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The innovative Cherenkov Camera based on SiPM sensors of the ASTRI-Horn telescope: from the T/M and electrical design to the full assembly and testing in a harsh environment

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ABSTRACT

ASTRI-Horn is a prototypal telescope of an imaging atmospheric Cherenkov telescope developed by the Italian National Institute of Astrophysics (INAF), proposed for the Cherenkov Telescope Array (CTA) Observatory. The CTA Observatory represents the next generation of imaging atmospheric Cherenkov telescopes and will explore the very high-energy domain from a few tens of GeV up to few hundreds of TeV. It will be composed of large-, medium-, and small-sized telescopes; ASTRI-Horn is an end-to-end prototype proposed for the Small Sized array.

The main scientific instrument of the ASTRI-Horn telescope is an innovative and compact Camera with Silicon-Photomultiplier based detectors and a specifically designed fast read-out electronics based on a custom peak-detector mode. The thermo-mechanical assembly is designed to host both the entire electronics chain, from the sensors to the raw data transmission system and the calibration system, and the complete thermoregulation system.

This contribution gives a high level description of the T/M and electrical design of the Cherenkov Camera, it describes the assembling procedure of its different subsystems and their integration into the complete camera system. A discussion about possible design improvements coming from the problems/difficulties encountered during assembly is also presented. Finally, results from engineering tests conducted in-field are also presented.

Keywords : imaging atmospheric Cherenkov telescope, very high-energy gamma rays, Cherenkov Telescope Array, ASTRI, SiPM, assembling

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1. INTRODUCTION

In 1989 the detection of a clear signal at teraelectronvolt (TeV) energies from the Crab nebula opened a new window in the field of astrophysical and astroparticle Physics research with ground-based instrumentation [1] . The use of Imaging Atmospheric Cherenkov telescope (IACT) is now a solid technique with enormous scientific potentiality.

More than 150 sources have been detected up to now thanks to the current major arrays of IACTs: H.E.S.S.[2] VERITAS [3] and MAGIC [4] Many astrophysical source classes have been established, some with many well-studied individual objects, but there are indications that the known sources represent the tip of the iceberg in terms of both individual objects and source classes.

The future infrastructure devoted to deepen the study of astrophysical sources at these energies is the Cherenkov Telescope Array (CTA). It will be the major global observatory for very high-energy gamma-ray astronomy over the next decade and beyond [5]

CTA will cover a huge range in photon energy from 20 GeV to 300 TeV, it will improve with respect to current instruments on all aspects. A wider field of view and a better sensitivity will permit to survey hundreds of times faster than current instruments. The angular resolution will approach 1 arc-minute (at high energies) allowing detailed imaging of a large number of gamma-ray sources. An improvement of nearly two order-of-magnitude in the collection area makes CTA a powerful instrument for time-domain astrophysics.

Exploring the extreme universe the scientific spectrum of CTA is extremely broad: from probing environments from the immediate neighborhood of black holes to cosmic voids on the largest scales. Moreover, the CTA observatory will exploit synergies with gravitational wave and neutrino observatories as well as with classical photon observatories. Combining CTA data with those from other instruments in a multi-wavelength and multi-messenger approach will lead to a deeper understanding of the broad-band non-thermal properties of gamma-ray emitters.

The Observatory will operate arrays on sites in both hemispheres to provide full sky coverage and will hence maximize the potential for the most rare phenomena such as very nearby supernova, gamma-ray bursts or gravitational wave transients. At the southern site three classes of telescopes are planned to be installed: Small Size Telescopes (SST), Medium Size Telescopes (MST) and Large Size Telescopes (LST), see Figure 1. In the northern site, only MST and LST are envisaged.

Concerning the SST class of telescopes, different options are available for the implementation of the CTA observatory. The Italian National Institute for Astrophysics (INAF) leads one of these; ASTRI-Horn is the end-to-end telescope prototype developed in this context. Others options under study can be found in [6] and [7] .

The ASTRI-Horn prototype is the basis of the ASTRI telescopes that have been proposed for the CTA SSTs sub-array. A Mini-Array composed of nine ASTRI telescopes is being developed and operated by INAF in the context of the preparatory effort for participating in CTA. This proposal is a collaborative effort led by INAF along with Institutes from Italy, Brazil, and South Africa [8] .

The ASTRI-Horn end-to-end telescope prototype is installed in Italy at the INAF observing station located in Serra La Nave (Mt. Etna, Sicily), 1740 m a.s.l. [9] Its dual-mirror optical layout is based on the Schwarzschild-Couder design allowing a nearly constant optical resolution over a wide field of view. The mirrors have a profile with a strong aspherical component; they have been manufactured via glass shaping technologies ad-hoc developed [10] and [11] First results about the optical validation of the telescope are presented in [12] The focal surface instrument, the Cherenkov Camera, is based on an innovative concept conceived and realized in INAF that results in a compact, low-power and smart instrument [14] .

The first detection of the Crab TeV source obtained with ASTRI-Horn in presented in [15] .

In the following sections we give an overview of the design and solutions adopted for the Cherenkov Camera; we comment about the assembling procedure, the in-field tests and possible improvements to be made for the forthcoming Cameras of the Mini-Array.

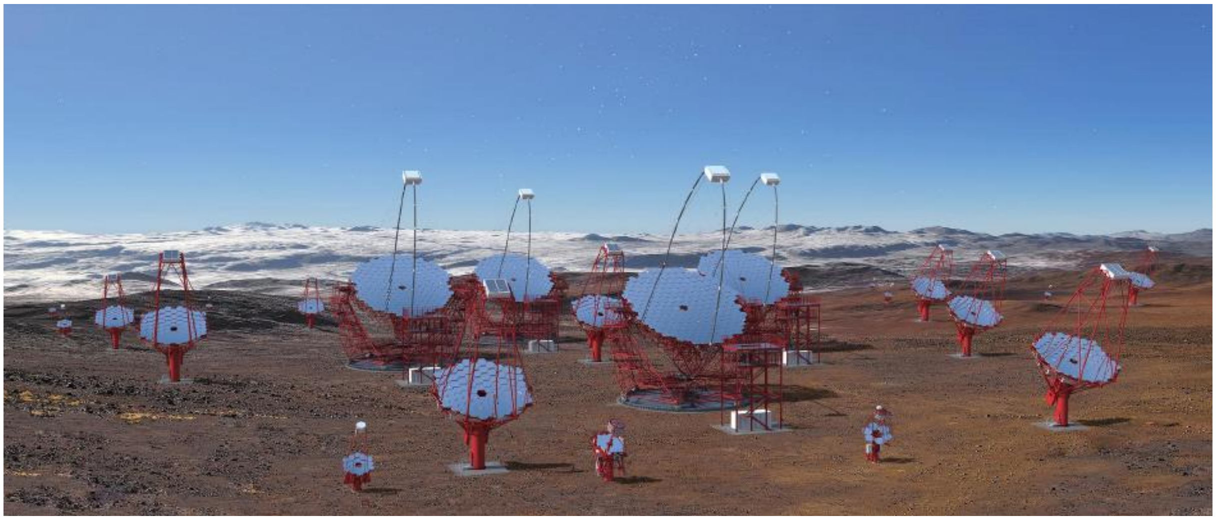

Figure 1 An artistic view of the telescopes composing the CTA Observatory. SST, MST and LST are shown in scale.

2. THE CHERENKOV CAMERA DESIGN

The optical design adopted by ASTRI-Horn presents some peculiarities of the focal surface: it has a large field of view with a nearly constant angular resolution across it, it has mm-size Point Spread Function (PSF) and a de-magnifying power. All these characteristics have been the design drivers for the Cherenkov Camera. In particular leading the use of Silicon Photomultiplier (SiPM) array as sensors to compose the curved focal surface. These sensors are an innovation in the field of Cherenkov Telescopes that has started few years ago with the project FACT [13] when a refurbished HEGRA mechanical structure has been equipped with a Camera composed of single pixels GAPDs coupled with Winston cones to match the PSF and physical size of the detectors. The ASTRI-Horn Camera represents a step forward on this path because the use of cutting edge SiPM arranged on a monolithic tile of 8x8 pixels.

