

Development of a Camera for Tera-electron Volt Gamma-ray Astronomy



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This dissertation is submitted for the degree of
Doctor of Philosophy

Exeter College

September 2016

*C'è che ormai che ho imparato a sognare,
non smetterò.
(Negrita)*

*Now that I learnt to dream,
I won't stop.*

Declaration of Authorship

The research described in this thesis was carried out by me, based at the Department of Physics, University of Oxford between October 2014 and September 2016, under the supervision of Prof. Garret Cotter. I was supported by the People Programme (Marie Curie Actions) of the European Union Seventh Framework Programme FP7/2007-2013/ under REA grant agreement n [317446] INFIERI “INtelligent Fast Interconnected and Efficient Devices for Frontier Exploitation in Research and Industry“. I declare that no part of this thesis has been accepted, or is currently being submitted, for any degree or diploma or certificate or any other qualification in this University or elsewhere.

Chapter 3 – The work described in this chapter was carried out in collaboration with a small group of members of the Gamma Cherenkov Telescope (GCT) consortium. Scientific decisions on the testing programme were made equally between the team; I focus on the work that I undertook myself. Part of this work has been published as a refereed paper,

De Franco & Cotter, *Test bench for front end electronic of the GCT camera for the Cherenkov Telescope Array*, Journal of Instrumentation, Vol 11, 2016.

Chapter 4 – The work described in this chapter was carried out in collaboration with Dr. Richard White and Dr. Richard Bose of the GCT consortium at the Physics Department of the University Leicester. Scientific decisions on the testing programme were made equally between the team, and I focus on the work that I undertook myself.

Chapter 5 – I lead the work described in this chapter, and it was carried out mostly by myself, as the deputy software coordinator for the GCT, with the supervision of Prof. Cotter and small contributions from Dr Arnim Balzer and Prof. Akira Okumura of the GCT consortium.

The work described in chapters 3–5 is briefly described in a conference proceeding,

De Franco et al., *The first GCT camera for the Cherenkov Telescope Array*, in proceedings of the 34th International Cosmic Ray Conference (ICRC2015), The Hague, The Netherlands, 2015.

Chapter 6 – The work described in this chapter was carried out in collaboration with five members of the GCT consortium at the Observatoire de Paris in Meudon with all team members contributing equally. This work is described in a conference proceeding,

J-L Dournaux, Andrea De Franco et al., *Operating performance of the gamma-ray Cherenkov telescope: An end-to-end Schwarzschild-Couder telescope prototype for the Cherenkov Telescope Array*, Nuclear Instruments and Methods in Physics Research Section A, 2016

Chapter 7 – I lead the work described in this chapter with supervision of Prof. Cotter. The Axion-like-particle oscillation model was developed by Dr. Miguel Sanchez Conde and the gamma-ray absorption model by Dr. Yoshiyuki Inoue. Data for secondary gamma-ray fluxes was kindly provided by Dr. Oleg Kalashev. A paper on the results of this work, on which I am lead author, is in preparation for submission to *Astroparticle Physics*.

I hereby certify that the work in this thesis is wholly my own, except for the contributions aforementioned.

Acknowledgements

First and crucially I thank my supervisor Prof. Garret Cotter for letting me discover this wonderful world of gamma-ray astrophysics. Not only you guided me through the field, but also encouraged to explore my own scientific interests and to become an independent researcher. I'm very honored to have been your student. Thank you for all the lessons you taught me, not only for the one in physics. I will treasure them.

Thanks also to Jason Watson, Paul Morris and everyone who has been part of the γ^3 in Oxford over the past three years. It was really a privilege to work together, to share comments and suggestions.

I want to thank all the members of the Gamma-ray Cherenkov Telescope sub-consortium for the three very exciting and productive years of collaboration. In my life, I have never hated anything more than the camera when it just wasn't working. On the other hand, no joy and satisfaction was greater when I saw those first Cherenkov shower images on that screen in front of me, in the control room in Meudon. It has been a great pleasure to work together. I also extend my thanks to the broader community of the Cherenkov Telescope Array, especially Dr. Yoshiyuki Inoue and Dr. Miguel A. Sánchez-Conde for their very valuable contributions to the work on prediction for extragalactic survey presented in chapter 6.

I acknowledge the support I received from the People Programme (Marie Curie Actions) of the European Union Seventh Framework Programme FP7/2007-2013/ under REA grant agreement n [317446] INFIERI "INtelligent Fast Interconnected and Efficient Devices for Frontier Exploitation in Research and Industry". I also thank all the members of the network for the inspiring collaboration.

During my time in Oxford I shared the office in the tower with wonderful persons. Thanks to all for the chats, the relaxed environment and especially Andrea & Andre for the coffee breaks.

Oxford is a great and multicultural place, where it's easy to meet people and make new friends. But it's not so easy, in any part of the world, to find friends of the caliber of Andrea, Ashley, Christiane, Kimiko, Kyoko, Yeli. You made Oxford a truly special place. Thank you.

The people I met during the Vulcanus in Japan program are the craziest, funniest and most friendly I've ever met. I couldn't have asked for better companions for an adventure. No matter how far you are, you're always close to my heart, thank you for all the special time together and your friendship.

To my friends from high-school and university of Genova. It's hard to live far from you all, thank you for making me feel home so quickly every time I came back.

Special thanks to Mirko for being a true friend and always been there to support and cheer me up every time I needed, since high-school. I wish there would be words to say how much I am grateful for your friendship, an indissoluble brother-like bond.

The best thing that happened in my life was meeting Masako. I married you already twice and I would marry you many million times more. Thank you for making my days so special. Thank you for your sacrifices to let me chase my dreams. This thesis would have not been possible without your support.

My dad is a retired mechanic, my mom a clerk. They worked hard and sacrificed so much so that nothing was out of my grasp. All through these years, I only had to stretch my arm just a tiny bit further to get what I wanted, to be where I wanted to be. They provided all I needed to get here, and this thesis is their achievement as much as it is mine.

My sister Manuela is the pillar of my life, my hero and the person I always look up to. I will never forget the moment you were born and we brought you back home from the hospital. That moment changed my life. Sorry I'm always far from you. I miss you every single day and you give me a reason to come back home.

Development of a Camera for Tera-electron Volt Gamma-ray Astronomy

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Submitted for the degree of Doctor of Philosophy

Trinity Term, 2016

Abstract

In this thesis I describe the development of a compact camera for ground-based multi TeV gamma-ray astronomy, using the Imaging Atmospheric Cherenkov Telescope (IACT) technique. The camera is based on multi-anode photomultipliers (MAPM) and is designed for use on the Gamma Cherenkov Telescope (GCT), which is proposed to be part of the Small Size Telescope (SST) array of the Cherenkov Telescope Array (CTA). GCT achieves high performance with a compact and cost efficient design via a Schwarzschild-Couder (SC) dual-mirror optical system. The GCT optical design allows the use of a compact camera of diameter roughly 0.5 m. The curved focal plane is equipped with 32 tiles of 64-pixels MAPM for a total of 2048 pixels of $\sim 0.2^\circ$ angular size, resulting in a field of view of $\sim 9^\circ$. The GCT camera is designed to record the flashes of Cherenkov light from electromagnetic cascades, which last only a few tens of nanoseconds. I give a detailed description of the design, the challenges encountered during testing in the lab, and the performance of the most critical components.

I give details on the custom front-end electronics modules that provide the required fast electronics, facilitating sampling and digitization, as well as first level of triggering. The camera-level triggering system is a custom backplane, developed to reject spurious triggers on the night sky background, which typically is of the order of few tens of millions of photons per pixel per second. This is to be compared with the rate of the astrophysical signal, which is of the order of few hundreds of events per second at the relevant energies. Additionally I provide a detailed description of all the software needed for the data acquisition and control of the camera, from the very low level drivers to high level and user friendly processes.

I follow the commissioning of the camera, from the individual core components to the integration of the system. I then describe the integration of the camera on the GCT prototype telescope structure, and the achievement of “first light”, validating for the first time the full proof-of-concept of an IACT with SC optics.

I also report a study I performed on expectations for an extragalactic survey for blazars with CTA. The cumulative source count distribution of blazars is presented, including implications from two different phenomena: axion-like particle (ALP) to gamma-ray oscillations in the intergalactic magnetic field, and secondary gamma rays from hadronic origins. I conclude that a shallow and wide survey will provide the best science return for CTA, that the impact of ALP is modest and that the secondary mechanism of gamma-ray production would allow detection of blazars up to redshift of 1 in the multi-TeV energy band.

