to provide a fast computation and reduce the amount of data stored. Once the user specifies the value of the

topological trigger, the range of trigger threshold typing minimum, maximum and delta values in photo electrons units and how much accurately the computation should be performed, the process will run for a while until all the thresholds are evaluated. Once the process is completed, a new window (Figure 8) will appear with the results of the computation in terms of values in a matrix and a chart representation of those values. An output file with these results will also be produced. This tool provides to the user an easy way to select the correct threshold value for the observation.

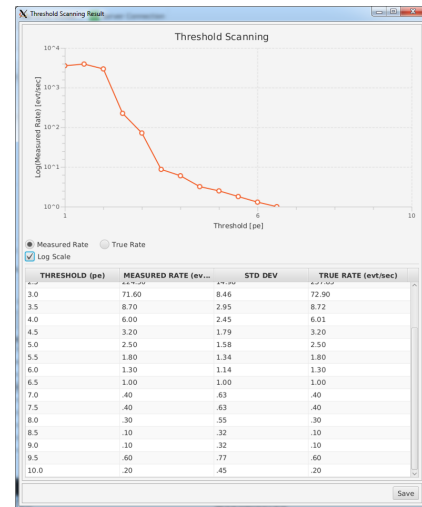


Figure 8: Output result of the scan threshold process

4. Conclusions

The software for the control and monitoring operations of the ASTRI camera has been developed and extensively tested. It has been used during all the camera commissioning activities in laboratory and on site. Some features were implemented and integrated in the software package to provide useful tools for the performance validation and scientific verification phase. The expertise acquired with the ASTRI prototype handling will be the basis for the design and implementation of an array of pathfinders to be placed at the CTA Observatory southern site.

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