As second, the signals coming from the detectors are collected and manipulated by proper ASICs that recognize and hold-on the signal's peak. This read-out chip has customized signal shaper and peak detector circuitry; it provides high efficiency auto-trigger capability and very fast camera pixels read-out. Other noticeable characteristics are very low power needs (300mW/chip), low data transfer (just two values/pixel/event), one discriminator output per pixel (for instance, for topologic trigger generation) and the internal DAC for fine-tuning the bias voltage of the pixel (one for each input channel). Again, this electronics represents an innovative and unique solution with respect to the classical signal sampling technique adopted so far on Cherenkov Telescopes.

The camera trigger is a topological one that is activated when the signal rises above a given threshold in a programmed number of contiguous pixels. A GPS receiver is used for time synchronization and to time tag the triggered events. Data registered by the Camera either at the occurrence of a trigger condition (the so called scientific events) or upon user's request (calibration and/or housekeeping data) are then automatically sent to the camera server.

A more detailed description of the ASTRI-Horn camera working principles can be found in [15] and [14] .

Coming to a more hardware-oriented description of the camera, the main components can be organized in the following groups: the thermo-mechanical assembly, the Photon Detection Modules (PDMs), the Back-End Electronics (BEE), the Voltage Distribution Boards (VDB) and the ancillary devices. In the following subsections we give a description of each group. A blow-up view of the camera is shown in Figure 2. The envelope, at closed lids, is of about 520 x 660 x 560 mm for a total mass of 75 kg.

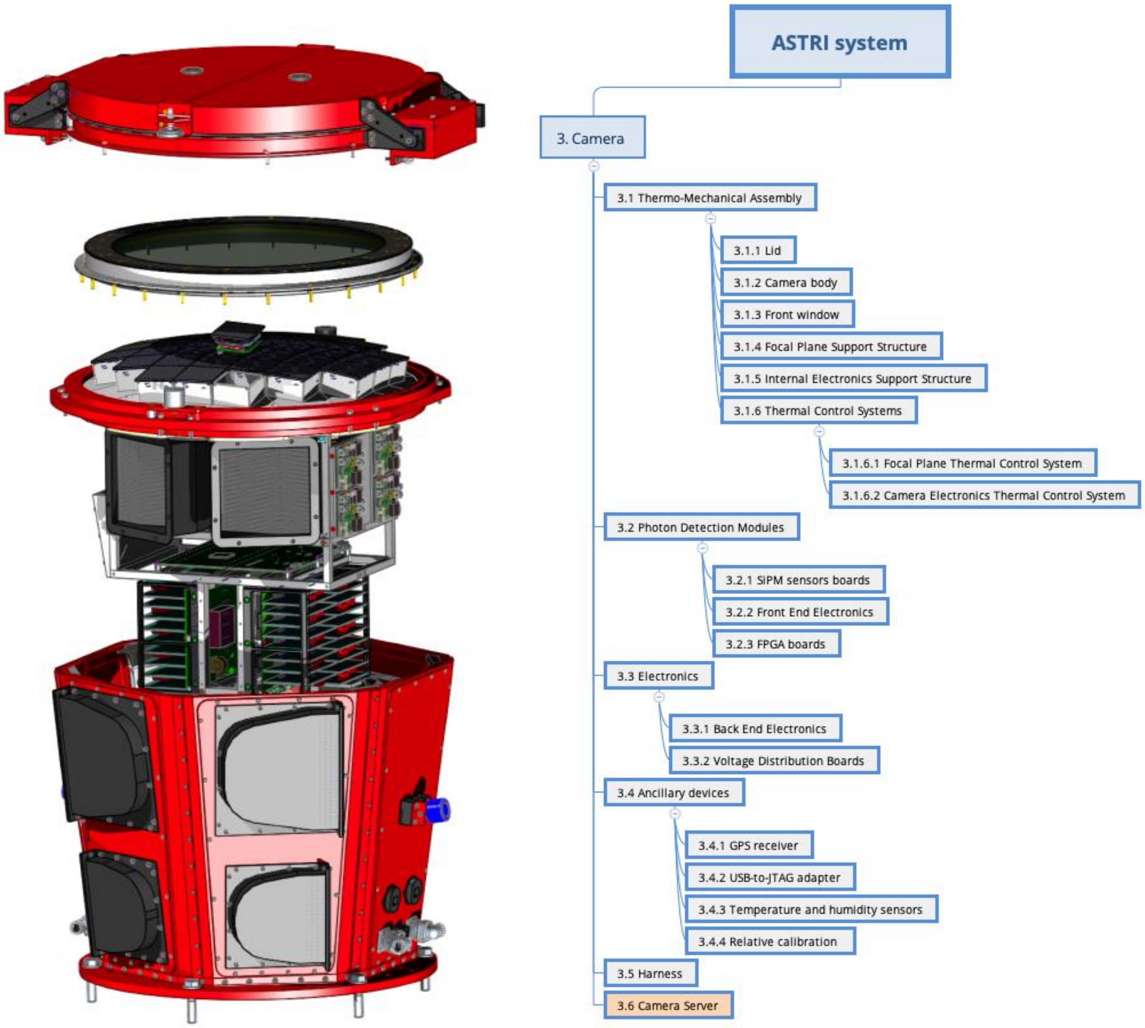

Figure 2 Blow-up view of the ASTRI-Horn camera (left) and its product breakdown structure (right).

2.1. Thermo-mechanical assembly

The camera body is the main mechanical part; it has a truncated cone shape on a dodecagonal section. It has been manufactured in Aluminum. Its main parts are:

- the bottom flange to interface the telescope structure;
- the backbone with 6 large removable panels that create access windows on the electronics. The panels also give interface to power, network and other devices;
- the upper flange to interface the focal plane support structure (FPSS), the lids and the front window.

Other mechanical parts of interest are:

- the lid that close with a light tight the focal plane. This allows us to calibrate the camera on-site while maintaining a controlled environment;
- the front window is the entrance of the photons. It protects with a watertight seal the PDMs and plays an important optical role;

- the internal electronics support structure that hosts and interfaces all the internal electronics and devices of the camera. It exhibits an high modularity structure;

However, the design solution adopted for this camera does embed also the thermoregulation system with the mechanical parts playing an active role on this.

The thermal control of the ASTRI-Horn camera makes use of 4 peltier devices installed on the bottom surface of the focal plane support structure. These units, properly driven by thermoelectric controllers, can both heat-up or cool-down the focal plane in such a way to keep the SiPM sensors at the desired operating temperature of 15±2°C. In more details the system works as follow.

The heat generated by the PDMs assemblies (hence by the SiPM themselves and by the Front-End Electronics (FEE)) is drained toward the peltiers by the boxes that gave mechanical support to the boards and by the focal plane support structure. The FPSS, that host up to 37 PDM modules, is a disk of Aluminum alloy properly machined that embeds a grid of heat pipes. Heat pipes are used to spread the heat and minimize the thermal gradients across the PDMs. Each peltier unit is than linked to a heat sink composed by a stack of metal foils blown by fans. The temperatures of the cold face of the peltier units and of the heat sink are monitored and used to feedback the thermal system.