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Chapter 1

Introduction

Very High Energy (VHE) gamma-ray astronomy is the study of astrophysical sources of photons with energy above 50 GeV. It is a relatively new field with a promising future. In 2003 only 20-50 galactic sources at TeV energies were predicted. Yet by 2012 more than 140 TeV sources had been found, with many of unexpected classes. This suggests that what we see now is just the tip of the iceberg. The planned Cherenkov Telescope Array (CTA) will bring about the next generation of ground based VHE gamma-ray astronomy. The improved sensitivity and Field of View (FoV) of CTA will allow for a 300 times faster survey, and with a 10 fold improvement in angular resolution will disentangle the clustered emission sources. One of the driving science goals is to shed light on the cosmic-ray acceleration mechanism and to explore the cut-off regime of the cosmic accelerators by observation of supernova remnants, pulsars, active galactic nuclei jets and lobes. In this chapter I give a brief introduction to the relevant VHE gamma-ray production processes and some of the astronomical sources in which they are observed. Furthermore CTA will be used to test very fundamental physics questions: what's the limit for Lorentz invariance violation, do axion-like particles exist and can we see a dark matter annihilation signature? I provide in this chapter a brief overview on these topics. All the CTA ambitious science goals put very stringent requirements on the technology to be used. I introduce the concept of the CTA detection technique based on Imaging Atmospheric Cherenkov Telescopes (IACTs) and the state-of-the-art of the field. I describe the CTA design, with particular attention to one of the prototypes proposed for the observatory: the Gamma-ray Cherenkov Telescope (GCT) on which I focused my research.

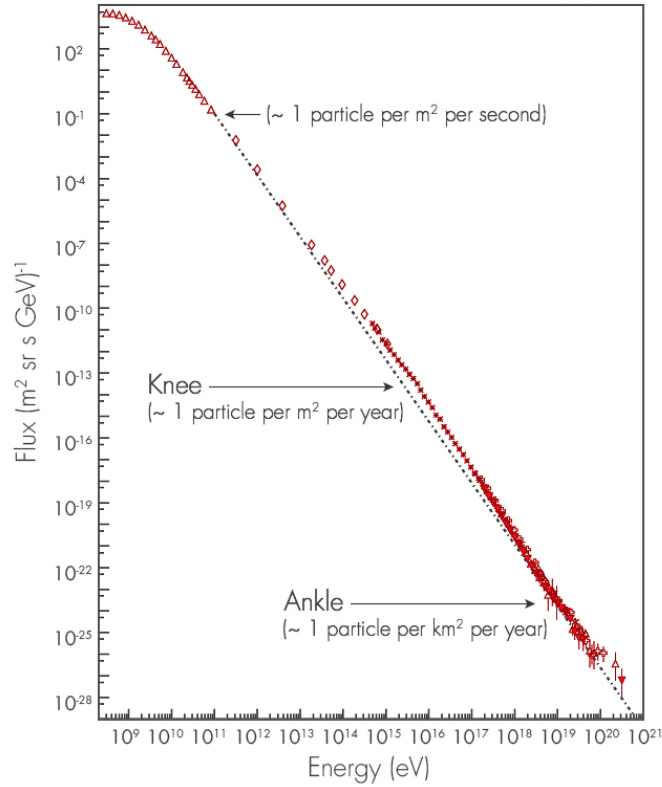


Fig. 1.1 All particles cosmic-ray spectrum.[1]

1.1 The VHE gamma-ray sky

1.1.1 Production mechanisms

Gamma-rays are photons typically emitted in nuclear decay with energy $\gtrsim 100$ keV. For comparison, these energies are roughly 9 orders of magnitude above visible light. Our Sun has a surface temperature of ~ 6000 K. Its emission of visible light due to thermal radiation is obvious to us. According to Planck's radiation law, the hottest astrophysical objects, e.g. in accretion discs around compact stars, can emit photons as energetic as ~ 10 keV. The observed astronomical photon spectrum extends up to multi-TeV and clearly its source must lie in non-thermal processes. Here I highlight two of the most relevant origins of such radiation.

Neutral pion decay

Cosmic-rays were discovered at the beginning of the 20th century independently by Victor Hess and Domenico Pacini. In Fig. 1.1 I report the cosmic-ray spectrum now measured by many experiments. The shape is well reproduced by a power law with two evident breaks called the 'knee' and the 'ankle'. It is widely believed that the main acceleration

sources of cosmic-rays are of Galactic origin, e.g. Supernova Remnants (SNRs), below the knee and extragalactic above the ankle, e.g. Active Galactic Nuclei (AGN), with a transition between the two regimes somewhere between the knee and the ankle. The composition of the cosmic-rays is largely dominated by light nuclei, protons (90%) and alpha particles (9%). Inelastic collisions of protons with matter typically lead to the production of a number of pions. In the case of the neutral pion, the largely preferred and almost instantaneous decay is to a pair of photons. This provides one of the most important mechanisms for astronomical gamma-ray production. Pions are the lightest of the hadronic particles and are present not only in proton-proton collisions, but in nearly all the sub-products of the interactions of their heavier cousins with matter.

Inverse Compton

As I will discuss later in this chapter, electrons are believed to be accelerated to ultra-relativistic energies in a number of astrophysical sources, SNRs, pulsars, AGNs, etc. Their role in production of VHE gamma-rays is critical. Two electromagnetic mechanisms that produce X-rays and sub-TeV gamma-rays are bremsstrahlung and synchrotron radiation. In the former an electron is deflected by a strong electric field, typical of the environment close to nuclei. In the latter an intense magnetic field curves the trajectory of the lepton. In both processes this results in the emission of a secondary non-thermal photon.

Especially relevant for the very high end of the gamma-ray spectrum is inverse-Compton scattering (IC). This process is analogous to the Compton effect, but in the case of IC, an ultra-relativistic electron collides with a photon of lower energy. The electron loses part of its kinetic energy, and the photon is up-scattered to higher energy. In a simple model assuming Thomson scattering in the electron's rest frame, it is easy to see that the maximum energy transfer is for a head-on collision, when the photon leaves the interaction with energy E_{out}

$$E_{out} = E_{in}\gamma^2(1 + \beta)^2 \approx 4E_{in}\gamma^2, \quad (1.1)$$

where E_{in} is the initial energy of the photon, β, γ refers to the electron. This mechanism is very efficient for ultra-relativistic leptons, as the photon energy gain is proportional to γ^2 . The photon field target can be self induced by other electromagnetic interactions like the above mentioned, or an independent external one. For example, the 2.7 K cosmic microwave background (CMB) offers a ubiquitous target for IC.

1.1.2 Astronomical sources

Supernova Remnants

Massive stars are believed to end their lives in supernova explosions. The blast blows off the star's outer layers into a supernova remnant (SNR), which heats the surrounding

medium and accelerates cosmic-rays to extremely high energies. The radiation from shell-like SNRs consists of both thermal and non-thermal emission, from shock-heated gas and shock-accelerated particles respectively. Such particle acceleration and escape processes are predicted by the theory of diffusive shock acceleration (DSA) at shock fronts [2, 3], but not entirely understood yet. This particle population yields VHE gamma-rays from interaction with ambient magnetic fields, ambient photon fields, or matter. During the free expansion of the SNR the abundance of relativistic particles increases, until the early stage of the Sedov phase when the maximum is reached. Correspondingly, the gamma-ray luminosity typically peaks 10^3 - 10^4 years after the supernova explosion. Several shell-like SNRs have a size greater than 0.1° , and this allows the structure of the shock to be resolved even at VHE using ground based instrumentation. A good correlation in many of these objects is present between the X-ray and TeV gamma-ray, probing the non-thermal emission from relativistic particles accelerated to multi-TeV energies. A long standing question concerns the relative contributions of accelerated electrons and protons to the VHE gamma-ray production. The former by IC on the CMB and the latter by interaction on the surrounding gas [4]. Recently the characteristic neutral pion-decay signature in the sub-GeV spectra of W 44 and IC 443 was discovered by Fermi-LAT [5], confirming hadronic CR acceleration. Yet, it is not clear whether SNRs are the origin of the bulk of the Galactic CR population up to energies beyond the knee. This argument is partly based on the energy input required to maintain the galactic CR flux

$$\frac{dE}{dt} \approx \rho V \tau \sim 5 \cdot 10^{40} \text{ erg s}^{-1}, \quad (1.2)$$

with the CR energy density $\rho \sim 1 \text{ eV cm}^{-3}$, the CR confinement volume $V \sim 10^{67} \text{ cm}^3$ and the characteristic residence time $\tau \sim 10^7$ years. The typical kinetic energy output of a supernova explosion is of the order of 10^{51} erg . With a rate of 2-3 explosions every 100 years, an efficiency of $\sim 10\%$ is sufficient to explain CR acceleration. This and the observed power-law spectrum with index around 2 can be explained by DSA models based on first-order Fermi acceleration [6–8].

