

A NECTAr-based upgrade for the Cherenkov cameras of the H.E.S.S. 12-meter telescopes

T. Ashton^b, M. Backes^{h,i}, A. Balzer^c, D. Berge^{c,a}, J. Bolmont^e, S. Bonnefoy^a, F. Brun^d, T. Chaminade^d, E. Delagnes^d, G. Fontaine^f, M. Füßling^a, G. Giavitto^{a,*}, B. Giebels^f, J.-F. Glicenstein^d, T. Gräber^a, J.A. Hinton^{h,g}, A. Jahnke^j, S. Klepser^{a,*}, M. Kossatz^a, A. Kretzschmann^a, V. Lefranc^{a,d}, H. Leich^a, J.-P. Lenain^e, H. Lüdecke^a, I. Lypova^a, P. Manigot^f, V. Marandon^g, E. Moulin^d, T. Murach^a, M. de Naurois^f, P. Nayman^e, S. Ohm^a, M. Penno^a, D. Ross^b, D. Salek^c, M. Schade^a, T. Schwab^g, K. Shiningayamwe^h, C. Stegmann^a, C. Steppa^a, J.-P. Tavernet^e, J. Thornhill^b, F. Toussenel^e, P. Vincent^e

^a DESY, D-15738 Zeuthen, Germany

^b Department of Physics and Astronomy, The University of Leicester, University Road, Leicester, LE1 7RH, United Kingdom

^c GRAPPA, Anton Pannekoek Institute for Astronomy, University of Amsterdam, Science Park 904, 1098 XH Amsterdam, The Netherlands

^d IRFU, CEA, Université Paris-Saclay, Gif-Sur-Yvette Cedex F-91191, France

^e Sorbonne Universités, Université Paris Diderot, Sorbonne Paris Cité, CNRS/IN2P3, Laboratoire de Physique Nucléaire et de Hautes Energies, LPNHE, 4 Place Jussieu, Paris, F-75252, France

^f Laboratoire Leprince-Ringuet, Ecole Polytechnique, CNRS/IN2P3, Palaiseau F-91128, France

^g Max-Planck-Institut für Kernphysik, P.O. Box 103980, Heidelberg D 69029, Germany

^h University of Namibia, Department of Physics, Private Bag 13301, Windhoek, Namibia

ⁱ Centre for Space Research, North-West University, Potchefstroom 2520, South Africa

^j JA consulting, St Michael Park 23, Avis, Windhoek, Namibia

ARTICLE INFO

Article history:

Received 31 October 2017

Revised 13 September 2019

Accepted 20 December 2019

Available online 17 January 2020

Keywords:

Gamma-ray astronomy

Cherenkov camera

High-energy instrumentation upgrade

PMT Cameras

NECTAr

H.E.S.S.

ABSTRACT

The High Energy Stereoscopic System (H.E.S.S.) is one of the three arrays of imaging atmospheric Cherenkov telescopes (IACTs) currently in operation. It is composed of four 12-meter telescopes and a 28-meter one, and is sensitive to gamma rays in the energy range ~ 30 GeV – 100 TeV. The cameras of the 12-m telescopes recently underwent a substantial upgrade, with the goal of improving their performance and robustness. The upgrade involved replacing all camera components except for the photomultiplier tubes (PMTs). This meant developing new hardware for the trigger, readout, power, cooling and mechanical systems, and new software for camera control and data acquisition. Several novel technologies were employed in the cameras: the readout is built around the new NECTAr digitizer chip, developed for the next generation of IACTs; the camera electronics is fully controlled and read out via Ethernet using a combination of FPGA and embedded ARM computers; the software uses modern libraries such as Apache Thrift, ØMQ and Protocol buffers. This work describes in detail the design and the performance of the upgraded cameras.

© 2020 The Author(s). Published by Elsevier B.V.

This is an open access article under the CC BY license. (<http://creativecommons.org/licenses/by/4.0/>)

1. Introduction

The first Cherenkov telescopes of the H.E.S.S. array were the four 12-meter diameter CT1–4, built and commissioned between 2002 and 2004 at the H.E.S.S. site in the Khomas highlands in

Namibia (see e.g. [1]). CT1–4 are also known as the “H.E.S.S. I array”. A fifth, 28-meter diameter telescope was built in 2012 in the centre of the square H.E.S.S. I array. The main goal of this new telescope, called CT5, was lowering the minimum gamma-ray energy threshold of H.E.S.S. from ~ 100 GeV down to ~ 30 GeV. To reach that goal, CT5 has a very large mirror area (614 m²), photosensors with higher quantum efficiency and a camera [2,3] with a much lower dead-time than the original CT1–4 ones. CT5 can trigger on low energy air showers with a rate of ~ 3 kHz, about ten times the event rate of the older, smaller CT1–4.

* Corresponding authors.

E-mail addresses: gianluca.giavitto@desy.de (G. Giavitto), stefan.klepser@desy.de (S. Klepser).

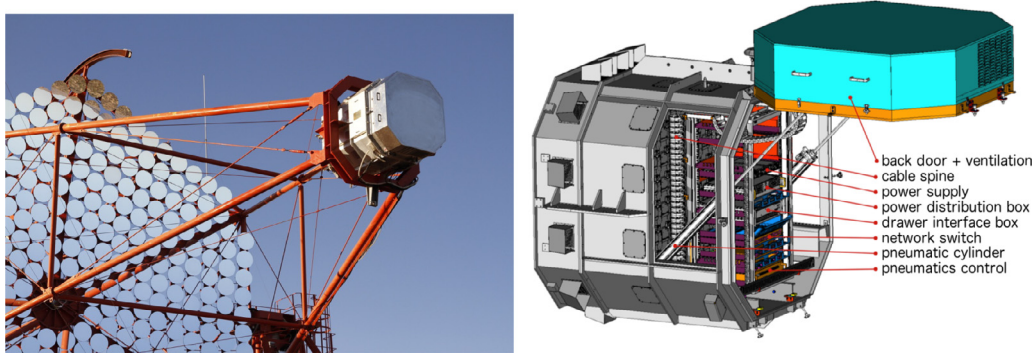


Fig. 1. Left: A picture of the first upgraded H.E.S.S. I camera, mounted on CT1. Right: Rear 3D view of the camera. The backplane rack is visible, the ventilation is contained inside the back door (in light blue). The mechanical structure of the camera was built at the LLR laboratory.

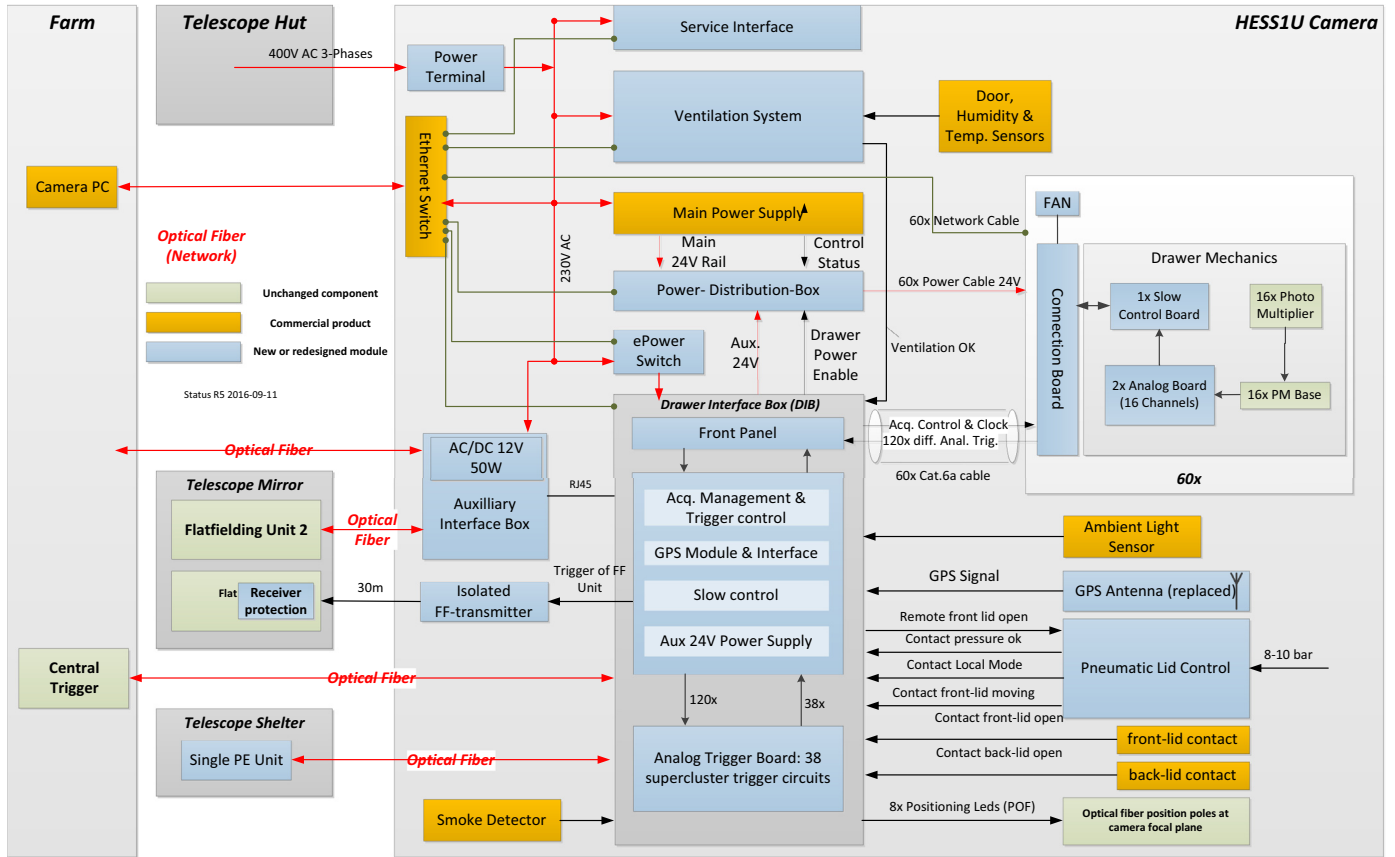


Fig. 2. This diagram illustrates how the various mechanical and electronic subsystems of the camera interact. Original, custom-made, and commercial off-the-shelf components are marked in green, blue and orange, respectively. Red lines represent the power distribution and the arrows its direction; if labeled “Optical Fiber”, they represent bidirectional optical fiber links. Green, circle-terminated lines represent copper Ethernet links. Black lines and arrows represent electrical signals. Physical locations of the subsystems are marked with light grey boxes: “HESS1U Camera” is the camera body, the “Telescope Shelter” is the camera daytime parking shelter; the “Telescope Hut” is a service container tied to the telescope structure, the “Farm” is the server room inside the array control building.

An important reason to upgrade the 14-year-old CT1–4 cameras [4] was to enable the CT1–4 array to trigger at a lower threshold, resulting in more events being recorded stereoscopically with CT5. This could not be achieved with the original cameras because of their rather large readout dead-time of ~ 450 μ s per event: lowering their trigger threshold by e.g. 30% would have increased the fraction of events lost due to dead-time to ~ 15 %.

An equally important reason to upgrade the old CT1–4 cameras was to prevent the inevitable increase of failures due to the ageing of the electronics, connectors and other critical parts that had

been exposed for 14 years to the harsh conditions of the Namibian site. Furthermore, many electronic components had become obsolete and could not be procured anymore, making the cameras increasingly difficult to maintain.

This work is structured as follows: general description of design and architecture (Section 2); tests performed on individual components and on the integrated system (Section 3); calibration procedures employed for commissioning and deployment (Section 4); performance achieved in the field (Section 5); conclusions (Section 6).