It worth a better explanation the role of the front window: it encloses the focal plane support structure equipped with the PDMs granting protection from the site environment, in particular against dust, water and humidity. Nevertheless, the main action is not related on these aspects, but on the performance of the camera. Since the SiPM sensors exhibit a remarkable sensitivity up to wavelengths of 800-900 nm the front window attenuates the infrared income from the night sky background where the actual contribution from the Cherenkov signal is very modest. This happens thanks to an appropriate filtering system. In fact, the front window is composed by a stack of 3 disks of Spectrosil® glass double-coated with a multilayer based on ZrO_2 and MgF_2 recipe. The transmission response of the assembly returns a cut of the signal for wavelengths above 550 nm.

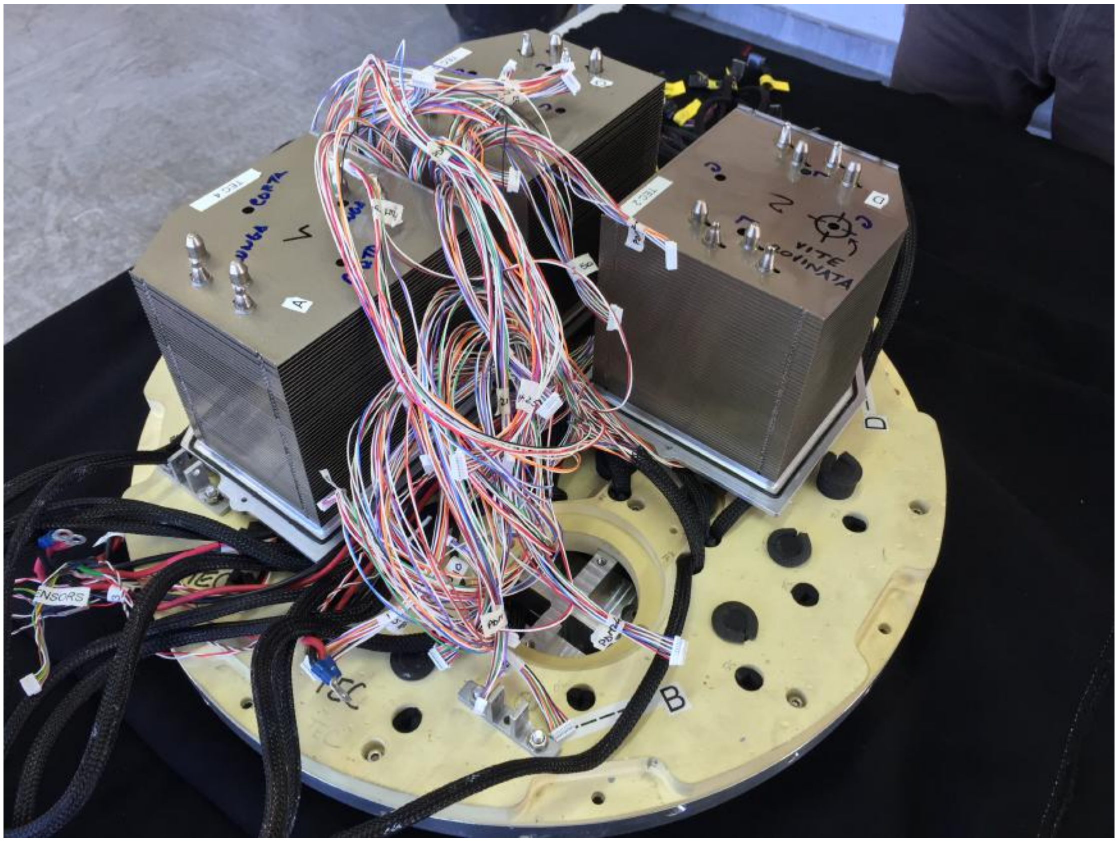

Figure 3 Some components of the thermal system of the ASTRI-Horn camera. Three out of four heat sinks installed on the bottom surface of the FPSS.

2.2.Photon Detection Module

The PDM is a box of about 57x57x30 mm that condenses a number of elements. It is the unit that contains the SiPMs sensors board, the FEE board, the FPGA board and the mechanical enclosure. See Figure 4.

Each PDM module is mechanically interfaced to the FPSS through a bolt screwed from the bottom side of it and 2 pins for centering. Thermal interfaces materials are used at each mechanical interface, both between boards and mechanic and toward the FPSS, to diminish the thermal resistance of the assembly.

The SiPMs sensors board is a monolithic tile that contains 64 pixels LCT5 type. Each pixel has dimensions of about 6.95x6.95 mm^2. The bottom side of the board hosts 2 40-pin electrical connectors for signals routing and 9 analog thermal sensors DS600+ for temperature monitoring purposes, plus minor electronics components. Details of the SiPM can be found in [17] .

Directly connected to the SiPM board is the FEE board that is in charge of the acquisition of the scientific signals. Since the SiPM sensors exhibit very fast response and excellent single photoelectron resolution, they need properly tailored electronics to handle with these features. It consists in 2 32-channel ASIC chips that read the faint pulse signals from each pixel, amply it and perform the required processing. The ASIC used in the ASTRI-Horn camera is CITIROC (Cherenkov Imaging Telescope Integrated Read Out Chip) [18] Each input channel is coupled in AC and has 3 separate chains to govern the high gain, the low gain and the trigger outputs. After programmable pre-amplification stages (one each for high and low gain) the fast pulse goes trough the slow shaping stages that integrates the signal with a programmable shaping constant. The shaped signal is than stretched by a peak detector circuit that allows acquiring the relevant information: peaking time and signal integral value (proportional to the incoming energy of the primary photon). Beside this, the signal also goes trough the fast shaping stage that is coupled with a programmable discriminator to set a threshold level for trigger generation output.

The FEE board is interfaced to and managed by the FPGA board. It hosts an ARTIX 7 chip from Xilinx. It provides the needed operations as setting up of CITIROC registers and operating modes, reading-out and delivery of digitalized data. The FPGA also preforms topological trigger algorithms and PDM-level trigger generation. Among the other tasks performed by the FPGA, it also performs a continuous sampling of the pedestal signal of each input channel thus evaluating, second per second, the variance of the samples. This gives information about the light that in average hits each pixel of the camera.

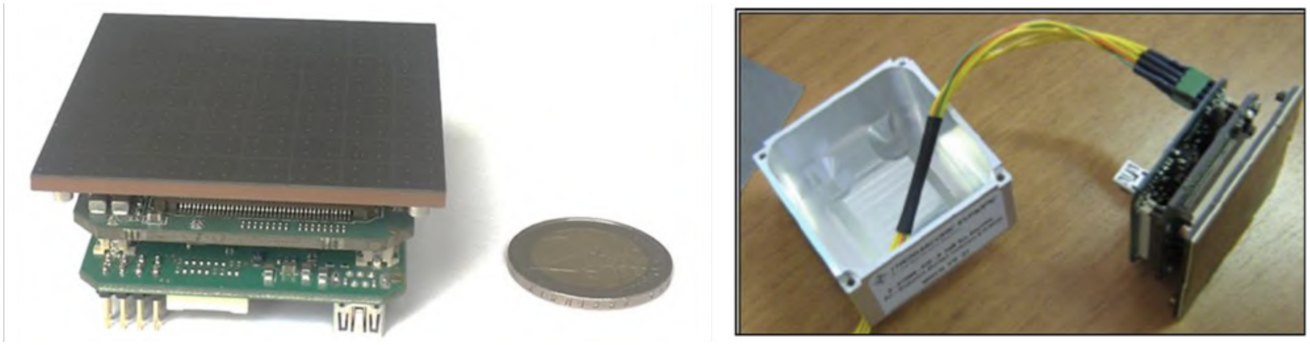

Figure 4 Electronics boards stack composing the PDM. The coin gives a dimensional reference to highlight the level of compactness.