Pulsars & Pulsar Wind Nebulae

Pulsars are neutron stars; remnants of supernova explosions. Pulsars exhibit an intense magnetic field and are accompanied by a relativistic wind outflow. The misalignment of the magnetic field axis with the rotation axis creates a rotating magnetic dipole that emits electromagnetic radiation with a luminosity

$$\dot{E} \sim 3 \cdot 10^{33} B^2 P^{-4} \text{ erg s}^{-1}, \quad (1.3)$$

and spin down; B is the surface magnetic field in units of 10^{12} G and P the period in milliseconds. The rotating field creates a voltage drop of the order of $10^{17} B/P$ V that can efficiently accelerate electron-positron pairs produced from electromagnetic cascades in the strong fields surrounding the pulsar surface. The accelerated leptons produce pulsed radiation via curvature mechanisms and IC. A variety of models exist to explain the high-energy emission from pulsars, among them the polar-cap model [9], the slot-gap model [10], the outer-gap model [11] and the two-pole caustic model [12]. The main difference between the models concerns the zone where the particle acceleration occurs, either close to the star surface near the poles, or close to the pulsar's light cylinder defined as

$$R_{LC} = \frac{c2\pi}{P}, \quad (1.4)$$

where c is the speed of light and P is the measured period [13].

Relativistic winds from energetic pulsars carry most of the rotational power into the surrounding medium terminating in a shock where the ram pressure of the wind is balanced by the pressure of the surrounding nebula. The particles accelerated at this shock produce a steady and very extended non-thermal radiation due to IC scatter on the lower energy photon field originating from the microwave background, thermal or synchrotron processes.

Binary Systems

A handful of binary systems have been observed in VHE gamma-rays. These sources are believed to be composed of a massive star and a compact companion. The mechanism behind the TeV emission is not yet clear and two main scenarios are envisaged [14–17]. In the so called micro-quasar scenario an accretion powered jet is the source of the particle acceleration. This system would work in a very similar fashion to a scaled down AGN, described further in this section. Another model is based on a collision between the ultra-relativistic pulsar wind and the very dense target provided by a companion stellar wind.

Active Galactic Nuclei

A fraction of galaxies host Active Galactic Nuclei (AGN), which are compact regions where a super-massive black hole (from 10^6 to 10^9 solar masses) accretes matters and powers collimated relativistic outflows, called jets. Depending on the angle between the direction of the jets and the observer, we call the source blazar or radio galaxy. The former has a jet pointing towards us, so the gamma-ray emission is heavily boosted by the Doppler effect, both in luminosity and energy spectrum. The latter are observed at higher angles and VHE observations, together with multi-wavelength studies, could help to resolve the structure of the jets. I will focus the attention of this section on blazars, because they

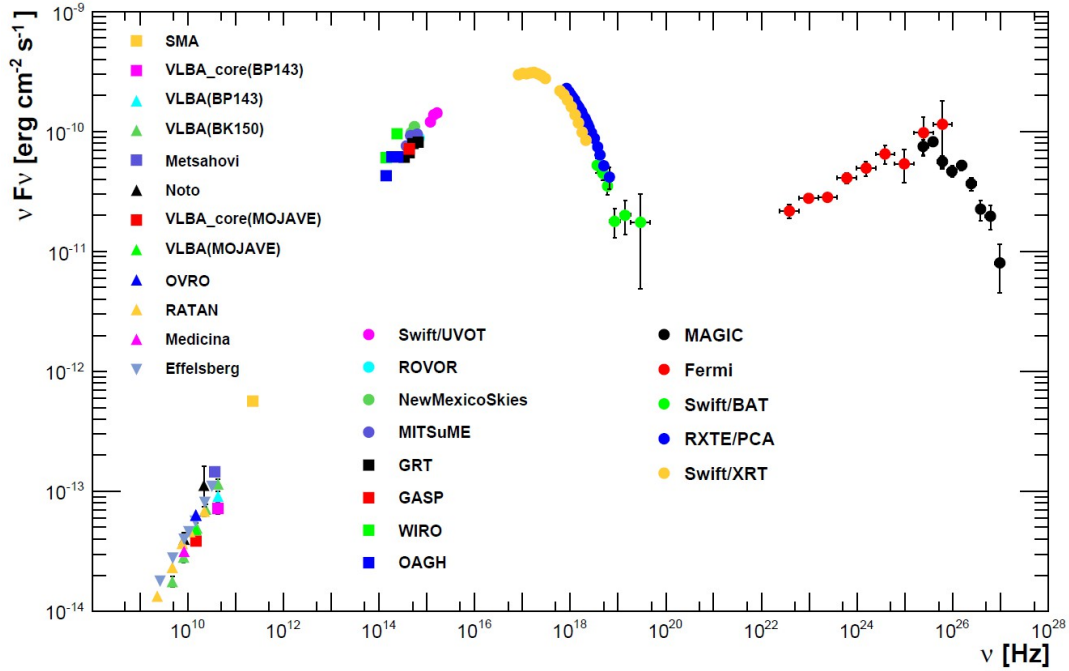


Fig. 1.2 Characteristic double-humped Spectral Energy Distribution. In this example Mrk 421 as measured in different wavelengths by a number of experiments. *From* [18].

represent the vast majority of the detected extragalactic sources in VHE. Furthermore an introduction on these objects is due before chapter 6 where I report my study on the expectations on the number of sources CTA (and other experiments) will be able to detect in a serendipitous survey. The angular resolution of VHE instruments is typically of the order of few arc-minutes, so blazars appear point-like.

The Spectral Energy Distribution (SED) of blazars shows a double-humped structure when plotted in terms of νF_ν , demonstrated in Fig. 1.2 and 1.3.

The first hump is commonly attributed to non-thermal electron synchrotron emission; the second one is widely believed to be due to leptonic IC processes. Different models assume IC on either the synchrotron self-produced photon field or on an external one. The name of the models are, respectively, Synchrotron Self-Compton (SSC) or External Compton (EC). Hadronic scenarios with VHE gamma-rays produced by neutral pion decay still remain possible. See chapter 6 for an averaged blazar SED derived from a recent study [19].

There are two categories of blazars, BL Lac objects and Flat Spectrum Radio Quasars (FSRQs), the latter distinguished from the former by the presence of strong and broad (rest frame equivalent width $\gtrsim 5\text{\AA}$) optical emission lines. Furthermore the BL Lacs are divided in three sub-categories according to the frequency of the synchrotron peak. Low frequency peaked BL Lacs (LBLs) have $\nu_p < 10^{14}$ Hz, High frequency peaked BL Lacs (HBLs) show $\nu_p > 10^{15}$ Hz, up to 10^{19} . With an Intermediate class (IBL). Blazar

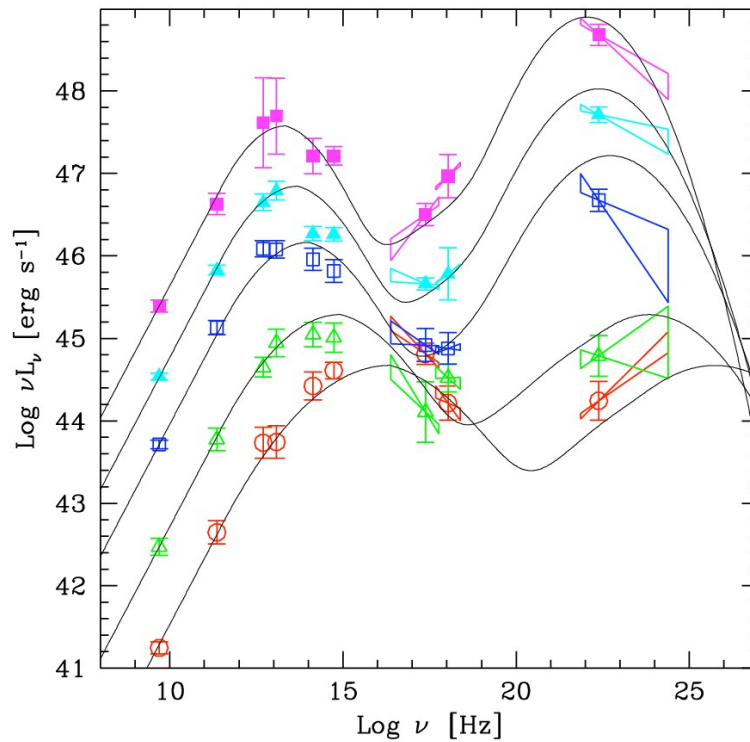


Fig. 1.3 The blazar sequence. Characteristic distribution of blazar SEDs as a function of source luminosity from FSRQ (top curve) to HBL objects (bottom curve). *From [20].*

population studies suggest a so called “blazar sequence” that shows a relation between the source luminosity, the position of the synchrotron peak and the ratio of high-to-low energy components [20–22]. An increase of the first corresponds to a decrease of the second and increase of the last.

Blazars show variability with timescales above months down to less than a day and emit radiation over almost 20 orders of magnitude in photon energy. Clearly multi-wavelength simultaneous observations are a very powerful tools to understand the nature of the non-thermal process happening in these objects. TeV and X-ray flux variations are often correlated, which supports the leptonic scenario, but in the literature it is possible to find counterexamples [23]. Another argument against hadronic models is the required strong magnetic field or target density to compensate for the longer cooling timescales and to account for the short term variability [24]. Yet neither of these two scenarios has been completely ruled out.