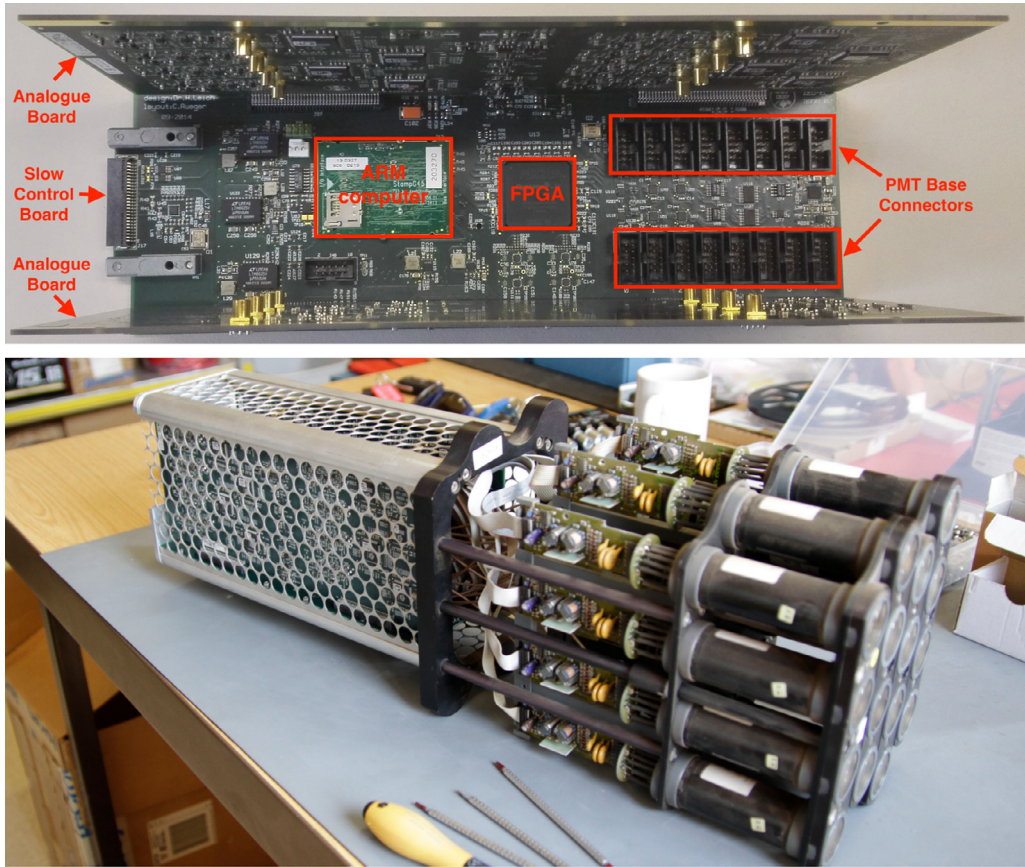


Fig. 3. Top: Annotated inside view of a partially assembled drawer. Bottom: A fully assembled drawer.

2. Architecture of the new cameras

Upgrading the H.E.S.S. I cameras meant replacing or refurbishing essentially every component inside them. Only the photomultiplier tubes (PMTs) and their high voltage power supplies (HV bases) were kept, due to their cost and relative robustness. This can also be seen in the schematic diagram of the camera subsystems (Fig. 2). When possible, commercial off-the-shelf (COTS) solutions were employed. A shared design feature of all custom electronic subsystems developed for the cameras is the usage of an FPGA coupled to a single-board computer, controlled via Ethernet.

Most of the development, production and testing of the cameras has been done at the DESY site in Zeuthen. A picture of one of the upgraded cameras on the telescope can be seen in Fig. 1, left.

2.1. Front-end electronics

Cherenkov light from particle showers in the atmosphere is detected and digitized in the front-end of the camera. The light sensors are 960 PMTs, organized into 60 modules, called “drawers” (Fig. 3). The drawers are arranged in a 9×8 rectangular matrix, with each corner of the matrix devoid of 3 drawers. A drawer consists of 16 PMTs, two 8-channel analogue boards, and a slow control board (see Fig. 3, top). The analogue boards host the electronics components responsible for the amplification, discrimination and digitization of the PMT signals (see Fig. 4, left); the slow control board hosts an FPGA (Altera Cyclone IV) controlling the whole drawer, an ARM9-based single-board computer (TaskIt Stamp9G45), the power regulators and the sockets for the PMT HV bases. The drawers are supported by a mechanical structure which separates the front from the back-end of the camera. Each drawer

is connected to a connection board secured on the back-end side of that structure, hosting sockets for network, trigger and power (see Fig. 5, right).

2.1.1. Analogue boards

The analogue signal from one PMT is sent to the analogue board via a 15 cm long coaxial cable. The PMTs produce negative polarity, single-ended voltage pulses of 2–3 ns duration (FWHM) with an amplitude varying from 1 mV to a few V, depending on the number of photons detected. Upon reaching the analogue board, the PMT signals are AC coupled, pre-amplified by a factor 9.8, split into three branches and further amplified by low noise single-ended to differential amplifiers, which also invert their polarity.

Two of the branches are routed to the two inputs of the NECTAr readout chip, for sampling and digitization. Their overall amplification factors are 15.1 (high gain, HG) and 0.68 (low gain, LG). The NECTAr chip inputs have a nominal range of 2 V, so high gain signals are clipped to 3.3 V, the most convenient voltage present on the board within the NECTAr chip tolerance range, to avoid affecting the low gain. An adjustable constant common-mode offset of about 0.2 V is added to the electrical signal to keep it within the input range even in the case of undershoot (this corresponds to a pedestal offset of around 420 ADC counts).

The signal in the third branch is amplified by a factor 45 and sent to a high-speed comparator, whose digital output is directly routed to the FPGA on the slow control board. This signal is referred to as the level 0 (L0) trigger signal.

2.1.2. Readout

Most of the performance improvements of the upgraded cameras are due to its readout electronics, based on the NECTAr analogue memory chip, designed at CEA/IRFU [5] (Fig. 4, right).

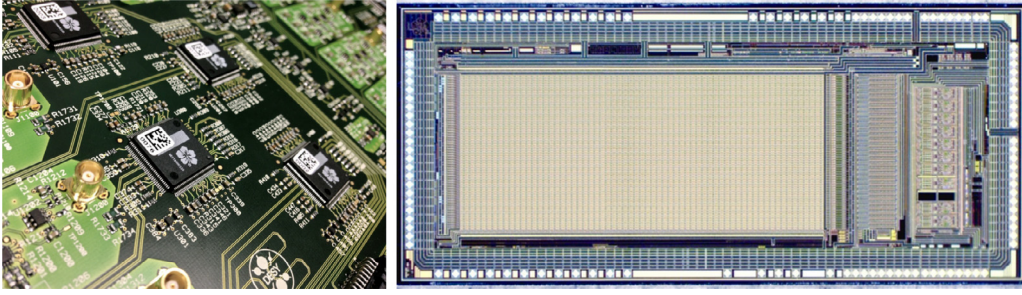


Fig. 4. Left: Part of the analogue board showing the analogue amplification stages (light green) and the NECTAr chips (black with a nectar logo). Right: Microphotography of the NECTAr chip.

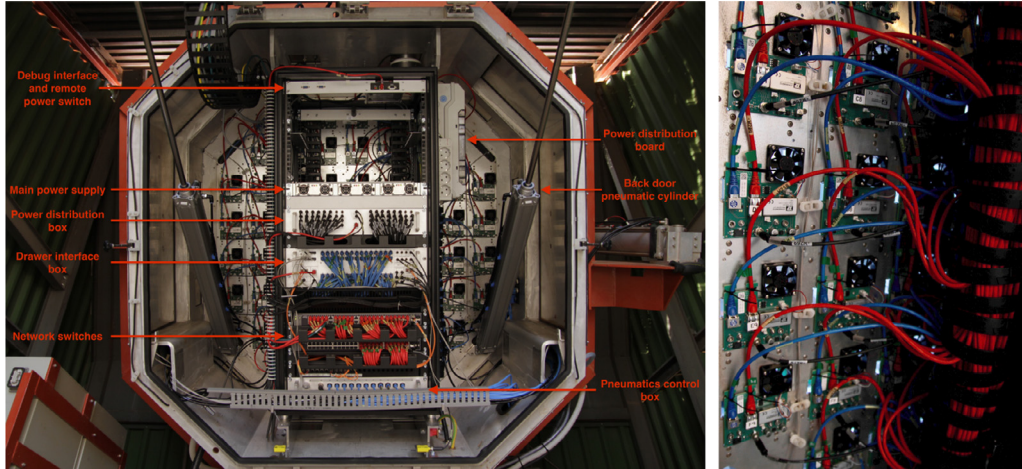


Fig. 5. Left: Photograph of the inside of the installed CT1 camera. Right: Photograph of the camera cabling solution, using cable spines. The cables carry Ethernet data (red); trigger, clock and control signals (blue) and power (black). The cables are connected to the drawer connection boards.

The NECTAr chip has two channels (one per gain), each equipped with a switched capacitor array of 1024 cells, acting as an analogue ring memory buffer. There are two modes of operation: writing and reading. During the writing phase, the input amplitude is stored sequentially on the array capacitors, with a switching frequency of 1 GHz. The writing process is circular over the whole array, so the charge stored in the cells is overwritten every 1024 ns by the new input. A trigger signal stops the writing and initiates the reading: the charges in the capacitor cells of a small region of interest (ROI) are read out and digitized by the on-chip 12-bit 21 Msamples/s ADC. The digital data is then transmitted to an FPGA by means of a serializer. For regular observations the ROI is currently set to 16 cells, and the data in the ROI is summed by the FPGA, and sent to the camera server as one integrated charge value per pixel and per gain. The choice of ROI length and simple summing charge integrator is inherited from the old cameras for compatibility with the existing H.E.S.S. analysis and simulation frameworks (see e.g. [6]). It is a sufficiently adequate choice for most applications since Cherenkov light from atmospheric particle showers reaching the camera has a typical temporal spread of less than 10 ns, except for the most inclined and energetic showers. The performance of the new camera readout and data acquisition systems, however, allows full waveform sampling with an ROI length of up to 48 samples, which is expected to increase the sensitivity of the array to high energy showers. This mode of operation is currently being tested on selected targets, along with more sophisticated charge integration algorithms (see also Section 5.3).

2.1.3. Slow control and connection boards

The FPGA and ARM computer of each front-end drawer are located on the slow control board. They are connected via a 100 Mbit/s memory bus, with a 16 bit word width; the ARM computer has a 100 Mbit/s Ethernet interface and acts as a device node of the distributed camera control software. The FPGA reads out sampling data from the NECTAr chip, collects other monitoring data such as PMT currents and L0 trigger counters, and directly controls all the electronics inside the drawer. The ARM computer runs a slow control server accessing the FPGA registers, reads out all FPGA data, buffers it and sends it over the network to a central camera server via TCP/IP using the ØMQ library [7]. The central camera server controls the drawer by means of remote procedure calls implemented using the Apache Thrift library [8].

The drawer slow control board also houses several point-of-load regulators and DC line filters, providing the required voltage supplies for all the drawer components. Also, the sockets for the PMT HV bases and the corresponding control and readout electronics are located at the front-facing end of the board.

The connection board has 2 RJ45 sockets, one for standard Ethernet and one for four Low Voltage Differential Signaling (LVDS) signals: two trigger outputs, a clock and a readout control input. A 4-pin M8 socket provides 24 V DC (see Section 2.2.4) to the main step-down (24 V to 12 V) DC-DC converter, which is also hosted on the connection board. This arrangement assures galvanic isolation of the electronics inside each drawer, preventing ground loops and current surges. It also isolates the rather noisy switching-mode DC-DC converter from the sensitive analog front-end part of the

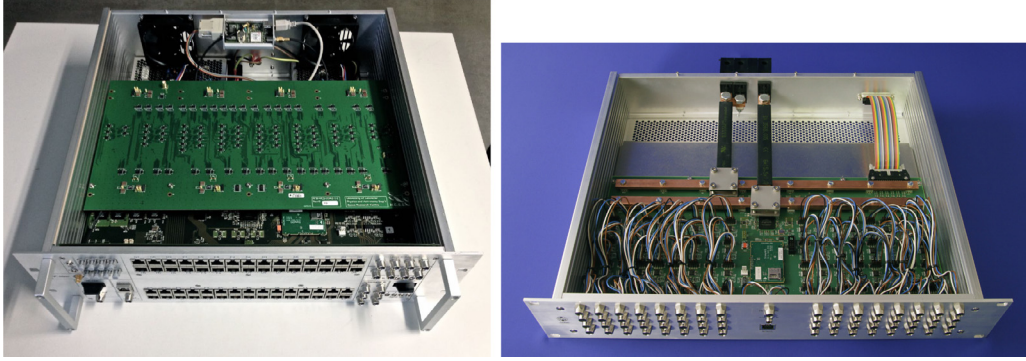


Fig. 6. Left: Drawer interface box, with top lid open to show the analogue trigger board on top of the main board. The GPS module is at the back. Right: Power distribution box.