2.3.Back-End Electronics

The BEE is a separate board about 220x250 mm wide that perform a number of common duties (see Figure 5). It is based on a powerful ZYNQ-7000 having a System on Chip feature that allows running a Linux-based operating system. The BEE is the contact point between the operator and the hardware of the ASTRI-Horn camera. It manages the communication with the PDMs, with the camera server (DAQ) and camera controller, with the VDB and with all the ancillary devices. Each command sent and/or data sent/received to/from the camera pass through the BEE. Moreover, the main tasks in charge of the BEE are: PDM trigger signal routing, provide clock and event time tag, storing events in a local memory, data packing and transmission toward the DAQ, operating modes management.

The BEE board hosts two more FPGAs from Artix family. In fact, since all the connections between the BEE and the PDMs are realized with differential lines to minimize the noise that can be captured/emitted by all other wires in the camera, the BEE have to buffer near six hundreds of signals. The ZYNQ chip does not have such number of I/O pins while the use of external buffers would lead to a prohibitive population of on-board chips on the BEE. The Artix solved the problem: using them, almost exclusively, to buffer the signals between the BEE and all the PDMs.

Concerning the real-time scientific data processing the main steps managed by the BEE are as follow. In case the BEE receives a trigger from one or more PDMs, it routes back this signal to all the PDMs of the focal plane. The PDM triggers undergo a decision algorithm to validate it. This could be used, for instance, to vetoing the trigger for unwanted PDM's combinations. If it is a valid trigger, this marks the start for the acquisition of an event. The data are sent, using SPI protocol, from the PDM to the BEE through a fast serial line. The data received by the BEE are then formatted, packed and sent to the DAQ through a dedicated LAN connection. The BEE is a real-time data processing system capable of consuming and processing events data at a rate up to 4 kHz.

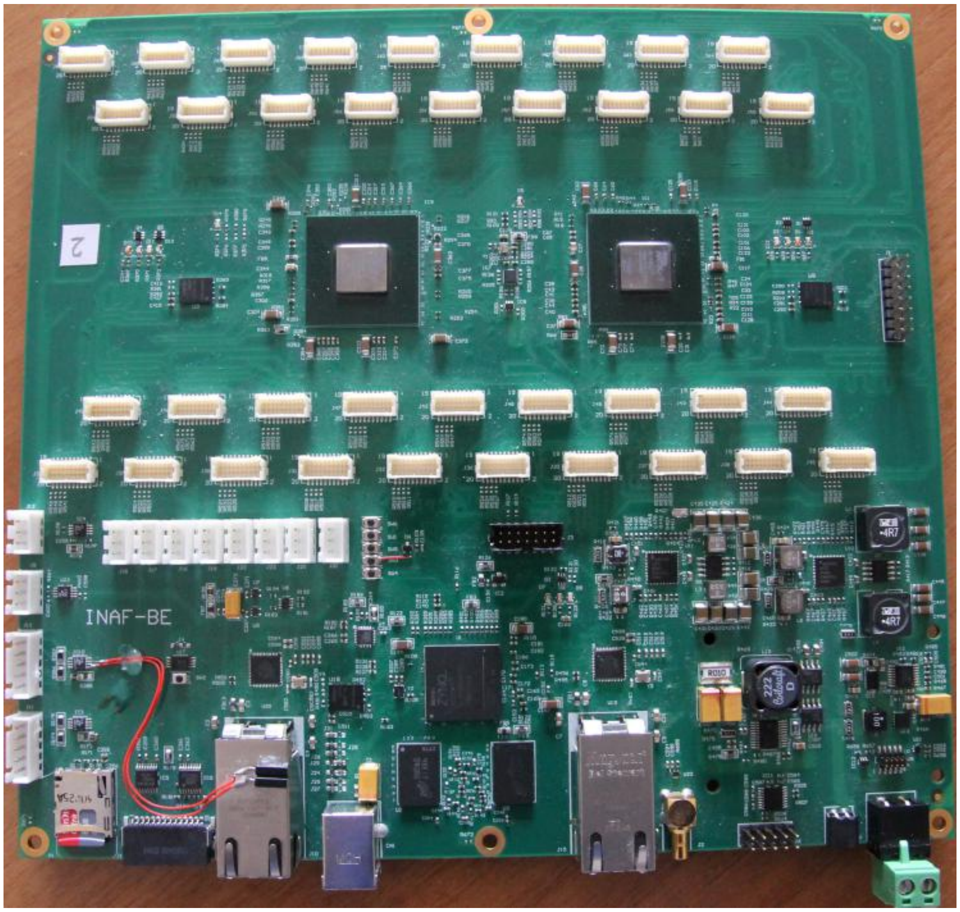

Figure 5 The Back-End Electronics board on-board the ASTRI-Horn camera.

2.4.Voltage Distribution Boards

The VDB is the equipment that provides the correct regulated voltages to all the PDMs. Moreover, it power supplies also the ancillary devices. It is composed by two mainboards and a set of 37 daughter boards.

The two mainboards are connected to the BEE in a daisy-chain way. Each of them is powered by a 24V DC line and has one power output at +5V, one at +12V and provides interfaces to 19 daughter boards. Each daughter board is devoted to supplies a single PDM providing him with +5.5V, +3.6V, -3.3V to power the FEE board, +7V to power the FPGA board and a high voltage to bias the SiPM sensors.

The BEE can command the switching ON/OFF of each single voltage of each main- and daughter- boards. Moreover, the high voltage line can be regulated between 35V and 75V to accommodate different SiPM sensors. This regulation can be done with steps of few mV to fine tune the bias supply on the basis of the current operation conditions.

All the outputs are protected against short circuit or excessive current. In particular the high voltage is provided with slow rising/setting ramp.

Housekeeping functions on voltages, currents and temperatures are available for monitoring of the VDB status.

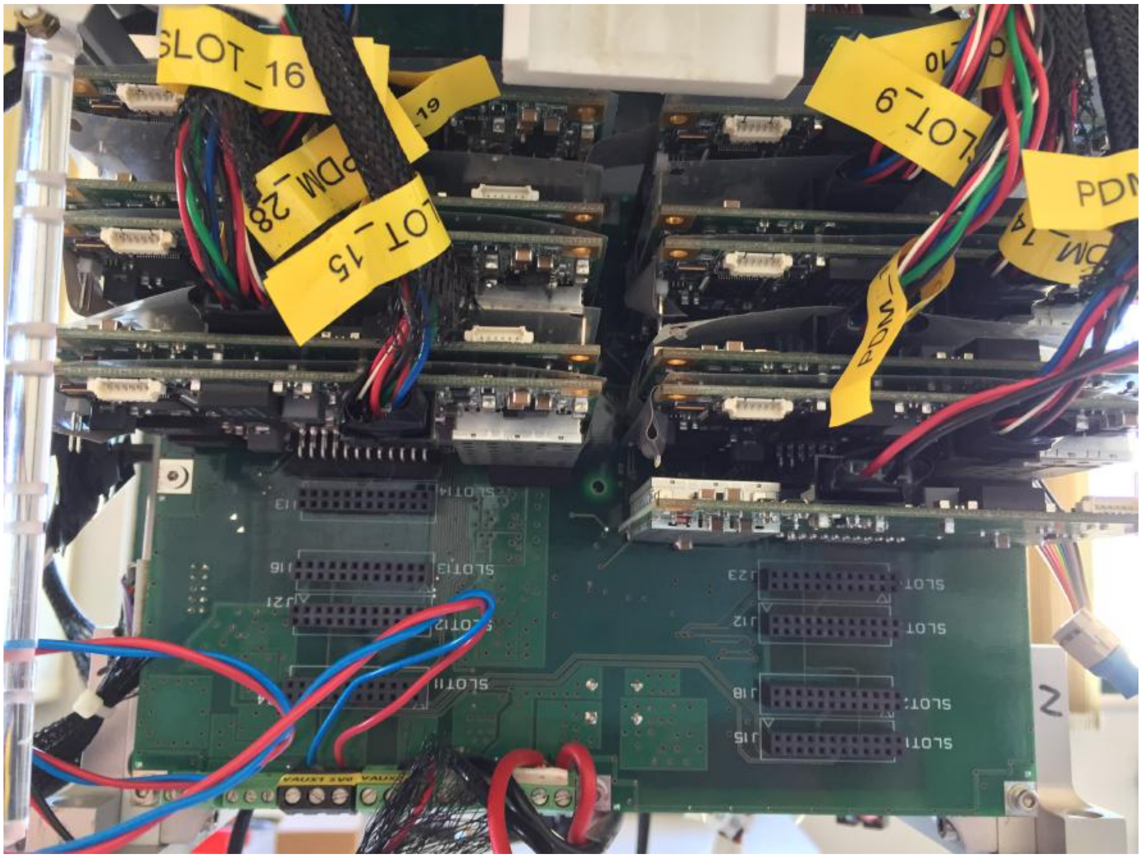

Figure 6 The Voltage Distribution Board integrated on its supporting structure. The picture shows one mainboard partially populated with daughter boards.