1.1.3 Astroparticle physics

Dark Matter

One of the most intriguing questions of this century for modern physics is the nature of the dark matter (DM). There is vast evidence to imply the presence of a gravitational mass that cannot be accounted for by any of the standard model particles from kiloparsec to megaparsec scales. The DM component is contributing 25% of the total energy budget of the Universe. For comparison, the baryonic component is about 4% [25]. It is evident that the DM is at the origin of the cosmic structure. Cosmological DM has to be non-relativistic when decoupling from thermal equilibrium in the early Universe to reproduce the observed large-scale structure we observe today. This argument is supported by a number of N-body simulations of structure formation [26–28] and studies performed on the galaxy distributions in large redshift galaxy surveys [29]. One of the most popular models explains the nature of this cold DM with weakly interacting massive particles (WIMPs). This category includes a vast range of non-baryonic particles with masses typically in the range of few tens of GeV up to few TeV. As the name suggests, their annihilation cross-section is set by weak interactions [30, 31]. WIMPs are expected to annihilate to particles of the standard model, thus associated to emission of charged cosmic-rays, neutrinos, multi-wavelength photons arising from interaction of secondaries and prompt gamma-rays. Unlike charged particles, the radiation component points directly back at the source¹. VHE gamma-ray astronomy might be the key for indirect detection of DM.

Axion-Like Particles

Axions were proposed in the 1970's by Peccei and Quinn as part of the solution of the QCD strong-CP problem [32]. Axion-Like Particles (ALPs) are a special kind of axions for which the mass is not related to the coupling constant. This sub-class is a very valid candidate for cold DM. ALPs are expected to convert into photons and oscillate between the two states in the presence of an external magnetic field [33, 34]. This very distinctive feature is at the core of the detection method of many experiments like the CERN Axion Solar Telescope (CAST) [35, 36] or the Axion Dark Matter Experiment (ADMX) [37].

The existence of ALPs is important for the opacity of the Universe to VHE gamma-rays. Photons of energies above few hundred GeV have a large cross-section for pair-production annihilation on the diffuse Extragalactic Background Light (EBL) of photon fields with lower frequency. This effect distorts the original spectrum of the observed source. Especially for objects at redshift above 1, the TeV gamma-ray flux is so depleted that detection is very challenging. ALPs would not be absorbed on the EBL, thus the

¹This is true also for neutrinos, but they are intrinsically harder to detect, due to the low cross-section of their interactions with matter.

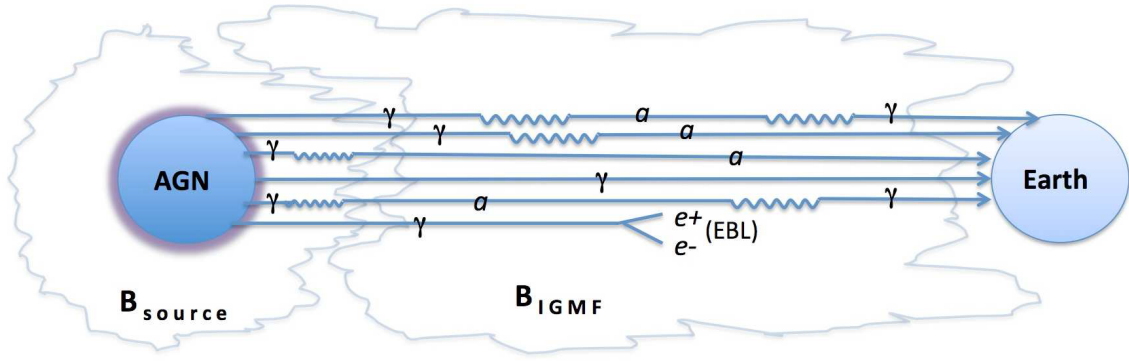


Fig. 1.4 Diagram of the ALP/photon oscillation in the presence of an external magnetic field. Either near the source, or during the propagation in the intergalactic medium. Without ALPs a photon can be detected at Earth or absorbed on the EBL. ALP might modify the opacity of the Universe to VHE gamma-rays. *From* [44].

probability of a gamma-ray surviving annihilation and propagating a further distance is increased. Of course, an ALP has to oscillate back to a photon to be detected as gamma-ray at Earth. Gamma-ray astronomy might be able to see signatures of these particles in the distortion induced on the spectra of extragalactic sources like AGNs [38–42], or possibly even in Galactic sources [43]. In Fig. 1.4, a diagram is shown of the oscillation mechanism of ALP/photon and its possible importance for VHE gamma-ray astronomy. In chapter 6 I report my own study on ALP's influence on extragalactic source population studies in the era of CTA.

Lorentz invariance violation

General Relativity (GR) has been tested extensively, and very recently gravitational waves have been detected [45], another of the predictions of GR. Yet we still lack a consistent description of Quantum Gravity (QG). Some models [46] have been proposed for QG to predict dynamics at the Plank Energy defined as

$$E_{Pl} = \sqrt{h/G_N} \sim 1.22 \cdot 10^{19} \text{GeV}, \quad (1.5)$$

where gravitational effects should become as strong as the other forces and the notion of space-time is likely to need revision. This opened up the possibility for violation of the Lorentz invariance. For example, quantum fluctuations may produce a foamy space-time structure at the Planck scale. This would lead to a non-trivial refractive index and anomalous dispersion of light in vacuum. In other terms, light might propagate in vacuum with a speed dependent on the photon energy [47]. VHE gamma-ray emission from very rapidly variable object, like AGN or gamma-ray bursts, has been proposed as a test against the Lorentz invariance. [38, 48].

1.2 Imaging Atmospheric Cherenkov Telescopes

Astrophysical gamma-rays at GeV energies and above have such a large interaction cross section with matter that they cause electron-positron pair production in the high atmosphere, at around 20 km above ground level. This prevents direct gamma-ray detection with ground based instruments, compared with satellite-borne detectors that can be used to measure the energy and incident direction of gamma-ray impinging directly on the instrument. While the photon interaction cross section at all energies between GeV–TeV ensures production of an electromagnetic cascade in the atmosphere, the gamma-ray energy spectrum has a negative power law distribution (with exponent of about 2.7), thus the sensitivity of the instrument is mainly determined by its effective detection area in this energy range. The expected number of detected photons at 1 TeV is roughly 0.2 per m² per year, so to collect significant statistics a very large collection area is required. Because of the difficulties and the cost of building very large satellites this solution is not feasible. In the second half of last century a new, ground based, technique has been developed [49], using the Cherenkov light emission of secondary particles produced by gamma-ray interacting in the atmosphere.

1.2.1 Air Shower Model

When a primary photon of energy greater than few MeV enters the Earth's atmosphere it undergoes electron-positron pair production. These particles encounter the electromagnetic field of the medium and after traveling, on average, one radiation length X_0 they lose part of their energy via Bremsstrahlung, emitting a secondary photon which in turn, after a mean free path comparable with X_0 decays into an $e^- - e^+$ pair. The two processes go on creating a shower of particles until the mean energy per particle reaches a critical value E_{crit} below which the Compton and photovoltaic effects start to prevail over pair production. The number of particles in the cascade at an atmospheric depth X is

$$N(X) = 2^{X/X_0}, \quad (1.6)$$

Assuming an equipartition of energy over all the particles we can write

$$N_{max} = N(X_{max}) = E_0/E_{crit}, \quad (1.7)$$

and, for the length of shower at its maximum extension X_{max}

$$X_{max} = X_0 \ln(N(X_{max}))/\ln 2 = X_0 \ln(E_0/E_{crit})/\ln 2, \quad (1.8)$$

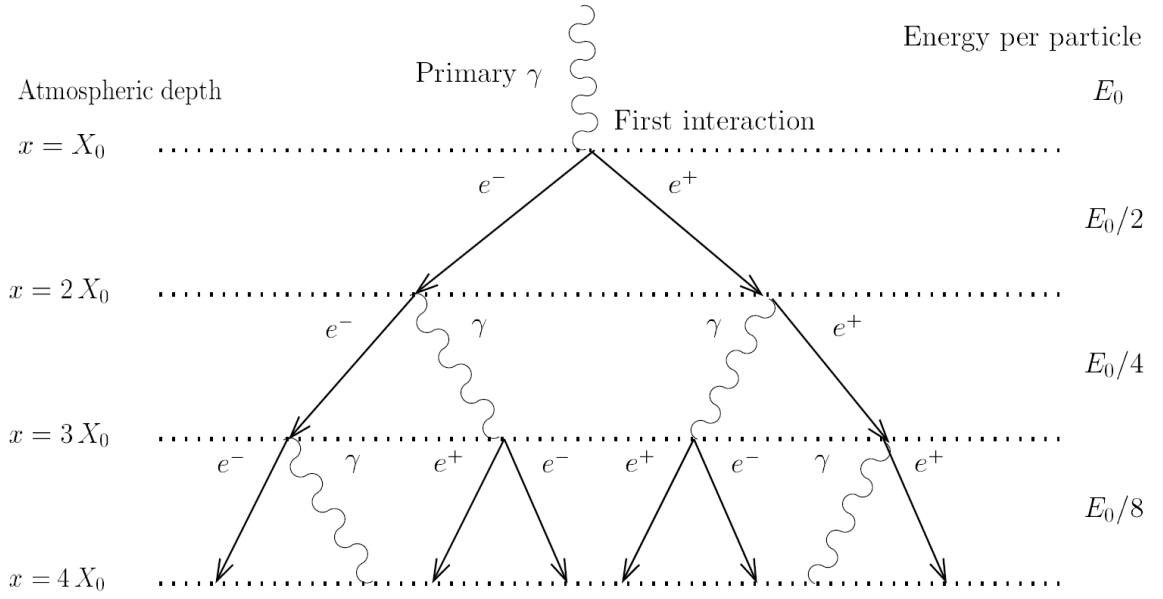


Fig. 1.5 Simple model to explain the electromagnetic shower initiated by a primary gamma-ray entering the atmosphere. From [51].