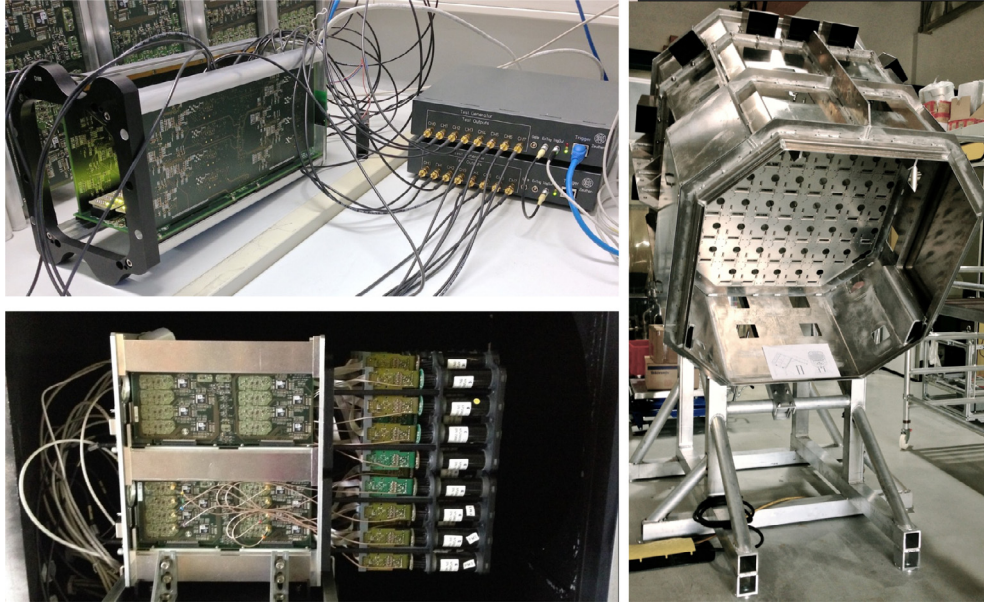


Fig. 7. Left, top: table-top drawer test-bench used for the quality control of the mass-produced drawers. Note the daisy-chained pulse generators stacked one on top of the other. Left, bottom: mini-camera. Right: full copy of the camera body used for testing at DESY in Zeuthen. The camera inclination reproduces the parking position in Namibia: this helped training the deployment. The mechanical structure was fabricated at the LLR laboratory in France.

drawer, and allows it to be efficiently cooled. The 12 V output of the DC-DC converter is routed to the regulators on the slow control board.

2.2. Back-end electronics

The back-end electronics is deployed inside one 19 inch rack located in the back side of the camera (see Fig. 1, right, and Fig. 5). New components developed specifically for this upgrade are described in the following.

2.2.1. Drawer interface box

The drawer interface box (DIB) is the central hub of the camera. As such, its functions include: trigger and readout control interface and clock distribution to the drawers; camera-level trigger generation; interface to the array central trigger and to the auxiliary camera components, such as the front position LEDs, the pneumatics control and the ambient light sensor (see Fig. 2); GPS timestamping of events and a safety interlock logic to ensure the protection of people, PMTs and camera electronics.

The DIB is composed of three interconnected boards: front panel board, main board and analogue trigger board (see Fig. 6, left). The front panel board houses connectors for the drawer trig-

ger, clock and control signals, the central trigger fiber interface, the front position LEDs lightguides and the other camera sensors and actuators; the main board is where the FPGA and ARM computer are located and all signals are routed; finally the analog board is a mezzanine of the main board, whose purpose is to generate the level-1 (L1) camera trigger (see Section 2.2.2).

Furthermore, the DIB is equipped with a GPS module that delivers a pulse-per-second (PPS) signal, to which the main 10 MHz clock, provided by a high precision temperature stabilized quartz oscillator, is disciplined. This clock is also distributed to the drawers. The GPS module also sends a timestamp to the DIB via a serial interface. This is used to timestamp events at the camera level. The precision of the camera GPS timestamp is better than few μ s, of the order of the signal transit time between the camera and the central trigger.

2.2.2. Camera trigger and array trigger

The camera trigger architecture is the same as it was in the old camera electronics, a N -majority over “trigger sectors” of 64 contiguous pixels [9]. Therefore, an N -fold coincidence within a sector is sufficient for the camera to trigger. Usually N is set to 3. There are 38 sectors in the camera, which overlap horizontally by one half drawer and vertically by one full drawer.

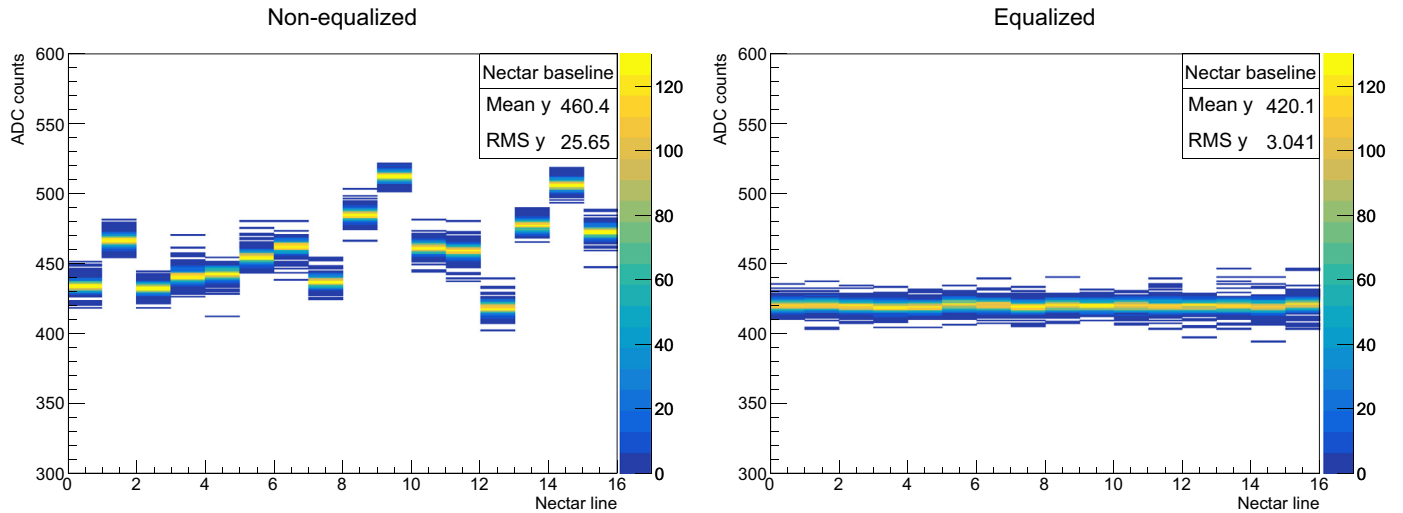


Fig. 8. Equalization of the NECTAr switched capacitor array baseline to a nominal value of 420 ADC counts. The plots show the histogram of NECTAr cell readout values ordered by line before (left) and after (right) calibration. Both offset and RMS are adjusted using the line DACs. The final RMS of ~ 3 ADC counts is lower the average RMS of ~ 4 ADC counts because this data comes from a low-noise back channel on the drawer (see Section 5.1).

This trigger architecture is implemented as follows: the signal from of each PMT is amplified and compared to a threshold P to produce the L0 signal, which is then routed to the FPGA on the slow control board and sampled there at 800 MHz. The sampled L0 signal can thus be delayed or stretched in steps of 1.25 ns. Then, the FPGA counts the number of pixels with an active L0 in each half of the drawer separately. These two numbers are continuously sent as two LVDS pulse-amplitude modulated trigger signals to the DIB. The amplitude modulation has 8 discrete levels with an amplitude of 33 mV each.

In the DIB these amplitude-modulated signals are made single-ended and isochronally routed to 38 analogue summaters, one per sector, located on the analogue trigger board. Due to the overlapping geometry, each signal is distributed to up to 4 sector summaters. The amplitude of the output of each summaters is proportional to the number of active L0 signals in each sector. This sector sum signal is then routed to a comparator, where a sector threshold Q corresponding to N active pixels is applied. All comparator outputs are subsequently routed to the FPGA of the DIB where they are combined in an OR to form the camera L1 trigger. When an L1 trigger is present, a length-encoded “stop” signal is broadcast to all drawers via the LVDS readout control lines, and an “active” signal is sent to the central array trigger in the control building via an optical fibre. Upon receiving the “stop” signal, the drawer FPGA stops the NECTAr writing, and immediately performs the readout and digitization of the region of interest, storing the data in a front-end buffer.

During regular observations, the H.E.S.S. central trigger [10] sends back an “accept” signal to the CT1–4 cameras only if a coincidence of at least two telescopes “active” signals occurs within an 80 ns window (after correcting for their pointing-dependent light propagation delay). This signal is received by the DIB and forwarded to the drawers, initiating there the storage of the data held in the front-end buffer. Should no “accept” signal arrive, the front-end buffer is discarded after a hold-off time t_b , slightly longer than the readout dead-time and the maximum latency of the signal response from the central trigger. If another L1 trigger is issued by the camera before the hold-off is expired, a “busy” signal is sent to the central trigger instead, but no signal is sent to the drawers. “Active”, “accept”, and “busy” triggers share the same fibre connection, so they are pulse-length coded.

A design choice different from the original H.E.S.S. camera trigger, and inspired by the digital camera trigger design for CTA

[11] is the 800 MHz sampling of the pixel trigger comparator output (the old logic was asynchronous). One advantage of using a synchronous logic is that the L0 signal can be delayed and stretched, another is the possibility to implement alternative L1 trigger logic architectures. Indeed, two of them have been implemented: a compact next-neighbour (NN, [12]) logic, and a pseudo-analogue sum trigger logic [13]. In both cases no changes in the analogue part of the trigger are made, only the FPGA firmware is different.

In the NN logic, the L1 signal is issued only when a cluster of neighbouring pixels inside a drawer is simultaneously active. In the FPGA this is implemented with a simple look-up table. The implementation however does not take into account NN groups overlapping two drawers.

The pseudo-sum trigger algorithm works by measuring the duration of the L0 signals, instead of just counting the active ones. The idea behind this is that the duration of the L0 signal is proportional to the total charge deposited within the corresponding pixel, because for PMT-like pulses the duration above a certain threshold is proportional to their amplitude (the pulses are roughly triangular, see Fig. 9, left). This measurement is performed in the FPGA for each half-drawer separately, in units of 1.25 ns, within a 5-ns window. The windowing limits the maximum contribution of any L0 signal to 4 counts, and is meant to avoid problems due to PMT after-pulsing similarly to an amplitude clipping. The sum of the duration of the L0 signals of a half-drawer in the preceding 5 ns is transmitted to the analogue trigger board, so the output of any sector summaters is proportional to the total charge deposited within the corresponding sector, with an individual pixel clipping given by the windowing.

2.2.3. Ventilation, pneumatic and power systems

The ventilation system consists of a single 250 mm Helios KVV 250/4/50/30 centrifugal fan, two filters in series (coarse and fine) and a 6 kW air heater. The whole system is attached to the back door. When operating, it forces a ~ 360 l/s airflow from the back to the front of the camera, where the outlets are located. The filters ensure that very little dust enters the camera. The heater is turned on automatically if the external humidity is higher than 75%, to prevent condensation, or the external temperature is below 5 °C, to minimize temperature gradients across the camera. In operation, the drawer temperature is kept stable at ~ 32 °C, with a gradient of ± 5 °C along the top-bottom direction.