2.5.Ancillary devices

Other devices complement the functions of the ASTRI-Horn camera. In particular the camera hosts:

- a commercial GPS receiver board;
- an USB to JTAG adapter;
- a set of temperature and relative humidity sensors to monitor those parameters inside the camera body and around the focal plane area;
- a subsystem for relative calibration of the PDM.

The GPS receiver is used to give the reference time to the camera. In fact, each event triggered and recorded by the camera is time-stamped using the pulse per second output provided by the GPS. Actually, the BEE provides the time information with about ten nanoseconds precision, thanks to a proper circuit embedded in the FPGA part. The GPS board is directly installed on top of the BEE while a proper cable links, through a proper interface on a panel of the camera body, to an antenna placed on board the ASTRI-Horn telescope structure.

The BEE follows the JTAG protocol; for debug and firmware upgrades an USB-to-JTAG converter is permanently hosted inside the camera body. An interface is placed on a panel of the camera body for easy access.

The camera body hosts all the electronics of the ASTRI-Horn camera; it is protected against accidental water ingress but it is not waterproof. Moreover, it has ambient air forced ventilation devices as part of the thermoregulation system. A number of sensors have been placed to monitor the temperature and humidity inside the camera and the BEE directly reads them. Additional sensors are placed also in the focal plane proximities.

The ASTRI-Horn camera is equipped with a subsystem that allows its relative calibration. A laser LED source is installed inside the camera body and driven, through the BEE, by a proper hardware. The system can pulse the laser with programmable frequency and duty cycle. The light emitted by the laser is guided to the focal surface using an optical fiber. This fiber runs around the entrance window where a proper supporting flange ensures optical contact with one of the Spectrosil® glass disk of the window. Since the optical fiber is cladding-free it glows from side and the light can enter and propagate through the glass disk. A fraction is also emitted out of plane of the disk so reaching the SiPM sensors. A calibrated photodiode is installed on the termination of the optical fiber to monitor the outgoing light. Details on the calibration strategy can be found in [19] .

2.6.Camera software architecture

The camera is controlled and operated by dedicated and customized software and firmware. The software, which implements the functionalities for data and command management of the instrument, is located in the BEE that represents the elaboration unit of the camera software.

The software system is basically composed by the open-source ALMA Common Software (ACS) for the high-level interface and the industrial-standard Process Control Unified Architecture (OPC-UA) for interaction with the hardware. To maintain a high grade of decoupling with the specific hardware adopted, the layers composed by ACS and OPC-UA define the interaction between user and subsystem in terms of high level commands.

While the layer composed by the camera software is responsible to implement the interfaces required by the previous layer. This is done translating incoming commands in terms of management of physical communication ports and external auxiliary devices provided by several vendors, data exchange between hardware subsystems. In this way the camera software layer is able to manage all the hardware devices in terms of monitoring and control with a high degree of granularity as well as with a low degree combining different commands to perform more complex operations. In the same way, combining different commands of different devices, the software implement the operating mode and the business logic of the entire camera in order to allow the data production functionality of the Camera.

The functionalities have been grouped 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, two main classes of software components have been identified: slow and fast. Slow software components are implemented in the processing system part of the ZYNQ FPGA of the BEE and run over ARM processors under Linux and Java Runtime environment installed on it. The high-level slow-control software 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. 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 programmable logic side of the ZYNQ FPGA of the BEE.

The defined architecture of the camera software is depicted in Figure 7 where the functional blocks, their deployment and how they interact each other are represented; details in [20] .

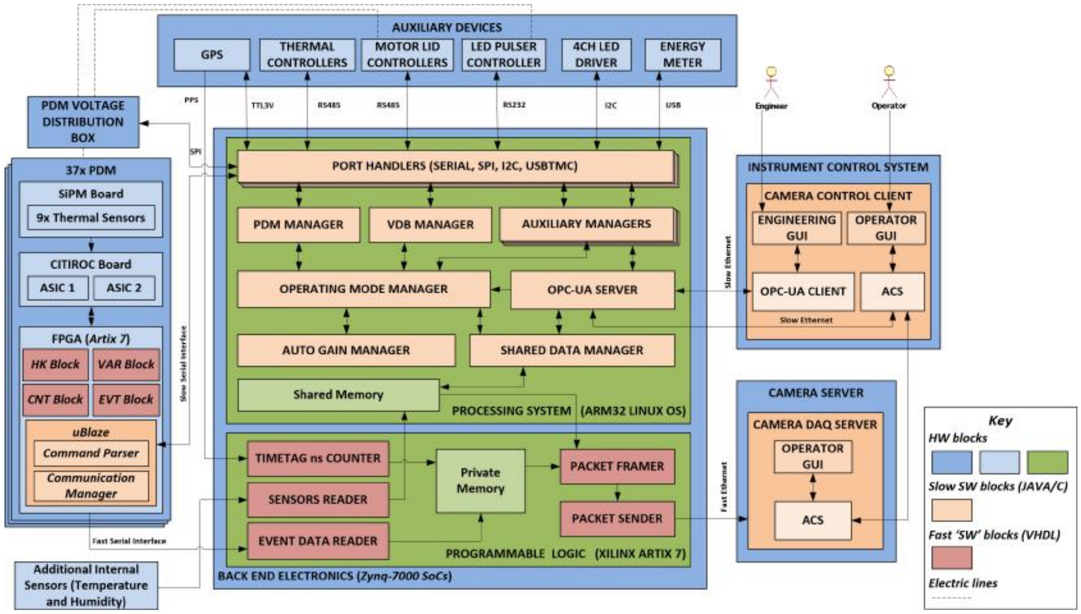

Figure 7 Camera software architecture.

3. THE ASSEMBLY PROCEDURE

The ASTRI-Horn camera is a complex system where mechanical, thermal, electrical, optical, software and firmware aspects have to be combined together and matched to grant a well working system. Hand in hand with design go the assembly, integration and verification aspects that sometime can suggest solutions or express needs.

In the case of the ASTRI-Horn camera this approach not always has been applied, unfortunately. Sometimes because of lack of clear design requirements, other times because of unexpected changes in requirements have forced the implementation choices.

Nevertheless, logic and organic assembling plan and procedures have been drawn and followed. Coupled with this plan also a testing flow has been made available. The testing flow helps in spotting out possible errors or inaccurate assembling.

The flow diagram of the assembly plan is shown in Figure 8 while the tests associated with each assembly phase are shown in Figure 9. As it can be seen, the test suggested on almost each phase is the same. We measure:

- the "stair", i.e. at very low light level (or in dark condition) we count the photons varying the threshold. The typical plot looks like a staircase where we get important information about the threshold of each pixel;
- the "pulse height distribution", i.e. we pulse light at a predefined frequency and we measure the height of the triggered events. The typical plot looks like a series of fingers where distance between the peaks of two adjacent fingers is the photoelectron equivalent gain.