This very simple model, sketched in Fig. 1.5 and first introduced by Heitler [50], makes some significant assumptions: it does not take into account the possibility of $e^- - e^+$ absorption in the atmosphere, and assumes single photon bremsstrahlung emission at every step of the cascade. Nonetheless, it correctly predicts the proportionality between the maximum number of particles in the shower and the energy of the primary photon (1.7) and the proportionality between the logarithm of E_0 and the maximum extension of the cascade (1.8). The first interaction typically happens after the gamma-ray travels one radiation length in the atmosphere, at an altitude of about 20 km above sea level. The shower reaches its maximum at approximately 10 km a.g.l for a 1 TeV vertically incident primary photon.

1.2.2 Secondary Cherenkov Radiation

The $e^- - e^+$ pairs are ultra-relativistic and their speed is greater than the speed of light in the medium, thus inducing Cherenkov radiation. The light yield per particle track and wavelength interval is given by the Frank-Tamm formula[52]

$$\frac{d^2N}{dx d\lambda} = \frac{2\pi z^2}{\lambda^2} \sin^2(\theta_c), \quad (1.9)$$

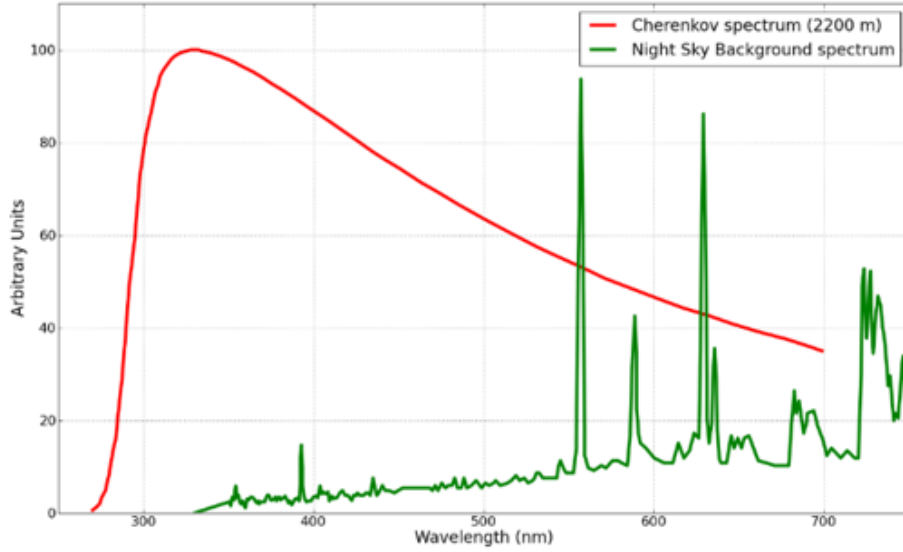


Fig. 1.6 Comparison of the Cherenkov light spectrum at 2200 m height after absorption in atmosphere, in red, and the Night Sky Background spectrum in green as calculated by A. Bouvier et al. with MonteCarlo simulations [53]

where z is the charge of the particle and θ_c the opening angle of the cone of the emitted radiation.

$$\cos(\theta_c) = \frac{1}{n\beta}, \quad (1.10)$$

with n the refractive index of the atmosphere. As shown in Fig. 1.6, this emission is peaked in the blue after absorption in the atmosphere. The sum of the emission from every single particle in the shower results in a cone of Cherenkov radiation which illuminates a region of typically a few hundred metres diameter at ground level. The intensity of Cherenkov light emitted can be measured and is obviously proportional to $N_{\max}$, which in turn is proportional to the energy of primary γE_0 as shown in (1.7). It can be shown by Monte Carlo simulations that the total light yield is roughly 100 photons/m² for a 1 TeV gamma-ray. The Cherenkov light flashes last few nanoseconds, so a very high speed camera is needed to record the events and to discriminate them from the night sky background light as shown in Fig. 1.6.

1.2.3 Hillas Parameters

When viewed by a telescope from below, the air showers generate elongated elliptical images on the camera. Hillas [54] showed that the direction of the gamma-ray can be well reconstructed by the geometry of this image. The parameters to be considered are the center of gravity of the image, the two half axes of the ellipsoid and ϕ , which is the angle of the main axis relative to the x -axis of the camera (see Fig. 1.7). This set of parameters are

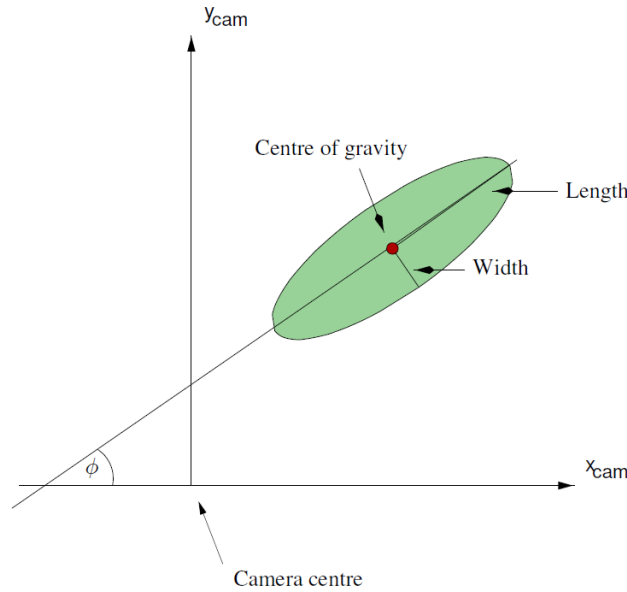


Fig. 1.7 Illustration of Hillas parameters in an elliptical shower image.

also helpful to distinguish γ initiated showers from those initiated by hadronic cosmic-rays. Hadronic showers are about 10,000 times more frequent than gamma-ray showers, and the secondary particles they produce (mainly π and muons) emit similar Cherenkov radiation. These events can be easily discriminated by the image shape they produce on the camera. The lateral aperture of an electromagnetic shower (γ initiated) is mainly due to $e^- - e^+$ multiple scatterings, so the cascade is fairly compact and self-contained. Hadron-initiated events show large aperture due to inelastic hadronic scatterings which introduce large lateral momentum. The difference can be very marked, as shown in Fig. 1.8.

1.3 State-of-the-art of IACT experiments

In the past decade the IACT technique has been very successful. It has lead to many significant discoveries and deepened our understanding of the VHE gamma-ray Universe. At present, the main ground based observatories are the High Energy Stereoscopic System (HESS²), the Very Energetic Radiation Imaging Telescope Array System (VERITAS³) and the Major Atmospheric Gamma Imaging Cherenkov Telescopes (MAGIC⁴).

HESS is an experiment in Namibia, near the Gamsberg mountains. It is composed of four smaller telescopes arranged in a square with sides of 120 m with a central larger telescope. The mirror diameters are respectively ~ 12 m and ~ 28 m. The cameras of the

²<https://www.mpi-hd.mpg.de/hfm/HESS/>

³<http://veritas.sao.arizona.edu/>

⁴<https://magic.mpp.mpg.de/>

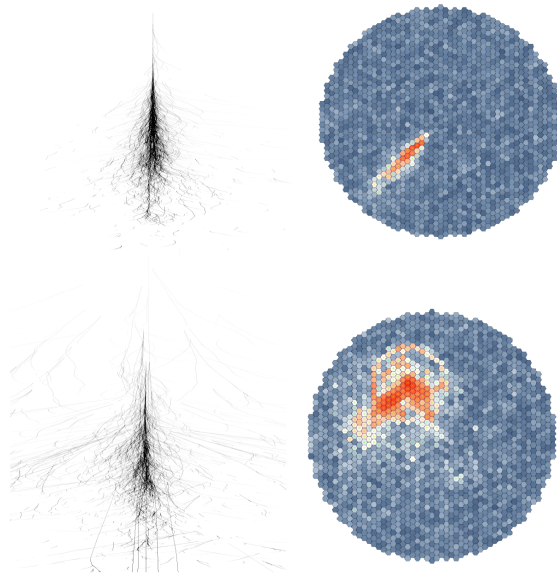


Fig. 1.8 Comparison of two simulated particles showers and the resulting images on camera (for the H.E.S.S. telescope). The one on the top panel is initiated by a gamma-ray (300 GeV) and the one bottom one by a proton (1 TeV).

smaller telescopes have 960 pixels for a total field of view (FoV) of 5° , sampling at 1 GS/s and average readout rate of 300 Hz. The larger telescope is instrumented with a camera able to read out all the 2048 pixels with an average rate of 3600 Hz, again sampling at 1 GS/s and FoV of $\sim 3.2^\circ$.