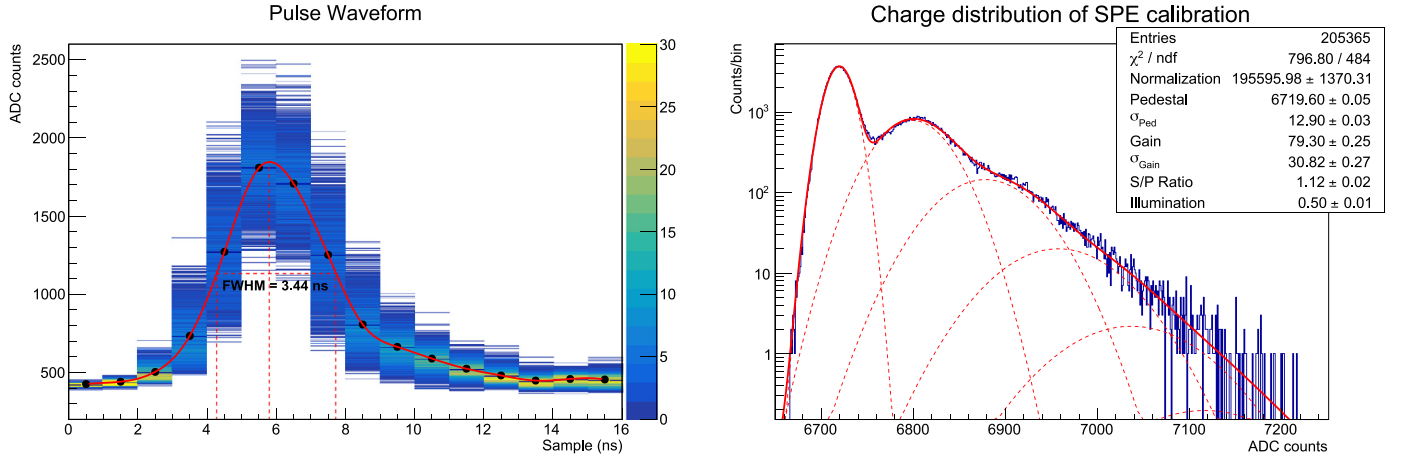


Fig. 9. Left: The digitized PMT pulse from the flat-fielding unit as recorded by the readout. The plot shows the distribution of over 2000 light pulses. The red line is a spline interpolation of the average values in each sample. The FWHM of this interpolation is also shown with dashed lines. Right: The distribution of charges from a typical PMT gain calibration run, fitted to a linear combination of Gaussian functions as described in [14], section 6.2, equation 6. In this particular case, γ_e^{ADC} ("Gain") is 79.3 and σ_p is 12.9 ADC counts, corresponding to a gain of 2.7×10^5 and a noise level of 0.16 p.e.

Both absolute temperature and temperature gradient have no measurable effect on the data and on the trigger efficiency. The internal temperature of the camera is stable for the typical range of external night temperatures, between 0 and 25 °C.

The pneumatic system consists of two cylinders for the back door, one cylinder and five clamps for the front lid. Compressed air is provided by an industrial compressor located in the camera shelter. A custom-built pneumatics control box implements a simple control logic using air valves. There are two modes of operation: local or remote. In local mode, all remote operations are inhibited and the front lid and back door can be opened manually using switches on the outside of the camera body. In the default remote mode, only the front lid can be opened and closed using a relay controlled by the DIB. In this mode, a power failure or safety alarm causes the the front lid to close automatically. The status of the pneumatic system is monitored by four sensors: a contact sensor for the back door, two end switches for the front lid, and the remote/local switch. An air horn is blown for a few seconds as a warning before any movement happens.

The camera power is supplied via standard industrial 400 V three-phase AC mains. Care was taken to ensure that the load was balanced over all three phases. The ventilation system is directly powered by the mains, while a distribution board provides 230 V single-phase AC to the network switches, the front-end power supply, and the DIB. The DIB AC power is remotely controlled by a commercial network power switch.

The 24 V DC to the drawers is generated by the main front-end power supply, a commercial TDK-Lambda FPS-S1U unit, equipped with 3 load-sharing FPS1000-24 modules. It is distributed to the drawers by a custom-built power switch called Power Distribution Box (PDB), see Fig. 6, right. The PDB monitors the current drawn by each drawer, samples the current and voltage ramps at power-up, and can shut the drawers off autonomously if it detects an over-current. This device also employs the FPGA + ARM computer design found elsewhere in the camera. The power consumption of the whole camera is between 3 and 9 kW, depending if the air heater is used or not.

2.2.4. Cabling

The cabling uses industry solutions such as standard Ethernet twisted-pair cables wherever possible to ensure ease of procurement and replacement. The data (both readout and slow control) between drawers and backplane is transmitted via TCP/IP over

Ethernet by means of standard Cat. 6 cables. The LVDS pulse-amplitude modulated trigger, readout control and 10 MHz clock signals are transmitted on standard Cat. 6_A Ethernet cables of equal length (with a tolerance of ± 40 mm, corresponding to ± 0.2 ns). The power is delivered to to each drawer on 4-wire cables terminated with threaded 4-pin M8 connectors. Ethernet and power cables are bundled in special pre-built cable spines (see Fig. 5, right). Auxiliary sensors and actuators are connected using 3-wire or 4-wire electrical cables and standard threaded M8 connectors, except for the GPS antenna which is connected via a standard coaxial cable and SMA connector.

2.3. Auxiliary and calibration devices

Several sensors are deployed inside and outside the camera to monitor door position, temperature, humidity, ambient light and smoke presence. Their signals are fed to a safety interlock system that ensures safe camera operations for both shift crew and hardware. The interlock logic is implemented in the firmware of the DIB FPGA, so it cannot be disabled and is independent of the software implementation.

For the calibration of the gain of the individual PMTs, a device called single photo-electron (SPE) unit is used. It is located in the shelter, facing the front of the camera. Due to its position, it can be used only when the telescope is fully parked. The SPE unit uses an LED to emit pulses of blue (370 nm) light with pulse frequencies ranging from 38 Hz to 156 kHz. The intensity of the pulses ranges from ~ 0.1 to ~ 200 photo-electrons, and their duration is less than a nanosecond. It was designed at the LPNHE laboratory in Paris for the original H.E.S.S. array. A plastic diffuser in front on the LED ensures complete camera illumination, with a uniformity of about 50% [14]. The pulse frequency and intensity are controlled by the camera server via UDP. An adapter board was added to the SPE unit, allowing it to send its trigger signal to the camera via an optical fibre connection. This additional trigger signal is synchronous to the light pulses and it is required for calibration purposes (see Section 4.2).

To perform the pixel-wise calibration of the light collection efficiencies of PMT photo-cathode and funnels [15], another device called flat-fielding unit is used [14,16]. It is located in the centre of the telescope mirror dish and, similarly to the SPE unit, it has a LED that emits short (< 3 ns FWHM), blue (390–420 nm) light pulses of fixed intensity (~ 100 p.e. at the PMTs). A holographic

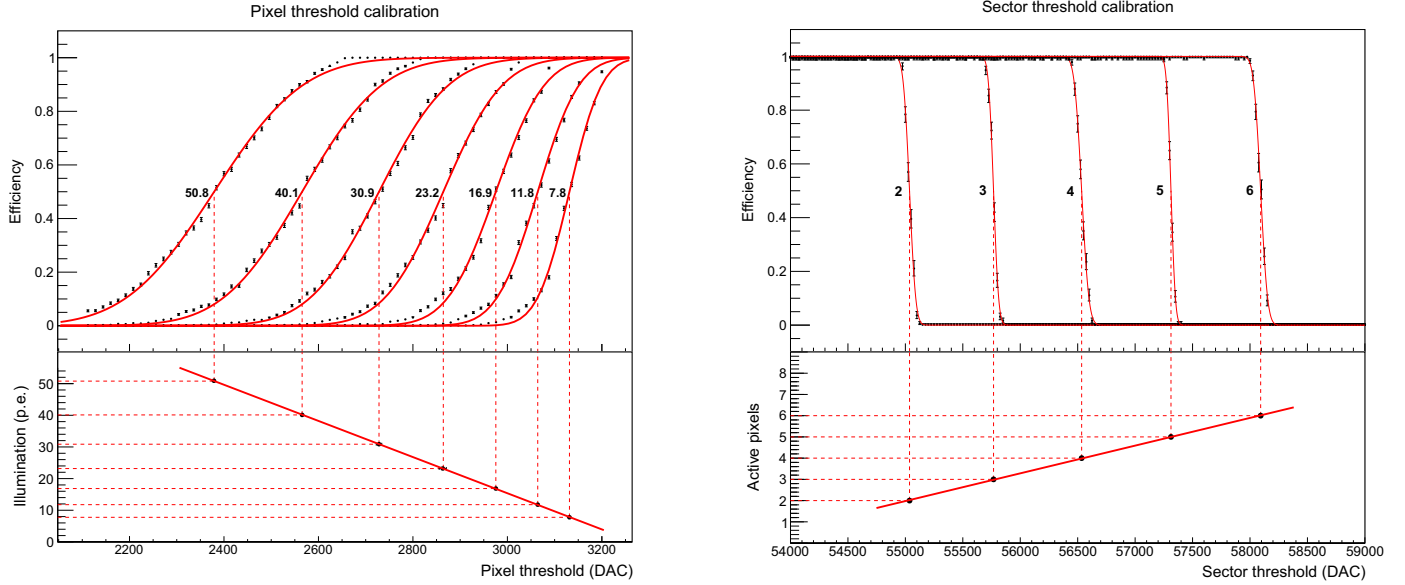


Fig. 10. Efficiency curves from pixel (left) and sector (right) threshold calibration. The value of the pixel and sector thresholds P and Q are given in units of DAC counts (0.76 mV/count). Lower insets show a linear dependency of the sigmoid center on the illumination level (in p.e.) and the number of actively triggering pixels for pixel and sector thresholds, respectively. The error bars on the efficiencies are calculated following approximation 1 of [24].