The values registered pixel by pixel for all the camera pixels have to be invariant, or minimally affected, from one integration step to the other.

It has to be remarked the importance of the chosen procedure as detailed in figure: even if seem repetitions, it turned out to be a great problems spotter.

In the following a description of the different blocks is given.

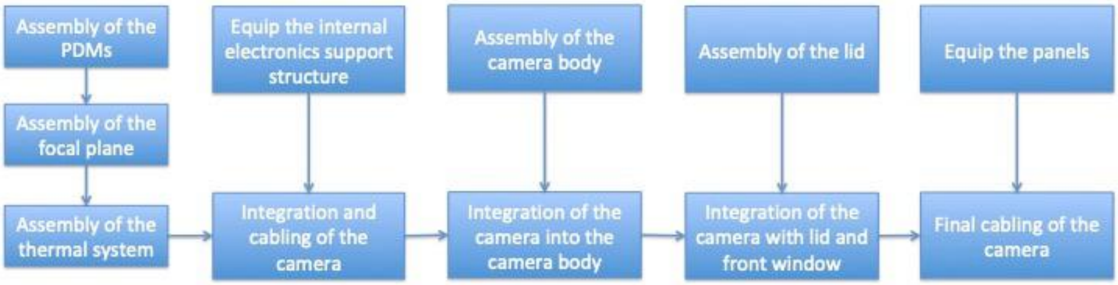

Figure 8 Assembly plan of the entire ASTRI-Horn camera.

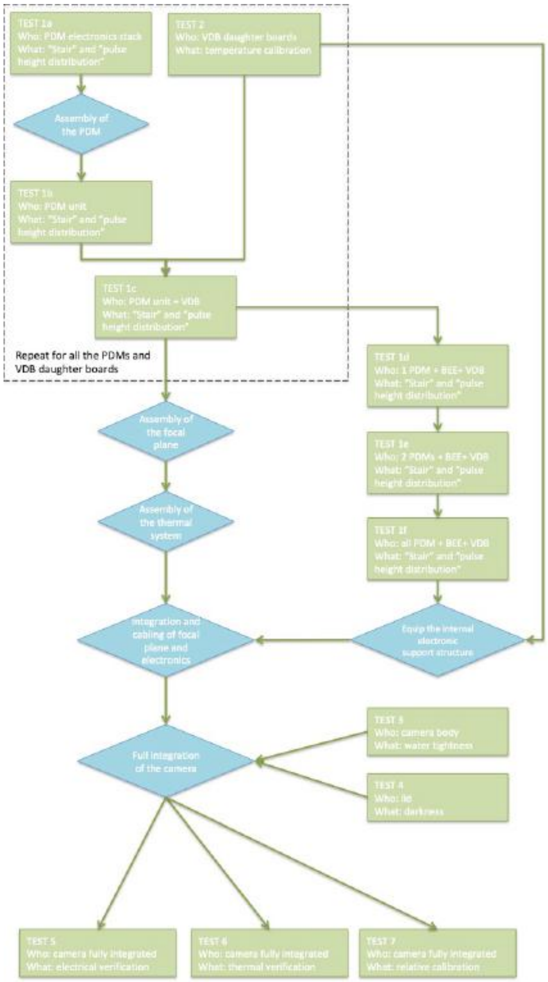

Figure 9 Step-by-step testing plan followed during the assembly of the camera.

The most complex and dense part of the camera to be assembled is the focal plane because it comprises the PDMs with their cabling and a large part of the thermal system. The PDMs have to be assembled with great care one by one and in advance. This step is a prerequisite for the entire assembly procedure. The stack of electronics boards composed by the SiPM, the FEE and FPGA boards have to be integrated into its aluminum box equipped with the proper gap filler to diminish the thermal resistance. Performing the planned test after this integration step returns a first issue on the quality of the results obtained. In fact, it turns out that the noise produced by the switching voltage regulator of the FPGA board was amplified by the box itself and picked up by the ASIC destroying the scientific signal from the SiPM. A proper shielding solution has been studied and implement inside the box also granting a minimal impact on the thermal aspects.

In parallel the performance of the daughter boards composing the VDB have been verified and calibrated to give an output as much constant as possible versus the operating temperature. The measurements of the planned tests have been repeated on the fully assembled PDMs now powered by the VDB. To keep the results inside our confidence level, a filtering device has been added to the high voltage output of each daughter board. Moreover, the values of the low-voltage lines have been slightly changed (diminished) to mitigate the FPGA board noise.

It is now possible to proceed over with the integration of the camera by installing all the PDMs on the corresponding positions on the FPSS. In this step it is mandatory also to pass through the FPSS and its insulation layer all the cables that feed the PDMs: the power supply and the data cables. To this end proper slots are available. After a careful routing of the cables along the bottom side of the focal plane, the heat sinks (already equipped with the peltier cells, the thermal sensors and the thermal interfaces) can be installed. A particular care is mandatory in this integration step. The contact between each heat sink and its place on the FPSS has to be full in order to ensure the proper heat transfer between the relevant components. A failure in this step will bring to an inadequate functioning of the thermal system so missing the chosen working temperature of the SiPM sensors.

In the mean time, the internal electronics support structure is populated with the BEE board, the entire VDB system, the controllers of the thermal system and the ancillaries. The relevant cables are also routed on it.

At this point the focal plane is entirely populated with PDMs, the main parts of the thermal system are installed and all the relevant cables are routed through. This part can be now integrated on the internal electronics support structure already equipped. The data cables from the PDMs are connected to the proper connectors on the BEE, while the power supply cables are brought to the VDB daughter boards.

At this stage of the assembly process the focal plane and the internal electronics support structure form a self-standing unit that, at a certain extent, already represents the camera itself. The system could be switched on for testing purposes and a number of functionalities could be verified. The camera is then ready to be integrated into the camera body and the final cables routing and connection are performed.

At last, the entrance window and the lid are integrated, the optical fiber is put in place and the 6 panels are connected and fixed to the body.

System tests can be carried out to verify the correct assembly of the ASTRI-Horn camera. Tests concern both engineering and scientific verifications.

Some pictures at different stages of the assembly are shown in Figure 10.

Figure 10 ASTRI-Horn camera at different stages of its assembly. (Top row left) The focal plane and the thermal system are assembled together. Routing of the data and power supply cables is also done. (Top row right) The internal electronics support structure equipped with the BEE, the VDB and the other electronics boards. (Bottom row left) the camera is going to be let into the camera body. (Bottom row right) the ASTRI-Horn camera fully assembled.

4. ON-FIELD TESTS

In this chapter we discuss few measures conducted with the ASTRI-Horn camera installed at the telescope. We put some attentions on the thermal aspects of the system that is of crucial importance to guarantee the correct working point for the sensors of the camera whose performance is very sensitive to their operative temperature.

Starting from a steady situation, with the camera thermalized with the ambient temperature, we have switched on the system and started to monitor timing, temperatures and power. Concerning temperatures, we have recorded the values at different interesting points in the camera. We have repeated the same test both at nighttime and in daytime using the same configuration on the thermal controllers. The configuration used comes from a study done during the design phase of the thermoregulation system and we expect to keep the SiPM sensors at their working temperature. The constrains of the system are:

- the power output for each peltier is set to a maximum of 65W;
- the target temperature of the cold side of the peltier cells is 6°C;
- the temperature of the heat sinks to be kept below 35°C.

A summary of the measures is shown in Figure 11. Differences in the behavior of the thermal system are emerged.