VERITAS is an array of four 12-metres telescopes located at the Fred Lawrence Whipple Observatory on mount Hopkins in Arizona, USA. Their design is based on the 10 m Whipple telescope [55]. All the VERITAS telescopes have the same type of camera with 499 pixels, a total FoV of 3.5° . Digitization is performed with flash ADCs with sampling speed of 500 MS/s and readout capability of full array at rate up to 1 kHz.

MAGIC consists of two 17-metre telescopes located at the Instituto de Astrofísica de Canarias (IAC), Roque de los Muchachos Observatory in La Palma, Spain. The second telescope, referred to as MAGIC-II, was built during an upgrade campaign, so its camera has improved features. Both cameras have a FoV of 3.5° and a focal plane instrumented with 1039 pixels and can sustain a trigger rate of up to 1 kHz. MAGIC camera original sampling speed was 300 MS/s, but it has been updated with MAGIC-II to 1.64 GS/s.

The photosensors of choice of the cameras of all these observatories are photomultiplier tubes with light guide cones when necessary to adapt to the pixel size on the focal plane. PMT are notoriously extremely sensitive to bright light and can be easily damaged if not operated correctly. Observations during full moon nights are impaired by this restriction. An alternative solution was provided in 2011 with the First G-APD Cherenkov Telescope

(FACT⁵) [56], hosted at the same site as MAGIC. The telescope has a mirror area of 9.5 square metres, and its camera is equipped with 1440 pixels observing a total of 4.5 FoV. The photosensors used are Geiger-mode avalanche photodiodes (G-APDs) that allow observation even during full moon nights and have higher photon detection efficiency (PDE) than PMTs. Unlike the previous experiments FACT does not provide stereoscopic view of the air-showers, because it is not part of an array. Thus, its scientific program is more limited than that explored by the above mentioned experiments, mostly focused on blazar monitoring [57]. FACT represents the proof-of-concept of a Cherenkov telescope based on solid state radiation detectors and opened a new future for next generation IACTs. Its legacy will be carried and further explored by some of the telescope prototypes proposed for CTA [58–62]. See the conclusion of this thesis for the concrete example of a design of a Silicon photomultiplier based camera. Fig. 1.9, 1.10, 1.11 and 1.12 show a picture of the FACT, VERITAS, MAGIC and HESS telescopes, respectively. In Table 1.1 some of the key parameters of all the above mentioned experiments are given.

	HESS	VERITAS	MAGIC	FACT
n° telescopes	4 & 1	4	2	1
Mirror diameter (m)	12 & 32	12	17	3.5
Field of View (°)	5 & 3.2	3.5	3.5	4.5
n° pixels	960 & 2048	499	1039	1440
Sampling speed (GS/s)	1 & 1	0.5	1.64	2
Maximum readout rate (KHz)	0.3 & 3.6	1	1	0.25

Table 1.1 Key parameters of the state of the art observatories for VHE gamma-rays astrophysics.

⁵<http://isdc.unige.ch/fact/>



Fig. 1.9 Picture of FATC in La Palma, Canary Islands. Credit to the FACT collaboration.



Fig. 1.10 Picture of the VERITAS array in Arizona, USA. Credit to the VERITAS collaboration.

1.4 The Cherenkov Telescope Array

All the aforementioned collaborations have significantly contributed towards the technology and data analysis tools in recent years. A new experiment called Cherenkov Telescope Array (CTA) [63] has been proposed, designed and is currently in the prototyping phase. CTA is the next generation ground-based gamma-ray observatory, it will have a larger field of view ($\sim 8^\circ$) and a tenfold improvement in sensitivity and in angular resolution over



Fig. 1.11 Picture of the MAGIC array in La Palma, Canary Islands. Credit to Daniel Lopez, IAC.



Fig. 1.12 Picture of the HESS array in Namibia. Credit to the HESS collaboration.

the previously mentioned state-of-the-art telescope arrays. See Fig. 1.14 and Fig. 1.15 for a comparison. These ambitious design goals promise a lot of foreseen new physics [64].

CTA is an international collaboration involving more than a thousand members from about 200 institutes over 32 countries⁶ and it will operate as an open observatory. Coverage of most of the sky will be provided by two observatories, one for each hemisphere. The site of choice for the northern hemisphere is at the same site where MAGIC is: the Instituto de Astrofísica de Canarias (IAC), Roque de los Muchachos Observatory in La Palma, Spain. The southern array will be hosted on the European Southern Observatory (ESO) Paranal grounds in Atacama desert of Chile (official negotiation started July 2015). Two backup solutions have been identified. The locations of the two CTA observatories are shown in Fig. 1.13. Fig. 1.16 shows the expected differential flux sensitivity of the two arrays for three different exposure times, while Fig. 1.17 illustrates the expected angular resolution.

⁶As of September 2016

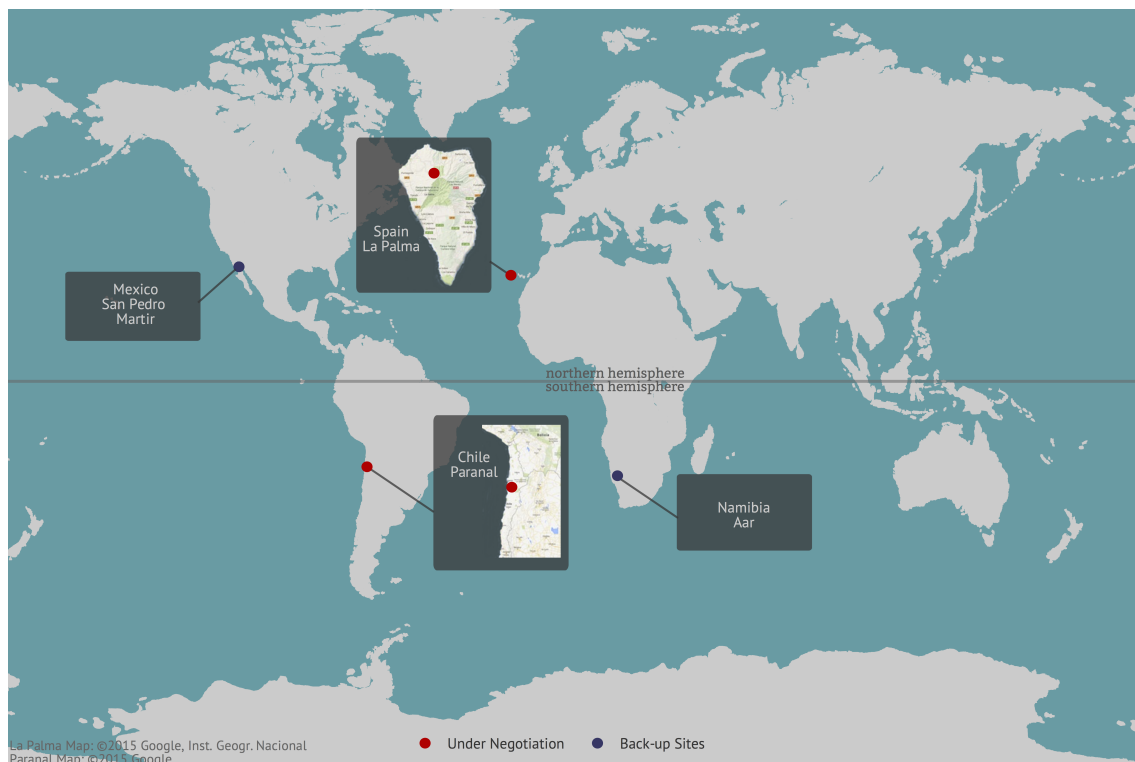


Fig. 1.13 Map of the candidate sites for the two CTA arrays. Credit to the CTA Consortium.