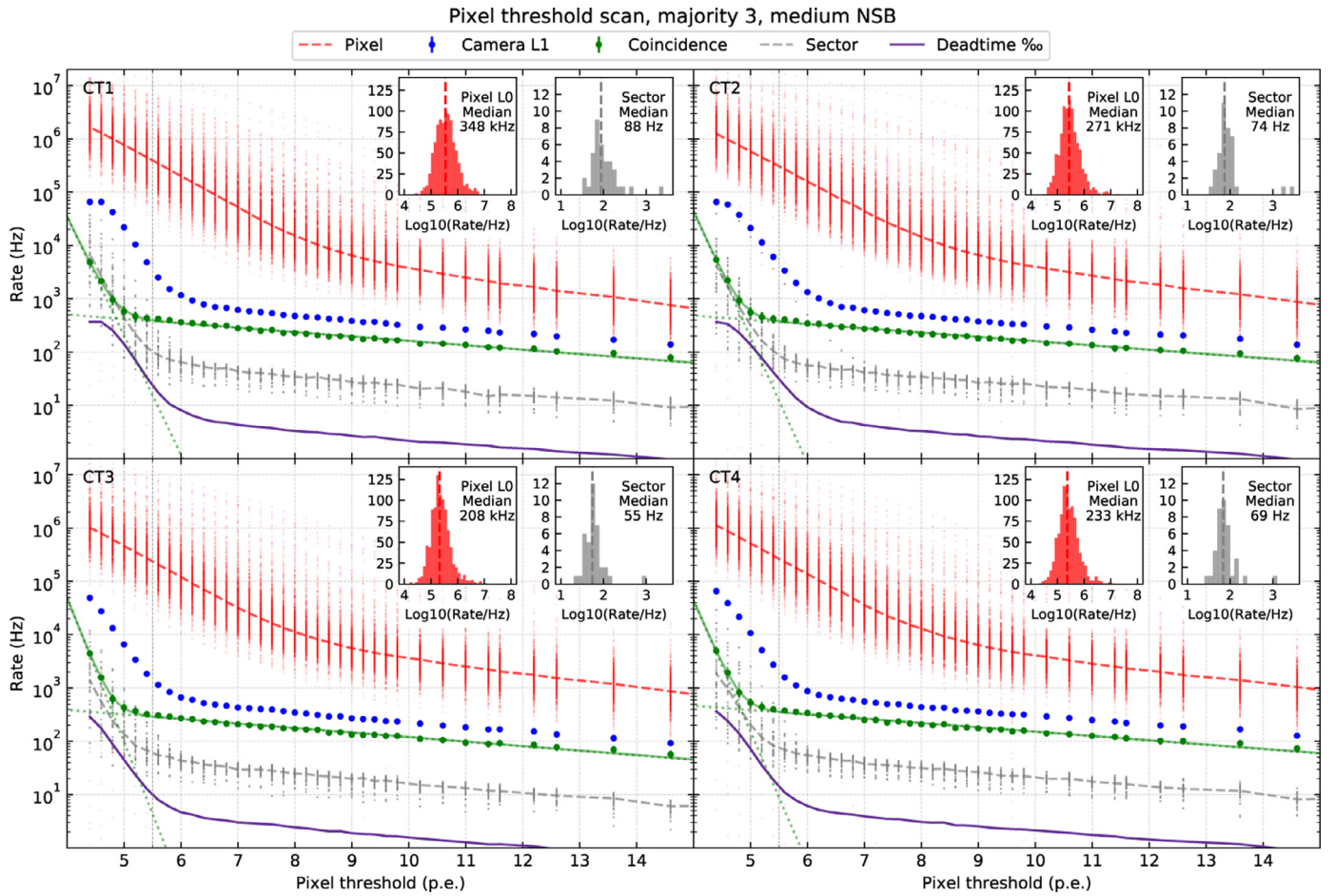


Fig. 11. Results of a threshold scan for a Galactic source with a typical level of NSB light. The graphs show trigger rate versus pixel threshold in photo-electrons. Pixel and sector rates are shown alongside camera L1 trigger rates and coincidence trigger rates with any other telescope in the array, including CT5. The coincidence trigger is formed after applying delays dependent on pointing direction. The green line is the result of the fit of a linear combination of two exponential functions to the coincidence rate data, the red and grey dashed lines show the median rates of pixels and sectors, respectively. The fraction of events lost due to dead-time is shown in per mille as a purple line. The cameras are operated at a nominal threshold of 5.5 p.e., shown as a vertical grey dashed line. Histograms of the rates of all pixels (red) and sectors (grey) at this nominal threshold are shown in the insets.

diffuser is placed in front of it. The high quality diffuser and the small angle subtended by the camera assure a uniform illumination. The stability of the flat-fielding intensity and its non-uniformity across the camera are within 5% RMS.

2.4. Camera network and software

All main subsystems (drawers, DIB, PDB and ventilation system) are connected via 100 Mbit/s Ethernet links to two interconnected 48-port switches located inside the camera. Their uplink to the main camera server is a 10 Gbit/s optical fibre connection. The camera server is a commercial 1-unit rack server with a 4-core Intel Xeon E3-1246v3 processor clocked at 3.5 GHz and 16 GB of DDR3 RAM. It is housed in the computer “farm” (see Fig. 2), an air-conditioned server room inside the main control building. The topology of the internal camera network is star-like: slow-control commands are issued only by the central camera server, which is also the endpoint of the monitoring, logging and event data streams. The devices on the network are independent from one another, and the only access point to the camera is through the camera server.

This distributed design improves the flexibility and resilience of the camera: for instance, during data-taking the ARM computer memory (256 MB per module, for a total of 15.6 GB) is used for buffering the data, preventing data loss during event bursts.

The software was written from scratch; it has a distributed, multi-architecture nature, as required by the new camera design. Its main functions are slow control and event acquisition; it also includes text-based and web-based user interfaces, extensive unit tests, integration tests and validation routines needed for the mass production, and a full commissioning and calibration suite able to take runs, analyze them and adjust camera parameters independently of the main H.E.S.S. DAQ.

The full codebase is around 100,000 lines of code long, composed by 82% C++, 11% ANSI-C and 7% python. Its implementation was one of the major efforts of the upgrade, and required around 6 man-years by a team composed of two full-time coders and four part-time contributors. This paid off with a 10- to 1,000-fold improvement in speed and reliability over the previous system (see Section 5.3 for some performance measurements).

To maximize efficiency, extensibility and maintainability of the codebase, the development team made use of well-tested off-the-shelf open source solutions wherever possible. A single source tree was used for both ARM and x86_64 architectures; cross-compilation was handled by the CMake build system. The operating system running on the ARM computers is the Yocto embedded Linux [17]. It runs a Linux kernel v3.0 patched by the manufacturer, and a custom-built DMA-enabled driver for communicating with the FPGA. The remote procedure call framework required to control the camera is implemented using the Apache Thrift library. The camera slow control software was interfaced to the already existing H.E.S.S. data acquisition software (DAQ, [18]) via the CORBA protocol. Data transfer is accomplished via the ØMQ [7] smart socket library. The raw data serialization protocol is custom, and optimized for speed; for monitoring and logging the general-purpose Google Protocol Buffers library [19] is used instead.

3. Test facilities and procedures

The development of a new detector generally requires planning and implementing test and verification procedures. The testing needs of H.E.S.S. I Upgrade cameras were identified early on in the project and grouped into four main stages (prototyping, integration, quality control, commissioning), for which four distinct test facilities were build, and are described in the following.

3.1. Table-top laboratory test bench

During the prototyping stage daily debugging and testing of the prototypes was needed to validate the design of the new electronics and the correct implementation of all features needed. These mostly manual and one-time characterization tests required a versatile laboratory test setup.

For this purpose, a table-top laboratory test bench was set up, equipped with an oscilloscope (LeCroy DPO 4104), an arbitrary function generator (Agilent 81160A), and several auxiliary instrumentation such as a variable attenuator and a digital multimeter. Many results shown here, such as the linearity shown in Fig. 13, left or the bandwidth shown in Fig. 12, right, have been obtained using this setup.

When the mass production of 270 drawers started, each one of them had to undergo more than 300 individual tests to pass the quality control. The tests mainly checked the functionality of the drawer, but also included the calibration of the NECTAr chip; and the characterization of readout noise, linearity, saturation, cross-talk.

The table-top test bench was thus refitted with four purpose-built, Ethernet-controlled 8-channel pulse generators, allowing to perform the above-mentioned tests automatically. The generators are built using the same FPGA-ARM computer combination used elsewhere and were seamlessly integrated in the test software. They deliver PMT-like pulses with fast (~ 1 ns) rising and falling edges, variable amplitude (from 0.6 - 300 mV), delay (0 - 64 ns in steps of 0.25 ns) and width (2-62 ns in steps of 0.25 ns). They have a RJ45 socket to provide the LVDS drawer clock and acquisition control signal, and to test the outgoing drawer trigger signals; an external trigger input, output and gate, which allow them to be daisy-chained, see Fig. 7, top left. Two daisy-chained generators can simultaneously test all 16 channels of one drawer: during the quality control, the test bench could therefore test two drawers in parallel.

Using this setup, running all the tests needed for quality control of a drawer took less than 30 min. Several of these tests only use self-contained testing functionalities of the drawer, such as the possibility of inject fake pulses at the PMT signal inputs to test the trigger path. Such tests can therefore be run even when the drawer is not on the test bench: during the commissioning of the cameras, they proved to be an invaluable troubleshooting tool.

3.2. Single drawer black box test bench

The integration of the new front-end electronics with the existing H.E.S.S. I PMTs was a critical step, and it required a setup to test a PMT-equipped drawer with a low level of background illumination, with the possibility of flashing it with Cherenkov-like light pulses.

A single-drawer “black box” test bench was built for this purpose. It consists of a simple aluminium box holding a complete drawer. A H.E.S.S. I SPE unit is used to illuminate the PMTs and is attached to the side of the box facing them. The inside of the box is painted black to minimize reflections. The black box was used extensively during the first stages of prototyping, and later on to devise the appropriate calibration routines. After prototyping was over, it was shipped to the H.E.S.S. site, where it was used during the deployment of the cameras, mostly to inspect malfunctioning drawers during the day. It is still being used on site occasionally for drawer maintenance and refitting.

3.3. Mini-camera

The verification tests needed during the integration and commissioning phases called for a fully functional camera. A 4-drawer

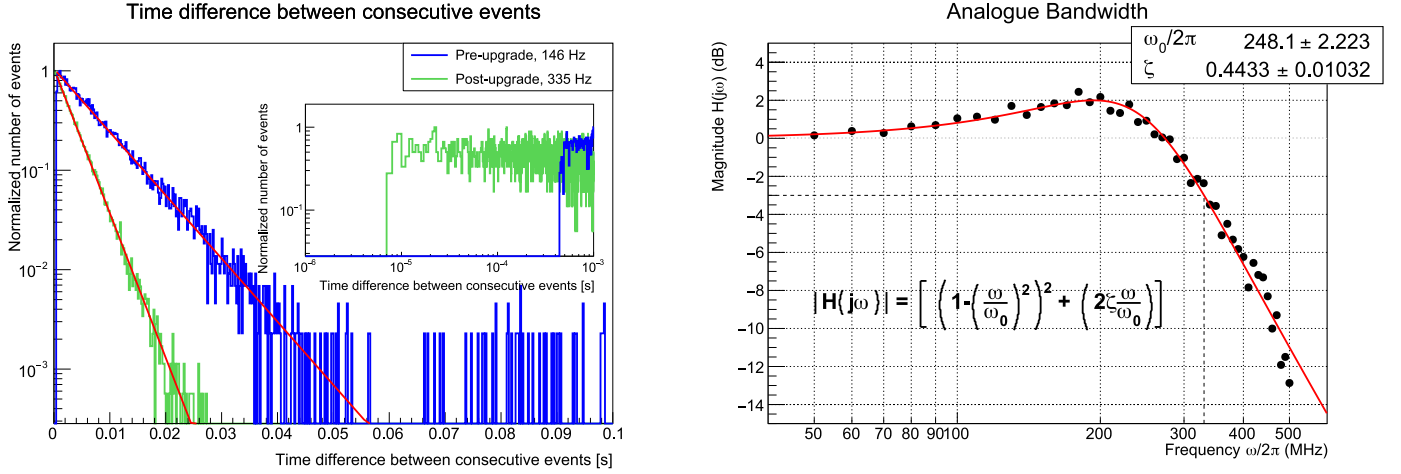


Fig. 12. Left: Normalized distributions of the time delay between two consecutive events in the original (blue) and upgraded (green) H.E.S.S. I cameras. The two runs from which this plot is taken had different average trigger rates. The log-log plot in the inset shows a zoom of the first millisecond with finer binning. From this plot the dead-time can be estimated as the shortest time between two consecutive events, i.e. the position of the left-most bin with entries. Before the upgrade it was $\sim 450 \mu\text{s}$, after the upgrade $\sim 7 \mu\text{s}$. Right: measurement of the end-to-end Bode magnitude plot of the readout electronics. The fit function form employed $|H(j\omega)|$ is the modulus of the transfer function of a second-order underdamped system $H(s) = \omega_0^2 / (s^2 + 2\zeta\omega_0 s + \omega_0^2)$, with damping ratio ζ and eigenfrequency ω_0 . The dashed lines show the -3 dB point of the plot, corresponding to $\omega/2\pi \sim 330$ MHz. The measurement was done injecting a pure sine wave of varying frequency into the system and measuring the relative amplitude of the digitized waveforms.