In the top one, we see the start-up of the camera during daytime. The ambient air temperature was around 23°C with a solar irradiation of about 1000 W/m^2. The temperature inside the camera was about 30°C as seen from the sensors on the heat sinks at the beginning of the acquisition. The thermal system took about 60 minutes to reach its target temperature (see tec1, tec2, tec3 and tec4 curves) while the SiPM sensors (red lines) get a steady temperature of about 18°C in about 120 minutes. The heat drained from the focal plane caused an increase in the heat sink temperature, in particular to those on the out-path of the airflow (see Figure 13). This temperature values are also confirmed from images acquired with IR camera. The ambient air temperature remained very stable during all the experiment. Concerning the electrical power used to thermalize the camera the system reached a peak of about 265W and kept it for 30 minutes then it lowered down to 150W to maintain the SiPM at temperature.

In the bottom one, we can compare the same experiment conducted at nighttime. This situation is representative of a typical observing condition. The ambient air temperature was around 20°C with some variations due to winds. Solar irradiation was obviously null, in fact the temperature inside the camera was about 20°C (see the heat sink plot). In this conditions the system took only 20 minutes to reach its target temperature while the SiPM sensors get a steady temperature of about 16.5°C in about 70 minutes. The peak power used was limited to 170W and then was used only 70W to maintain the temperature.

A part from power considerations, we note that during the day time run the system was not able to bring the focal plane at the desired working temperature of 15±2°C while in the night time run the temperature reached was inside the requirement. Thermal gradients were in both cases limited well below 1°C.

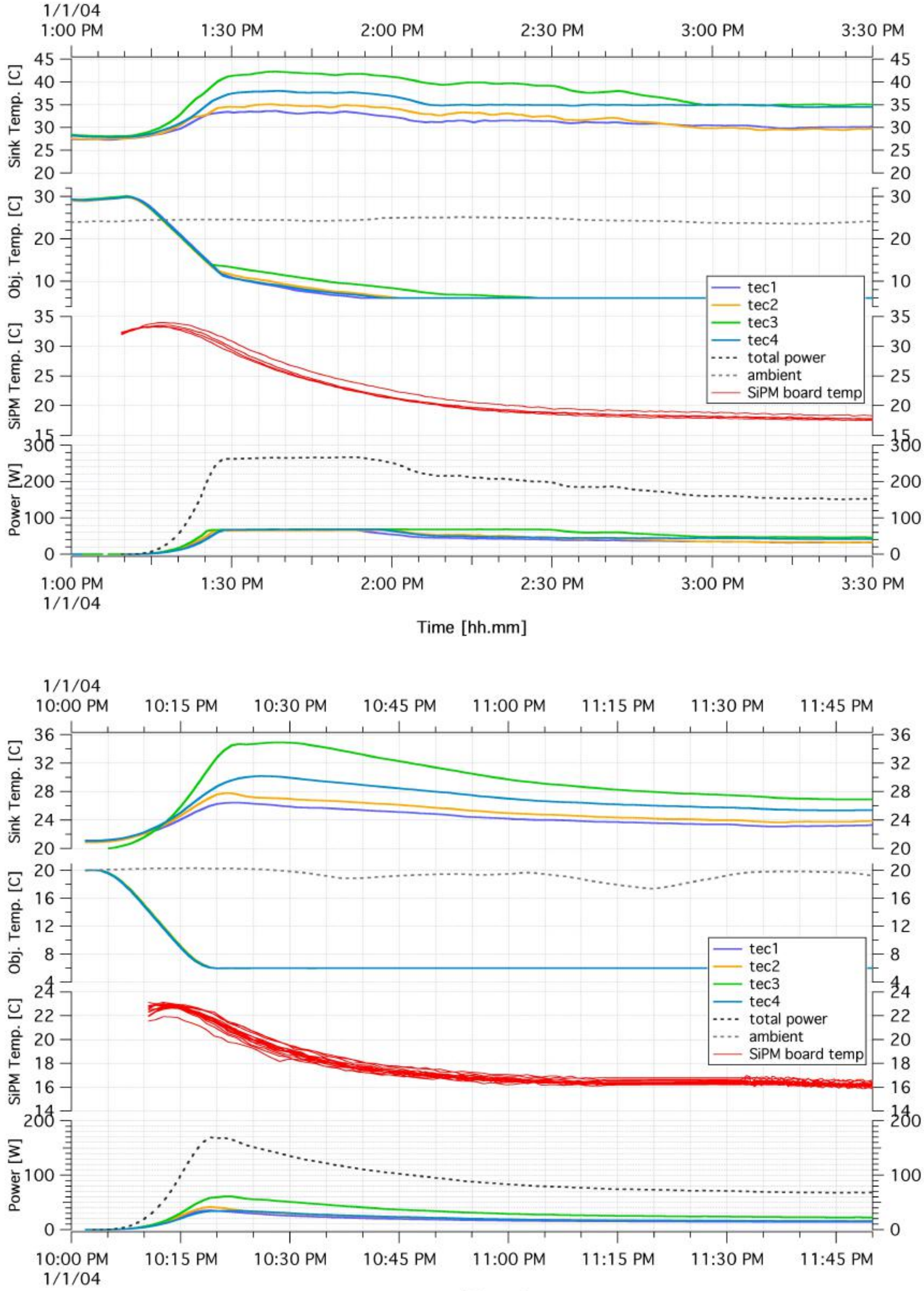

Figure 11 Thermal behavior of the ASTRI-Horn camera in the start-up phase during daytime (top) and nighttime (bottom).

To have a better knowledge of the system we have also compared its behavior at nighttime with closed lids and open lids configurations. The open lids configuration is actually how an observation happens. The focal plane is exposed to the cold sky but the SiPM sensors start to receive the Night Sky Background and they heat up. The temperature increase reached in average 18°C and system had to pump more power to bring back the temperature to the working temperature.

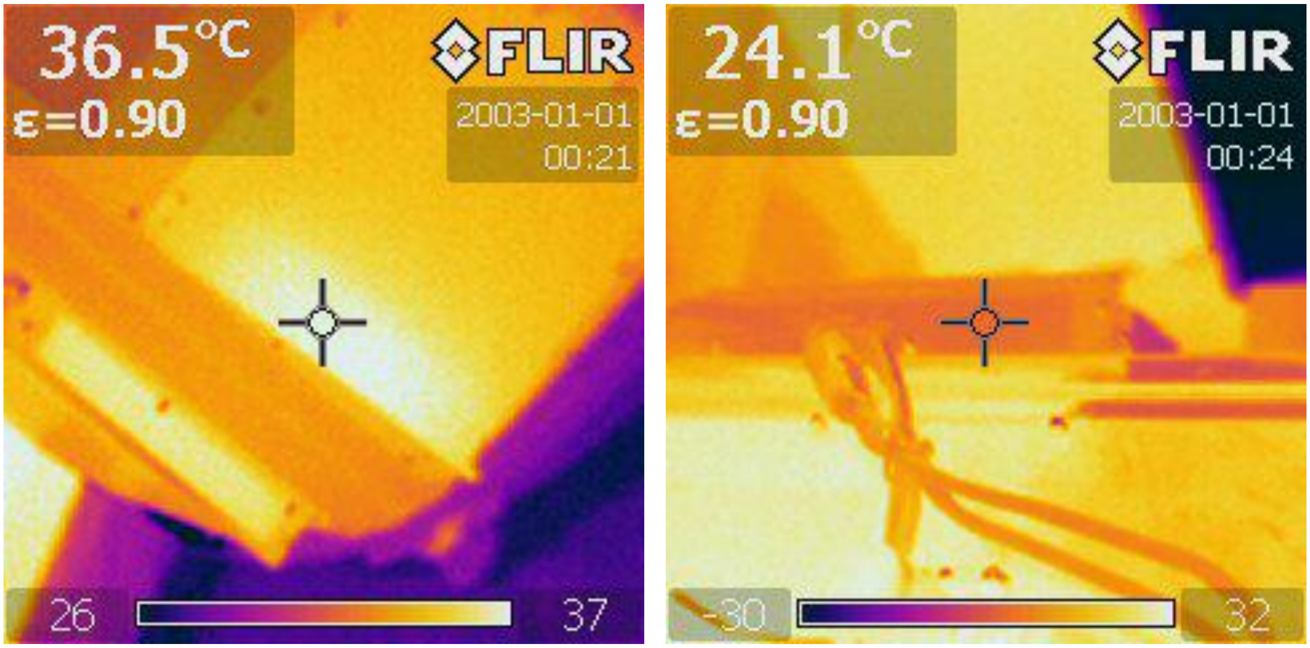

Figure 12 Images acquire with an IR camera of the output path (left) and input path (right) of the cooling airflow of the heat sinks.