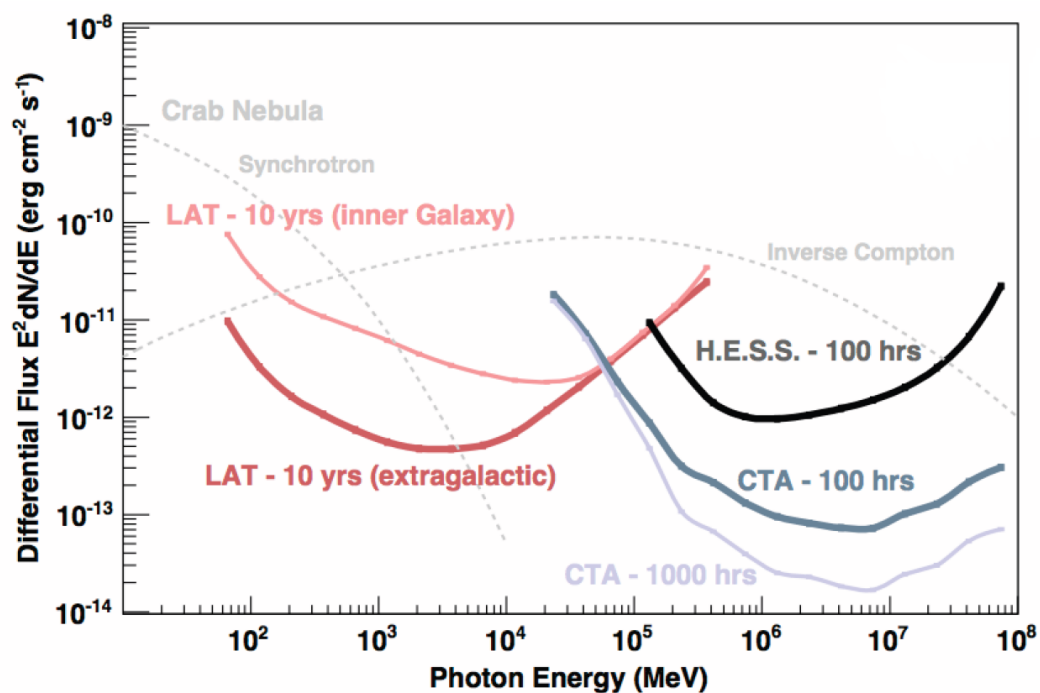


Fig. 1.14 Comparison of the differential flux sensitivity over the gamma-ray spectrum of CTA, Fermi - LAT and H.E.S.S [65].

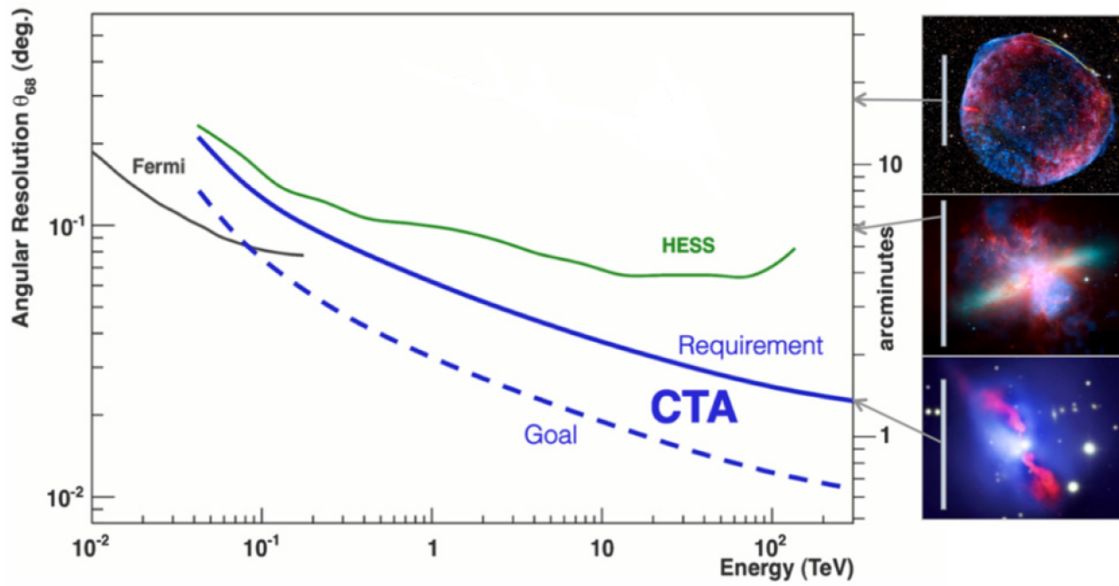


Fig. 1.15 Comparison of the angular resolution of CTA, Fermi - LAT and H.E.S.S.

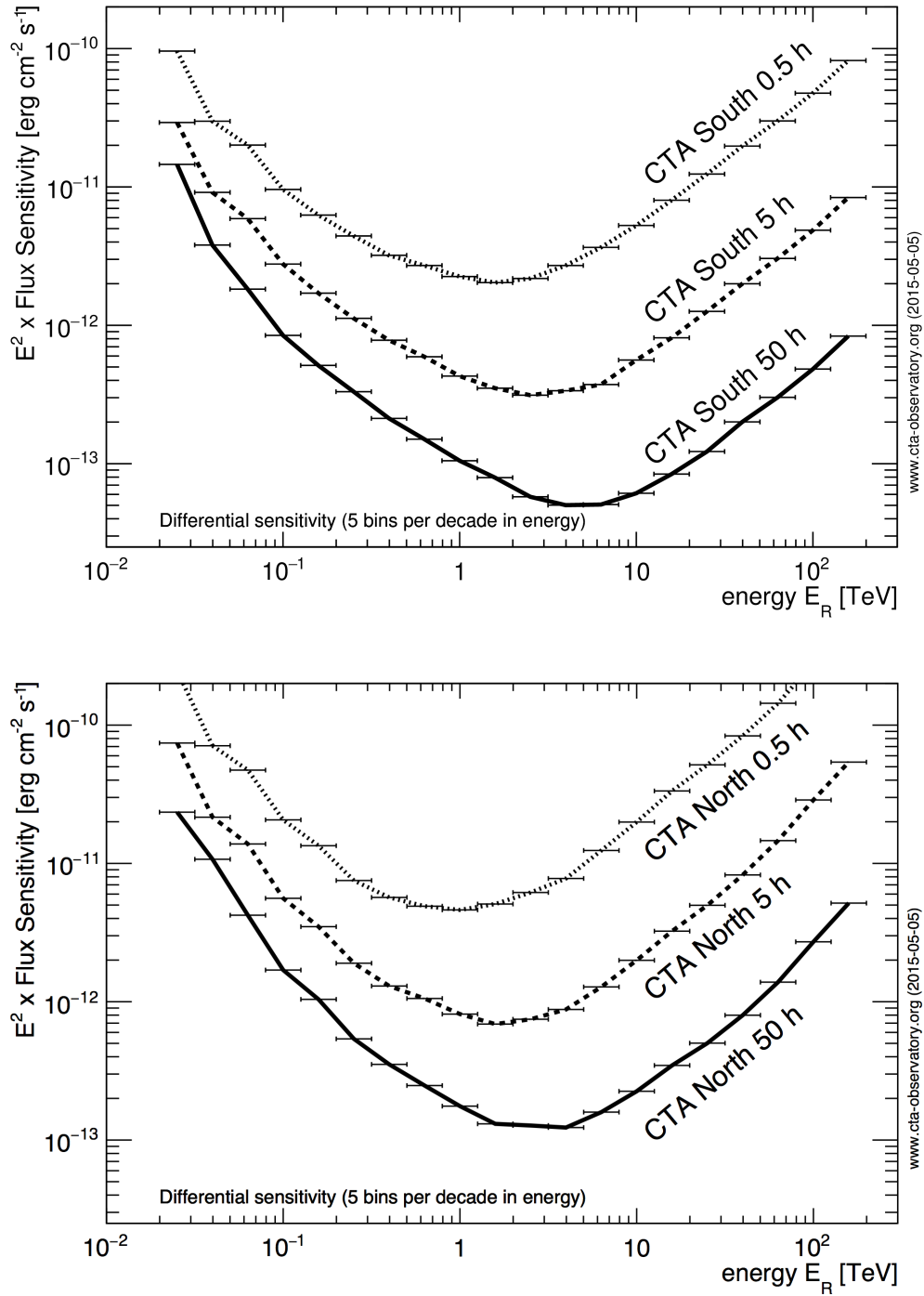


Fig. 1.16 Expected differential sensitivity for CTA-South (top) and CTA-North (bottom) for different exposure times. Credit to the CTA Consortium.