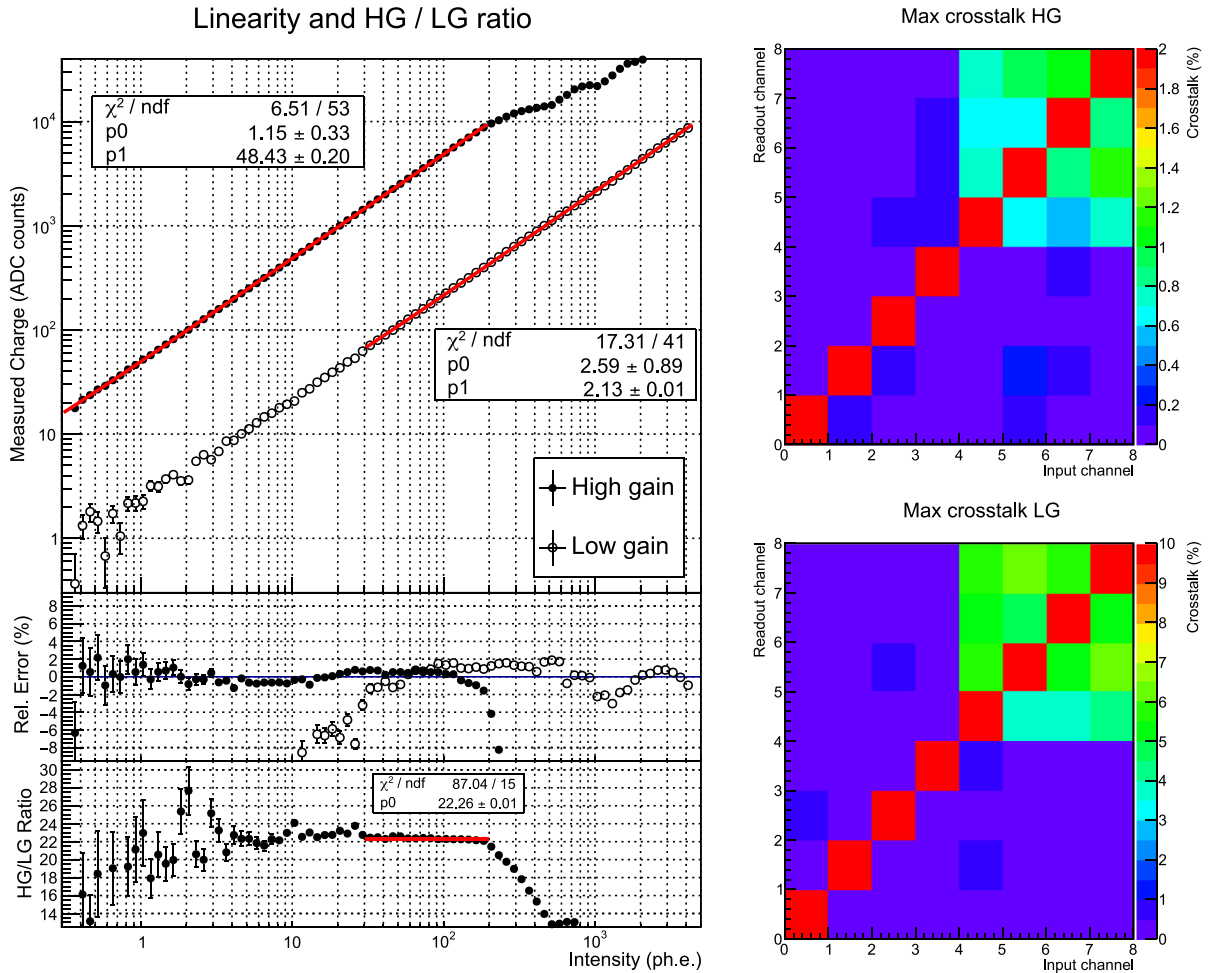


Fig. 13. Left: Linearity of a typical readout channel. The top frame shows the recorded charge versus the input pulse intensity, both for high (black circles) and low (white circles) gain. Two linear functions (red lines) fit this data, their fit parameters and χ^2 values are displayed next to them. The bottom panel shows the ratio between the two gains, and a fit to a constant value in the overlapping range 30–200 p.e.. Right: Maximum cross-talk inside one analogue board, for both high (top) and low (bottom) gain. The cross-talk is computed as the ratio $C(i, r)$ between charges recorded in any pair of channels; the x-axis corresponds to the channel i , where the test pulse is applied, the y-axis to the readout empty channel r .

“mini-camera” was built for this purpose (Fig. 7, bottom left), housed in a 1 m³ light-tight enclosure, with 64 PMTs, one DIB and a light source (an SPE unit). With it, it was possible to test the integration between front-end and back-end by recreating a minimal 1-sector trigger setup. This allowed testing the analogue trigger board and the other trigger functionalities of the DIB using realistic signals, as close to the field conditions as possible. The mini-camera was also used to develop and test the slow control and event builder software and to test their integration into the existing H.E.S.S. DAQ control software.

After the installation of the first telescope, the mini-camera served as the main commissioning test bench. In fact, it became the primary way of reproducing and troubleshooting in the laboratory problems found during the first months of field operations.

3.4. Full camera copy

Later in the project, the camera on-site assembly and integration had to be prepared and rehearsed as thoroughly as possible before actual deployment. This stage required a full camera, so a copy of the camera body was fabricated at the LLR laboratory and installed at DESY Zeuthen (Fig. 7, right). Due to its size, it could not be housed in a light-tight room, so the PMTs were not used, but all other components of all four cameras were mounted and tested first on this camera body, with the purpose of verifying their functionality and training the technicians involved in the assembly. Thanks to this, the on-site physical assembly of one camera could be finished in less than 5 working days. In 2015, the total down-time of the CT1 telescope, excluding commissioning and fine-tuning, was 18 days. In 2016, the CT2-4 telescopes had a total down-time of four weeks.

Other testing and validation activities performed on the copy camera included checks of the cable mapping; full trigger chain functionality check; assessment of the event builder performance and its integration with the H.E.S.S. software; configuration of the camera-internal network; evaluation of the capabilities of ventilation system, slow control software, and power supply; mechanical integration of the new back door and the pneumatic system.

4. Camera calibration

The following section is an overview of the calibration procedures needed to commission the upgraded cameras, partly updating the information found in [14].

4.1. Readout

4.1.1. Nectar line correction

The NECTAr switched capacitor array is arranged in 16 lines \times 64 columns of analogue storage cells. The analogue input is buffered by amplifiers providing the signal for each of the 16 lines. Since each line has its own input buffer and readout amplifier, a spread of the DC baseline levels between lines is observed. This dispersion is stable in time and can be compensated by DC line offsets regulated by 16 integrated digital to analogue converters (DACs). In order to calibrate their values, sample-wise pedestal runs are taken with a readout width of at least 16 samples, and the average difference between the sample baselines and a reference default value (defined as 420 ADC counts to reserve roughly 10% of the dynamic range for pulse undershoots) are calculated. The line offset DAC settings can thus be corrected to compensate this difference. By repeating this process several times, the default baseline offset is approached. In only 5 iterations, the RMS of the baseline decreases from ~ 20 to ~ 4 ADC counts on average, see Fig. 8. This procedure needs to be performed in principle only once, but in practice it is performed for the whole camera each time a drawer

is exchanged, or the PMT gain is re-adjusted, so about twice per year on average. The values of the line DACs are then permanently stored in a MySQL database. This correction is not strictly necessary for regular observations, where the only measured quantity is the charge integrated over 16 samples, minus a time-averaged pedestal baseline. This is because the width of the ROI is a multiple of the line dispersion period, so any event-wise baseline shift due to it is cancelled out.

4.1.2. Readout window adjustment

The NECTAr chips continuously store signals inside their analogue memory ring buffers until the arrival of an L1 trigger signal. When this happens, the region of interest is located L cells before the last sampled one, where L is the L1 trigger latency in nanoseconds. It is therefore necessary to measure the trigger latency L for each chip and trigger source. This is done by illuminating the whole camera with high intensity (~ 100 p.e.) reference light pulse (see e.g. Fig. 9, left) while varying the NECTAr register Nd controlling the start of the region of interest inside the chip buffer, until the sampled pulse signal is located at the center of it. Since the chip buffer is 1024 cells deep and circular, Nd is the complementary of L over the buffer length, $Nd = 1024 - L$.

The position of the readout window needs to be adjusted individually for two trigger sources having different latencies: the SPE unit trigger and the standard camera level 1 trigger. For the former, the SPE unit itself provides the reference light pulses; for the latter the flat-fielding unit is used. After a successful adjustment, the two sets of Nd values are stored in a MySQL database.

4.2. PMT gain flat-fielding

In order to reliably measure the amount of light arriving at the camera, it is necessary to equalize the gain of the electronic chain of each channel. This is done by varying the voltage applied to the PMTs, and illuminating the camera with pulses from the SPE unit, at an intensity so low that the average number of photons detected by a PMT for each light pulse is less than 1. The typical charge distribution of these calibration runs can be seen in Fig. 9, right. The charge is integrated over the standard 16 ns ROI. This distribution can be fit by a linear combination of Gaussian functions, as shown in [14], Eq. (6). This simple fit form is quite robust over a wide range of PMT illuminations (0.1–3 p.e.), but its result is biased: the actual PMT single photo-electron charge distribution is not a Gaussian, but an asymmetric distribution skewed towards lower values. So, the average single photo-electron amplitude is lower than the amplitude at the peak, as shown in [20]. This discrepancy is corrected later on in the analysis by a factor 0.855 derived from realistic simulation of the H.E.S.S. I PMTs [21]. After this correction, the systematic error in determining the PMT gain has been estimated with simulations to be within $\sim 5\%$. Other techniques for the single photo-electron calibration, such as those described in [22,23], are currently being evaluated.

Similarly to their predecessors, the PMT gain of H.E.S.S. I upgrade cameras is flat-fielded to a conversion factor $\gamma_{\text{ADC}}^{\text{PMT}}$ of 80 ADC counts (peak value obtained from the above-mentioned fit). This particular value is chosen empirically, based on the reproducibility and robustness of the fit results. The corresponding average PMT gain is 2.72×10^5 . The PMT voltages range from ~ 850 V up to ~ 1350 V, and are stored in a MySQL database. To achieve a precise gain flat-fielding (better than 4%), the procedure is iterated several times, each with a finer voltage step. The performance of the PMTs degrade with time, so their gains need to be flat-fielded every six months, adding on average 13 V to the PMT voltages. After gain flat-fielding, the position of the region of interest Nd is readjusted, because the PMT transit time t_p depends on the voltage V applied to it.

4.3. Camera flat-fielding

After equalizing the PMT gains, to correctly estimate the amount of Cherenkov light reaching the detector plane, one needs to calibrate the differences in light collection efficiency for each pixel. As mentioned previously, this is achieved by recording light flashes generated by the flat-fielding unit. In fact, assuming the flat-fielding light is homogeneous, one can easily calculate a correction factor C_i from the charge Q_i recorded by each pixel and its average over all camera pixels \bar{Q} : $C_i = \bar{Q}/Q_i$. This is done for the high and low gain channels separately. Flat-fielding runs are also used to calibrate the time of maximum information of each pixel, under the assumption that the flat-fielding pulses arrive isochronally at their entrance window. The flat-fielding is performed several times per observation period (one lunar month), and the obtained coefficients for the period are then averaged and stored in a MySQL database. As for the previous cameras, the distribution of the C_i coefficients is a Gaussian with an RMS of 10%, there is no discernible gradient across the camera. Trials with a new flat-fielding unit are ongoing.

4.4. Trigger

As described in Section 2.2.2, the camera trigger has several parameters which require dedicated calibrations. The most important ones are the pixel and sector thresholds P and Q , and the pixel L0 delay d . The L0 stretching l is set to zero to have a trigger response similar to the one of the old cameras. Central trigger delays also have to be adjusted after the installation of a camera.

Calibrating the pixel threshold P requires finding the relationship between its value as set by the electronics, in DAC counts, or mV, and its effective value in photoelectrons. This is done with special calibration runs, where a variable-intensity pulsed light source is needed. The SPE unit is used for this purpose. The camera is flashed with a fixed frequency f and an varying intensity I , between ~ 5 and ~ 50 p.e. The light pulse intensity in each pixel is measured from the mean of its charge distribution using a previously-determined PMT gain coefficient. While the run is ongoing, P is varied and the L0 pixel trigger efficiencies are measured as the ratio between the pixel trigger rate and f . The resulting graph is a sigmoid, whose mid-point marks the value of P needed to discriminate I photoelectrons (see Fig. 10, left). By repeating this procedure for several intensities, it is possible to determine the offset b and slope m of the linear dependency $P(I) = ml + b$, and thus the effective value of P in photoelectrons.