5. DESIGN IMPROVEMENTS

Being the ASTRI-Horn camera a prototype for a new concept of camera for Cherenkov Telescopes a number of aspects where not adequately touched and solved in the design phase. The development team was more interested in understand and solve the basic functionalities (triggering, energy e time reconstruction, fast data read-out) rather then optimize and built a "commercial-like" product. Some of the design choices were done on the basis of a poor knowledge of the real needs and on-line changes have been applied sometimes with unexpected backlashes. Moreover, some aspects related to harness, an easy assembly/disassembly, ordinary maintenance, updates are not well implemented.

Despite these, the camera got the results expected and show a good adaptability to different needs coming from the on-site use.

Nevertheless, changes and upgrades have been highlighted and new solutions have been drafted. We present here a list of some of them.

The lid subsystem is a quite a delicate part of the camera. Despite its excellent performance in terms of water- and light-tightness and overall protection of the focal plane the automatic opening/closing process is often failing. The reasons have been found in poor limit switches interfaces, in a softer shaft joint and in the motor drivers overheat.

The relative calibration subsystem based on the use of a side-glow optical fiber is working, but an improve in terms of amount of light and its uniformity can be surely achieved by simply refining the different optical interfaces between the components.

Major changes can be done on the focal plane area. Modifications to both thermo-mechanical and electronics aspects will improve the assembly/disassembly, maintenance and performance of the camera. Concerning the thermo-mechanical part, a reduction of the pieces and interfaces is foreseen. The PDM boxes and FPSS can be joined in a single piece so eliminating a large number of mechanical interfaces, joints (screws and pins) and thermal interface materials. A gain in the overall thermal resistance is expected as well as better thermal constant of the system. Moreover, front-side mounting of the PDM electronics stack is highly desirable to allow fast maintenance of the FEE and FPGA boards. A concept based on the use of small permanent magnets to hold the PDM in place is under study. A draft design of the proposed solution is shown in the right panel of Figure 13 in comparison with the present solution shown on the left panel.

On the electronics aspects, all the three boards of the PDM's stack will undergo a revision. The SiPM board will embed a copper thermal plane to cut down its thermal resistance; the FEE board will make use of an updated version of the CITIROC ASIC where the packaging of the chip itself is improved and some issues related to the high gain chain are solved; the FPGA board will use a completely different approach in term of on-site supply voltage regulator to dim the noise captured by the ASIC.

The BEE is a complex board that accomplishes a variety of tasks: from fast data reception, formatting and transmission to low-level duties such as the lid management. A review of the design if not of the entire concept is ongoing. A split of the functions into different boards is under evaluation.

Concerning the VDB, a simplification of the circuitry is ongoing. In fact, the present camera is capable of power on SiPM coming from various vendors. A large supply voltage range was necessary. Selecting the SiPM vendor the supply voltage become fix and, at the same time, more current can be made available extending the dynamic range for observations. The present modularity of the VDB system will be maintained.

Re-design area also involves the camera body with a general simplification of its components, the handling interfaces of the camera and the routing.

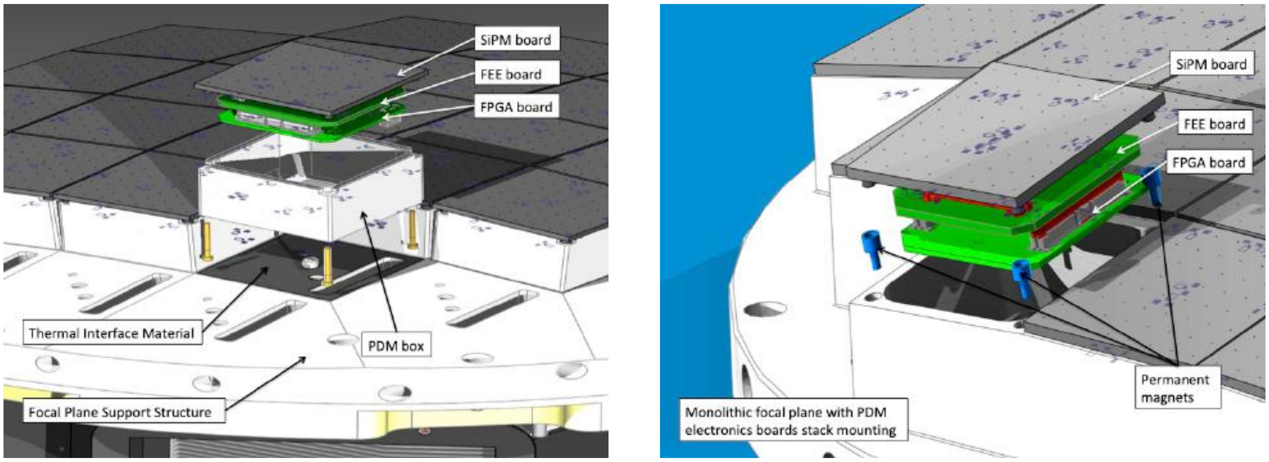

Figure 13 Detailed view of the focal plane area. (Left panel) The actual system based on the FPSS, the PDM box and the electronics boards stack. They are hold together by a number of screws and centering pins plus thermal interfaces. (Right panel) The new design that propose to merge the FPSS with the PDM box in a single piece and avoid the use of screws thus allowing the front mounting of the electronics stack.

6. CONCLUSIONS

In this paper we have shown the general architecture of the ASTRI-Horn camera and some of the innovative ideas adopted. A detailed description of the ASTRI-Horn camera is beyond the scope of this conference proceeding.

It is the first time that SiPM sensors are used in a Cherenkov Telescope camera without any light collection / light guide system, because the large SiPM pixel matches the optical PSF of the telescope. Moreover, it is the first time that monolithic pixels arrays of SiPM are used in this field.

Another important design solution adopted is the complete separation between the FEE and the BEE by placing the FEE just below the SiPM sensors avoiding wires carrying very low voltages analog signals form the sensors to the FEE.

The use of a “shaper” ASIC that integrate the signal rather than a sampler one allow us to keep the same data quality but with a smaller amount of data transferred to the BEE per event.

The camera also integrates the complete thermal system that makes use of solid-state components rather that liquid cooling.

On-field operation has proven to be essential in understanding system stability and reliability. Important feedbacks also concern the assembly and maintenance aspects, not properly addressed in the design phase. During the first period of the on-site commissioning a deep understanding on several engineering aspects has taken place; issues have been found and mostly are solved, in other cases mitigation actions have been undertaken. Nevertheless, the behavior shown by the ASTRI-Horn camera prototype is very positive.

Among a number of changes that needs to be applied, the path from this prototype camera toward a scientific instrument available for a wider community is well on its way. The procurements for further units of the ASTRI-Horn camera is already started, in particular concerning the SiPM sensors and the ASIC chips, and we foresee to have the new version of camera available in a year timescale.

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