The calibration of Q , the sector threshold, is likewise accomplished by means of special flat-fielding runs. With the flat-fielding unit activated at a frequency f , one enables N pixels in every sector, varies Q and measures the sector trigger efficiency as ratio between the measured sector trigger rate and f . The mid-point of the resulting sigmoid curve corresponds to the value of the threshold Q for the given N (see Fig. 10, right). Since N is discrete, this sigmoid is much steeper than the one for P . By repeating this procedure for several values of N , it is possible to determine the relationship $Q(N)$ in a similar way as for the pixel threshold. Finally, for the nominal multiplicity of 3, Q is set to a value for which all sectors have 100% efficiency when $N = 3$ and 0% when $N = 2$.

The L0 delays calibration is much simpler: using a modified drawer FPGA firmware, it is possible to send the sampled L0 information of all pixels on the data stream. This is done while flashing the camera with the flat-fielding unit, so all pixels are illuminated at the same time. The L0 delays d are then individually adjusted until the rising edge of all L0 signals is aligned.

After the above-mentioned calibrations, it is necessary to determine the operating point of P . To do that, P is varied while measuring the camera L1 and coincidence trigger rates during a regu-

lar observation run. This “threshold scan” is performed under optimal observing conditions, using the whole array, including CT5. It results in “bias curves” for all four telescopes, shown in Fig. 11. In these plots, the steeply falling part of the coincidence rate at thresholds lower than ~ 5 p.e. is due to noise from the night sky background (NSB) light, whereas the flatter part at higher threshold values is due to cosmic-ray showers. These two components can be fit by two exponential functions, and the value of P is conservatively chosen so that coincident events due to noise are less than 1% of all triggers. For regular camera operation, P is 5.5 p.e., which ensures stable operation even at higher levels of NSB light, up to ~ 250 MHz photon rate. Note that at this value of P , the single-telescope L2 trigger rates are already in the noise, with rates well in excess of 1 kHz, which with the old cameras would have caused more than 36% of the events to be lost due to dead-time, a figure that becomes around $\sim 1\%$ with the new cameras, thanks to the new NECTAr-based readout.

At the array level, it is important to measure the signal round-trip time between the central trigger and the camera, in order to adjust the fixed part of the central trigger coincidence delays, which also vary depending on the pointing direction. This is done by sending a trigger signal via optical fiber from the central trigger to the DIB, which then replies to it. The difference between the time of sending and that of receiving is measured at the central trigger with an oscilloscope. On average, the round-trip time was reduced by ~ 300 ns with respect to the original cameras.

5. Performance

We report some of the most significant performance metrics for the new Cherenkov cameras in this section. Some of them were measured in the lab, prior to the installation of the cameras, others in the field in Namibia, during or after commissioning.

Efforts are ongoing to fully characterize the performance of the new cameras in terms of gamma-ray sensitivity using simulations and standard candle data; and to exploit the several new features they offer. The results will be made available in upcoming publications by the H.E.S.S. collaboration.

5.1. Analogue front-end

The dead-time of a NECTAr chip when reading the nominal 16 cells region of interest is about $1.6 \mu\text{s}$ [25,26]. However, the minimum safe time interval between two events is greater than the nominal dead-time of the NECTAr chip, because of the trigger signal generation and the chip readout process on the FPGA take $\sim 4 \mu\text{s}$. Also, for the version of the NECTAr chip used here, the first 16 readout cells have to be read out and discarded because of stale values, adding another $1.6 \mu\text{s}$ to the dead-time. Due to all this, the hold-off time is set to: $t_b = 4 + (n + n/16) \times 0.1$ ns, where n is the total number of NECTAr cells read out ($n = 32$ for regular observations). This can be appreciated in Fig. 12, left, which shows that the overall dead-time of the upgraded H.E.S.S. I cameras, measured from the distribution of the time difference of two consecutive events during a regular observation run is $\sim 7.2 \mu\text{s}$.

The nominal analogue bandwidth of the NECTAr chip is 410 MHz [25,26]. The design of the analogue electronics uses components matching or exceeding that bandwidth. The end-to-end -3 dB bandwidth of the readout is ~ 330 MHz, more than four times higher than in the previous camera, see Fig. 12, right. One can see the benefit of such a high bandwidth in the sampled PMT pulse shape shown in the left panel of Fig. 9, where the FWHM is less than 3.5 ns. Such narrow peaks allow a better determination of shower time profiles, which can be used to improve the sensitivity of the analysis [27,28].

The design of the analogue part of the readout was optimized for low noise. The pedestal noise, which is the RMS of the value of a single NECTAr cell in the presence of no input signal is on average ~ 4 ADC counts, or ~ 2 mV. This corresponds to the pure electronic noise of the front-end. For the typical PMT gain of 2.72×10^5 , and charge integration window of 16 samples, the electronic noise of front-end and PMT combined has on average a RMS of ~ 16 ADC counts, or ~ 0.2 photo-electrons (p.e.). This is measured routinely during single photo-electron calibration runs, as the RMS value of the pedestal distribution (see Fig. 9, right). The noise intensity varies with the position of the channels inside the drawer: the channels whose amplifiers are physically located in the front of the drawer, closer to the PMTs (channels 4–7 and 12–15) have higher electronic noise (~ 0.25 p.e. RMS) than the ones who are in the back of the drawer (~ 0.15 p.e. RMS), forming two distinct populations. This is likely due to different noise pick-up along the routes of the traces on the analog circuit board. It is anyway not a problem because at the chosen gain, the single-electron signal is distinguishable in any case, being always at least 3 times higher than the noise.

The linearity and cross-talk of the readout were measured by recording a pre-calibrated, PMT-like pulse of variable intensity. The results, which can be seen in the left panel of Fig. 13, show that non-linearities in both high gain and low gain amount to less than 2%. The linear range of the high gain is 0.3–200 p.e. and that of the low gain is 30–4,200 p.e.: the total readout dynamic range is greater than 80 dB. The ratio between high and low gain is ~ 22 between 30 and 200 p.e. (see Fig. 13, left, bottom panel).

The data mentioned above was also used to characterize the cross-talk between two channels on the same analogue board. For the high gain channel the cross-talk is typically less than 0.5%, and never larger than 1%; for the low gain is at most 7% (see Fig. 13, right). It is measured using the largest PMT-like pulse inside the linear range of each gain, and taking the ratio $C(i, r) = Q_r/Q_i$ between the charge recorded in an empty channel (Q_r) to that measured in the input channel (Q_i). Similarly to the electronic noise, the cross-talk is also larger for the front channels (4–7 and 12–15) than for the back ones. This problem was studied in detail with auto-correlation and frequency domain analysis of the recorded noise, but no obvious cause was found [29].

5.2. Trigger

The optimization of the trigger described in the previous section increased the fraction of events triggered stereoscopically with CT5 by more than a factor of two. Before the upgrade it was 20%, after the upgrade it is 44%. This is a direct consequence of the reduced deadtime of the camera due to the NECTAr chip, which allows the camera pixel threshold to be lowered substantially.

In the case of observations with a low NSB light intensity in the field of view (i.e. an average pixel photon rate across the camera of less than 100 MHz), the nominal pixel trigger threshold can be lowered by 1 p.e., to 4.5 p.e. Preliminary studies on simulations showed that this simple adjustment results in marginal improvements in terms of threshold trigger effective area, which were not deemed sufficient to justify the manpower investment in the production and maintenance of a full new set of simulations and instrument response functions.

The next-neighbour alternative trigger architecture was also tested and simulated, but it was found not to deliver a substantially improved performance with respect to the default 3-majority scheme. The performance of the pseudo-sum trigger alternative is still under study due to the higher number of parameters to optimize and difficulty of implementing a realistic simulation.

5.3. Readout and slow control

The NECTAr chip design, the modularity of the camera, the advanced driver for the FPGA–ARM memory bus exploiting direct memory access (DMA) technology and the ample software buffering allow for a maximum achievable data acquisition rate with default settings (i.e. readout and storage of integral charge and timing information) of around 10 kHz per telescope. This is about twenty times higher than the usual CT1–4 acquisition rate during regular observations. It was determined by field tests under realistic conditions.

The bottleneck is the transfer of data to the H.E.S.S. main DAQ program, because the network bandwidth is only 1 Gb/s. Performance tests on a 10 Gb/s network showed that the cameras could sustain a constant individual data acquisition rate in excess of 50 kHz. The system can sustain short bursts of events at a much higher rate by buffering the data in the RAM of the ARM computer and of the camera server. This can be very important for some physics cases, such as transient events and especially GRBs.

The improvement of the new camera readout system allows to configure the readout so that full waveforms of up to 48 samples are stored alongside the integrated charge over 16 ns and the timing information. This is expected to be beneficial in the reconstruction of inclined or large impact parameter showers with energies larger than 1 TeV, for which the arrival time dispersion of Cherenkov light at the telescope is greater than 16 ns. This readout mode increases the amount of transmitted data by a factor ~ 17 (each drawer sends 51 data blocks instead of the usual 3). In order to keep up with the usual data acquisition rates (up to 700 Hz) when using this acquisition mode, the additional waveform data must be stored on the camera server hard disks, and is transmitted to the H.E.S.S. DAQ off-line on the following day. This mode is only used for selected targets, due to the much greater amount of data created when it is active. Initial results on the performance of this readout mode are reported in [30].

Regarding the slow control software performance, stress tests performed on the Apache Thrift RPC framework operating in the busy DESY lab network showed that it is capable of sustaining rates of 10,000 single point-to-point request/replies per second for more than 12 hours with no failures. One-to-many requests, such as distributing a command or collecting information from all drawers, are handled on the camera server by spawning one thread per connection. This strategy allows for a command distribution latency of ~ 8 ms.

5.4. Commissioning and long-term stability

The upgrade of the first camera, that of CT1, was carried out in July/August 2015. This was followed by an extended integration and commissioning period of 9 months. During this period of time, many bugs and problems were ironed out, while the rest of the array (CT2–5) continued scientific observations with minimally degraded performance. This strategy allowed us to compare old and new cameras after the first one was completely commissioned. The other three upgraded cameras were installed in September/October 2016 and underwent a much shorter commissioning phase of four months. In January 2017, a bright flare from the well-known Mkn 421 blazar was observed by H.E.S.S. using the new upgraded cameras, following an alert reported by the HAWC collaboration [31]. About 2 h of data were collected during this observation. The preliminary processing of the data using two independent analysis pipelines revealed a clear detection with a significance of 16σ . This was the first detection of a TeV gamma-ray source using the NECTAr chip technology [32] (see Fig. 14, for a significance sky map of this detection and an example event). The upgraded cameras have been employed in routine

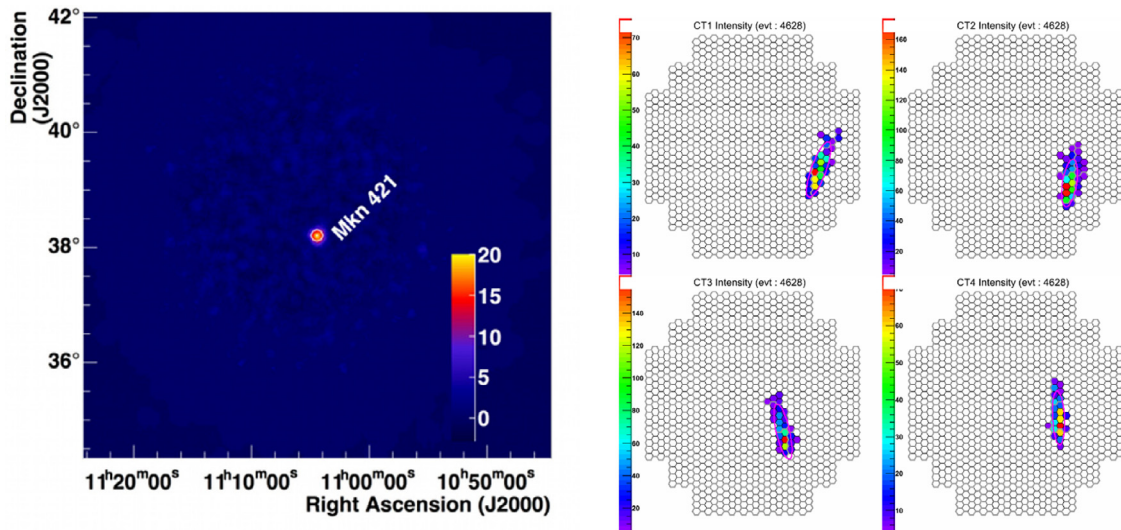


Fig. 14. Left: Significance sky map of Mkn 421, a well-known TeV gamma-ray emitting blazar, observed during the commissioning of the H.E.S.S. upgrade cameras. Right: Example 4-telescope event recorded with the upgrade cameras. Figure adopted from [32].

observations since January 2017, and since then have achieved an average weather-corrected data taking efficiency of 98.5%.

6. Conclusion

The four upgraded cameras of the 12-meter H.E.S.S. Cherenkov telescopes were successfully deployed on site in 2015 and 2016. They are equipped with a new NECTAr-based readout technology that substantially reduces the dead-time by a factor of 60 from $\sim 450 \mu\text{s}$ in the previous system to $\sim 7 \mu\text{s}$ in the new cameras. Furthermore, the new design allows for a more robust, versatile and efficient operation and maintenance, leading to improved performance and reliability. All components of the cameras were tested, integrated and calibrated, and their performance was validated in the field. The camera configuration was optimized, resulting in more than twice the amount of stereoscopically recorded showers by the H.E.S.S. array.

The achieved average data taking efficiency of the cameras is 98.5%. No major problems due to ageing were found during an ordinary maintenance campaign that took place in early 2019. Thus, all the primary goals of the project have been achieved.

In addition, the new cameras offer the possibility of using more sophisticated and flexible trigger and readout algorithms. The most promising of these new possibilities is to record fully sampled waveforms, which is being explored intensively in current observation campaigns and will be reported on in the future.

The new cameras are foreseen to be in use in the H.E.S.S. experiment for its remaining lifetime.

Acknowledgements

The support of the Namibian authorities and of the University of Namibia in facilitating the construction and operation of H.E.S.S. is gratefully acknowledged, as is the support by the German Ministry for Education and Research (BMBF), the Max Planck Society, the German Research Foundation (DFG), the French Ministry for Research, the CNRS-IN2P3 and the Astroparticle Interdisciplinary Programme of the CNRS, the U.K. Science and Technology Facilities Council (STFC), the IPNP of the Charles University, the Czech Science Foundation, the Polish Ministry of Science and Higher Education, the South African Department of Science and Technology and National Research Foundation, and by the University of Namibia.

We appreciate the excellent work of the technical support staff in Zeuthen, Durham, Hamburg, Heidelberg, Palaiseau, Paris, Saclay, and in Namibia in the construction and operation of the equipment.

The authors would also like to thank the anonymous reviewers for their valuable insights.

References

- [1] F. Aharonian, et al., Observations of the Crab Nebula with H.E.S.S., *Astronomy and Astrophysics* 457 (2006) 899, doi:10.1051/0004-6361:20065351. <https://www.aanda.org/articles/aa/abs/2006/39/aa5351-06/aa5351-06.html>.
- [2] J. Bolmont, et al., The camera of the fifth H.E.S.S. telescope. Part I: System description, *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 761 (2014) 46–57, doi:10.1016/j.nima.2014.05.093. <https://www.sciencedirect.com/science/article/pii/S0168900214006469>.
- [3] E. Delagnes, Y. Degerli, P. Goret, P. Nayman, F. Toussenel, P. Vincent, SAM: A new GHz sampling ASIC for the H.E.S.S.-II front-end electronics, *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 567 (1) (2006) 21–26, doi:10.1016/j.nima.2006.05.052. <http://www.sciencedirect.com/science/article/pii/S016890020600862X>.
- [4] P. Vincent, et al., Performance of the H.E.S.S. cameras, in: *Proceedings, 28th International Cosmic Ray Conference (ICRC 2003)*, Tsukuba, Japan, 31 Jul - 7 Aug 2003, volume 5, Universal Academy Press, 2003, pp. 2887–2890.
- [5] C.L. Naumann, et al., New electronics for the Cherenkov Telescope Array (NECTAr), *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 695 (2012) 44, doi:10.1016/j.nima.2011.11.008. <https://www.sciencedirect.com/science/article/pii/S0168900211020420>.
- [6] M. de Naurois, L. Rolland, A high performance likelihood reconstruction of γ -rays for imaging atmospheric Cherenkov telescopes, *Astroparticle Physics* 32 (5) (2009) 231–252, doi:10.1016/j.astropartphys.2009.09.001. <http://www.sciencedirect.com/science/article/pii/S0927650509001364>.
- [7] Code Connected - zeromq, 2019, (<https://zeromq.org/>). Accessed: 2019-07-02.
- [8] Apache Thrift - Home, 2019, (<https://thrift.apache.org/>). Accessed: 2019-07-02.
- [9] L. Rolland, Calibration of the cameras of the H.E.S.S. gamma-ray experiment and observations of the Galactic Centre above 100 GeV, Université Pierre et Marie Curie - Paris VI, 2005 Ph.D. thesis. <https://tel.archives-ouvertes.fr/tel-00010019>.
- [10] S. Funk, et al., The trigger system of the H.E.S.S. telescope array, *Astroparticle Physics* 22 (2004) 285–296, doi:10.1016/j.astropartphys.2004.08.001. <https://www.sciencedirect.com/science/article/pii/S0927650504001422>.
- [11] R. Wischnewski, U. Schwanke, M. Shayduk, Performance study of a digital camera trigger for CTA, in: *Proceedings, 32nd International Cosmic Ray Conference (ICRC 2011)*: Beijing, China, August 11–18, 2011, volume 9, p. 63. doi:10.7529/ICRC2011/V09/0692.
- [12] N. Bulian, et al., Characteristics of the multi-telescope coincidence trigger of the HEGRA IACT system, *Astroparticle Physics* 8 (4) (1998) 223–233, doi:10.1016/S0927-6505(98)00003-6. <http://www.sciencedirect.com/science/article/pii/S0927650598000036>.

- [13] M. Rissi, N. Otte, T. Schweizer, M. Shayduk, et al., A New Sum Trigger to Provide a Lower Energy Threshold for the MAGIC Telescope, *IEEE Transactions on Nuclear Science* 56 (6) (2009) 3840–3843, doi:[10.1109/TNS.2009.2030802](https://doi.org/10.1109/TNS.2009.2030802). <https://ieeexplore.ieee.org/document/5341435>.
- [14] F. Aharonian, et al., Calibration of cameras of the H.E.S.S. detector, *Astroparticle Physics* 22 (2) (2004) 109–125, doi:[10.1016/j.astropartphys.2004.06.006](https://doi.org/10.1016/j.astropartphys.2004.06.006). <http://www.sciencedirect.com/science/article/pii/S0927650504001227>.
- [15] K. Bernlöhr, The optical system of the H.E.S.S. imaging atmospheric Cherenkov telescopes. Part I: layout and components of the system, *Astroparticle Physics* 20 (2) (2003) 111–128, doi:[10.1016/S0927-6505\(03\)00171-3](https://doi.org/10.1016/S0927-6505(03)00171-3). <https://www.sciencedirect.com/science/article/pii/S0927650503001713>.
- [16] K.-M. Aye, et al., A Novel Alternative to UV-Lasers Used in Flat-Fielding VHE g-Ray Telescopes, in: *Proceedings, 28th International Cosmic Ray Conference (ICRC 2003)*, Tsukuba, Japan, 31 Jul - 7 Aug 2003, volume 5, 2003, p. 2975. <http://adsabs.harvard.edu/abs/2003ICRC....5.2975A>.
- [17] Yocto Project | Open Source embedded Linux build system, package metadata and SDK generator, 2019, (<https://www.yoctoproject.org/>). Accessed: 2019-07-02.
- [18] A. Balzer, et al., The H.E.S.S. central data acquisition system, *Astroparticle Physics* 54 (2014) 67, doi:[10.1016/j.astropartphys.2013.11.007](https://doi.org/10.1016/j.astropartphys.2013.11.007). <https://www.sciencedirect.com/science/article/pii/S0927650513001655>.
- [19] Protocol Buffers, 2019, (<https://developers.google.com/protocol-buffers>). Accessed: 2019-07-02.
- [20] K. Bernlöhr, Simulation of imaging atmospheric Cherenkov telescopes with CORSIKA and sim_telarray, *Astroparticle Physics* 30 (3) (2008) 149–158, doi:[10.1016/j.astropartphys.2008.07.009](https://doi.org/10.1016/j.astropartphys.2008.07.009). <http://www.sciencedirect.com/science/article/pii/S0927650508000972>.
- [21] K. Bernlöhr, CORSIKA and sim_hessarray mc simulation of the imaging atmospheric cherenkov technique for the H.E.S.S. experiment, 2002, (H.E.S.S. Internal Note), 02/04.
- [22] R. Saldanha, L. Grandi, Y. Guardincerri, T. Wester, Model Independent Approach to the Single Photoelectron Calibration of Photomultiplier Tubes, *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 863 (2017) 35–46, doi:[10.1016/j.nima.2017.02.086](https://doi.org/10.1016/j.nima.2017.02.086).
- [23] M. Takahashi, et al., A technique for estimating the absolute gain of a photomultiplier tube, *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 894 (2018) 1–7, doi:[10.1016/j.nima.2018.03.034](https://doi.org/10.1016/j.nima.2018.03.034). <http://www.sciencedirect.com/science/article/pii/S016890021830370X>.
- [24] D. Casadei, Estimating the selection efficiency, *Journal of Instrumentation* 7 (08) (2012) P08021, doi:[10.1088/1748-0221/7/08/P08021](https://doi.org/10.1088/1748-0221/7/08/P08021). <https://iopscience.iop.org/article/10.1088/1748-0221/7/08/P08021/meta>.
- [25] E. Delagnes, et al., NECTAr0, a new high speed digitizer ASIC for the Cherenkov Telescope Array, in: *2011 IEEE Nuclear Science Symposium Conference Record*, 2011, pp. 1457–1462, doi:[10.1109/NSSMIC.2011.6154348](https://doi.org/10.1109/NSSMIC.2011.6154348).
- [26] E. Delagnes, Specifications of the NECTAr0 Chip, 2016, (Internal Document Ifru CEA Saclay). V.4 2016-01-05.
- [27] E. Aliu, et al., Improving the performance of the single-dish Cherenkov telescope MAGIC through the use of signal timing, *Astroparticle Physics* 30 (6) (2009) 293–305, doi:[10.1016/j.astropartphys.2008.10.003](https://doi.org/10.1016/j.astropartphys.2008.10.003). <http://www.sciencedirect.com/science/article/pii/S0927650508001497>.
- [28] V. Stamatescu, et al., Timing analysis techniques at large core distances for multi-TeV gamma ray astronomy, *Astroparticle Physics* 34 (12) (2011) 886–896, doi:[10.1016/j.astropartphys.2011.03.008](https://doi.org/10.1016/j.astropartphys.2011.03.008). <http://www.sciencedirect.com/science/article/pii/S0927650511000703>.
- [29] K.P. Shiningayamwe, Investigating electronic pedestals of the analogue front-end boards of the upgraded high-energy stereoscopic system (H.E.S.S. I) cameras, University of Namibia, 2017 Thesis. <http://repository.unam.edu.na/handle/11070/1939>.
- [30] J. Zorn, Sensitivity Improvements of Very-High-Energy Gamma-Ray Detection with the Upgraded H.E.S.S. I Cameras using Full Waveform Processing, in: *Proceedings, 36th International Cosmic Ray Conference (ICRC 2019)*, Madison, WI, U.S.A., 24 Jul - 1 Aug 2019, volume ICRC2019, *Proceedings of Science*, 2019, p. 834.
- [31] I. Martinez, J. Wood, R. Lauer, HAWC detection of further increase in TeV gamma-ray flux from Mrk 421, *The Astronomer's Telegram* 9946 (2017).
- [32] H.E.S.S. Collaboration - Source of the Month - March 2017, 2017, (<https://www.mpi-hd.mpg.de/hfm/HESS/pages/home/som/2017/03/>).