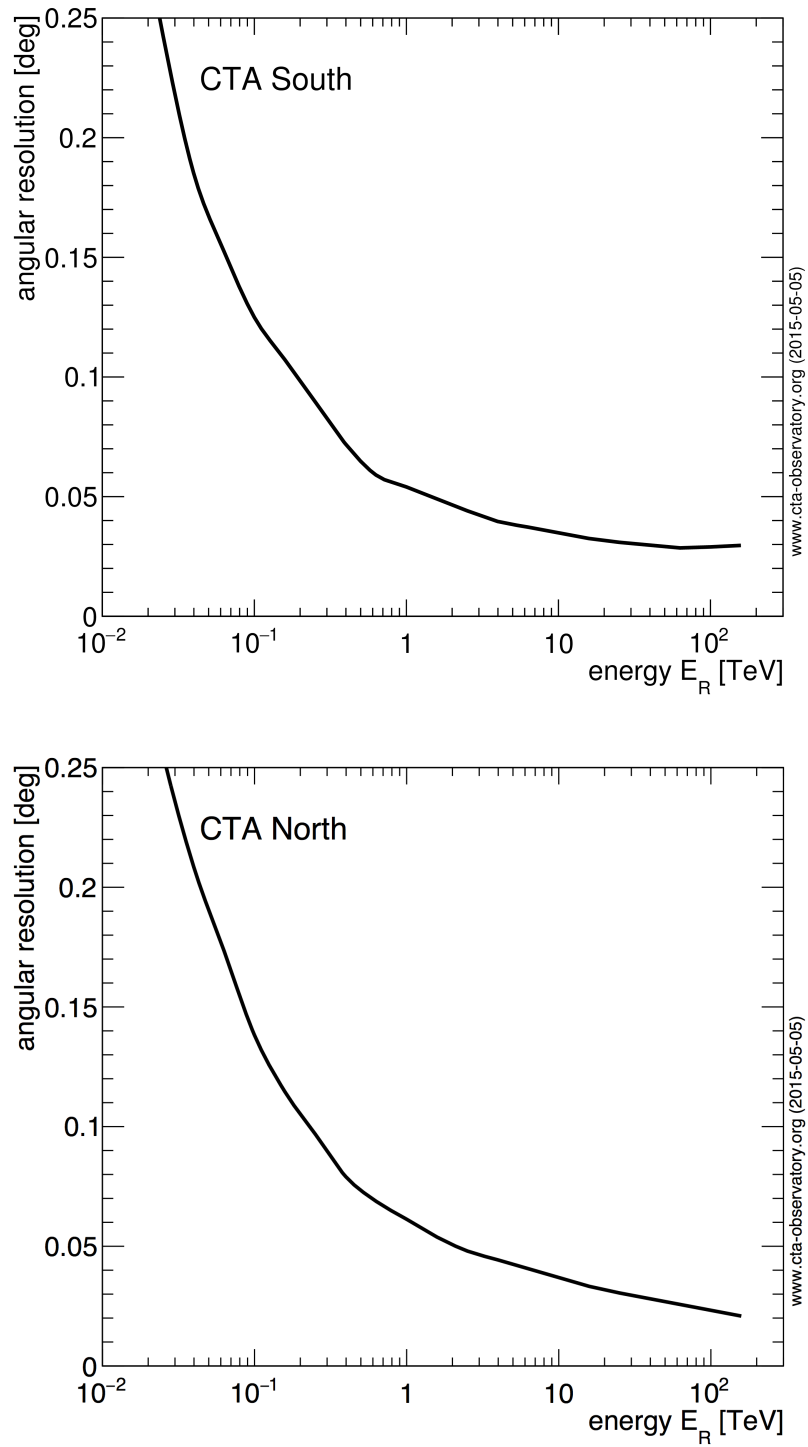


Fig. 1.17 Expected angular resolution for CTA-South (top) and CTA-North (bottom). Credit to the CTA Consortium.

1.4.1 Design

CTA has very ambitious goals in term of sensitivity and angular resolution over a huge span of gamma-ray energies. To meet this requirement, in a cost-efficient way, it will be composed of three different telescope designs of different sizes, each tuned to cover a specific part of the gamma-ray spectrum. An air shower initiated by a gamma-ray of a few tens of GeV produces a modest amount of Cherenkov radiation. Thus, it is necessary to use telescopes with a large collecting area to detect faint pool of light (mirror diameter ~ 28 m). These Large Size Telescopes (LSTs) should be packed in a compact array to be able to reconstruct the same event with stereoscopic view. See Fig. 1.18 for a design concept of an LST. At the high-energy end of the spectrum individual telescopes can be quite small while still being sensitive enough to detect an individual air shower. However the expected flux is so low (~ 0.2 photon/m²/year) that a large effective area is needed to detect a useful number of events. For this reason it is more efficient to have many Small Size Telescopes (SSTs) spaced a few hundred metres away from each other and spread over a huge area (of the order of ~ 4 km²). In the core regime of energies, between 300 GeV and 3 TeV, a trade-off is expressed by an array of Middle Size Telescopes (MSTs). In Fig. 1.19 a photo of the prototype structure of an MST is shown. In Tab. 1.3 I present some of the key parameters of the LST and MST designs. The CTA layout is under discussion of fine tuning to optimize the science return. The reference design is expected to split the hundreds of telescopes between the two hemisphere as in Table 1.2. The southern hemisphere array is optimized mostly, but not exclusively, for Galactic gamma-ray sources and the northern focusing mainly, but not exclusively, on extragalactic science. Because gamma-rays of multi-TeV energies have a short mean free path for interaction with extragalactic background and cosmic microwave background light, this means that only the southern site will host the large array of small size telescopes (SSTs).

Telescope per CTA array			
	LST	MST	SST
CTA-North	4	15	
CTA-South	4	24	72

Table 1.2 Number of telescopes for the baseline layout of CTA-South and CTA-North.

Two different camera designs are proposed for the MST, Digicam [66] and Flash-Cam [67]. Three different SST designs are under prototyping, one called SST-1M with a single mirror, while the other two use dual-mirror optics. In Table 1.4 some key parameters of the two types of SST are given. Two are of the design proposed for the dual mirror telescope, ASTRI and the Gamma Cherenkov Telescope (GCT). The CTA southern site is expected to have an array of around 70 SSTs and not only is their performance important,

but also their unit cost. Due to the size of the structure the cost of the camera is significant. Dual mirror design was first introduced mainly because it can reduce the size (and so the costs) of the detector. In the next section I will focus on a detailed description of GCT.

Key parameters of LST & MST designs		
	LST	MST
γ -ray energy	30 GeV - 300 GeV	200 GeV - 3 TeV
Diameter mirror	23 m	12 m
Dish area	298 m ²	100 m ²
Focal length	28 m	16 m
Mirror facets	1.5 m	1.2 m
Field of view	4.5°	8°
Pixel size	0.1°	0.18°

Table 1.3 Principal features of the Large Size Telescope (LST) and Medium Size Telescope (MST) designs.

Key parameters of SST one & dual mirror designs		
Two different design	Single mirror (SST -1M)	Dual mirror (SST -2M)
γ -ray energy	>3TeV	>3TeV
Diameter primary mirror	8 m	4 m
Diameter secondary mirror	none	2 m
Field of view	8°	8°
Pixel size	0.17°	0.17°
SSTs expected on CTA-South	10	60

Table 1.4 Principal features of the two different designs for the Small Size Telescope (SST)

1.5 The Gamma-ray Cherenkov Telescope

The Gamma-ray Cherenkov Telescope (GCT hereafter) is a design proposed for the SST array. The design has dual-mirror Schwarzschild-Couder optics that de-magnify the air shower image, allowing a reduction of the telescope's focal plane plate scale. This design has never been achieved before, especially for the difficulty of the production of the mirror and their alignment, but it would enable the use in the camera of commercially available, small form-factor photosensor elements tiled together. Furthermore, the dual-mirror optics shows a good off-axis point spread function, hence allowing a large field of view (FoV). The GCT sub-consortium was born from the merging of the Gamma-ray

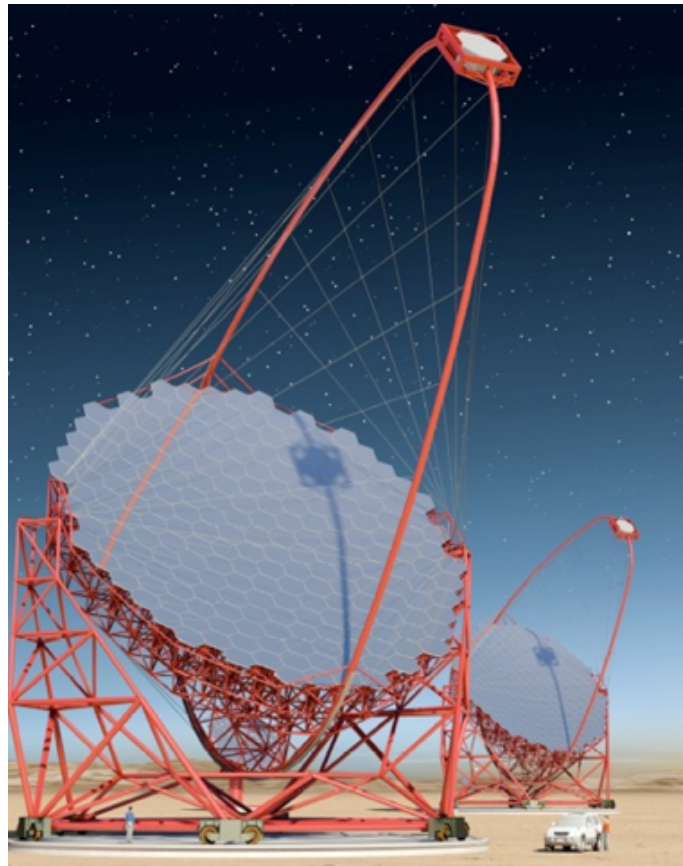


Fig. 1.18 Artist impression of the LST. Credit to the CTA consortium.

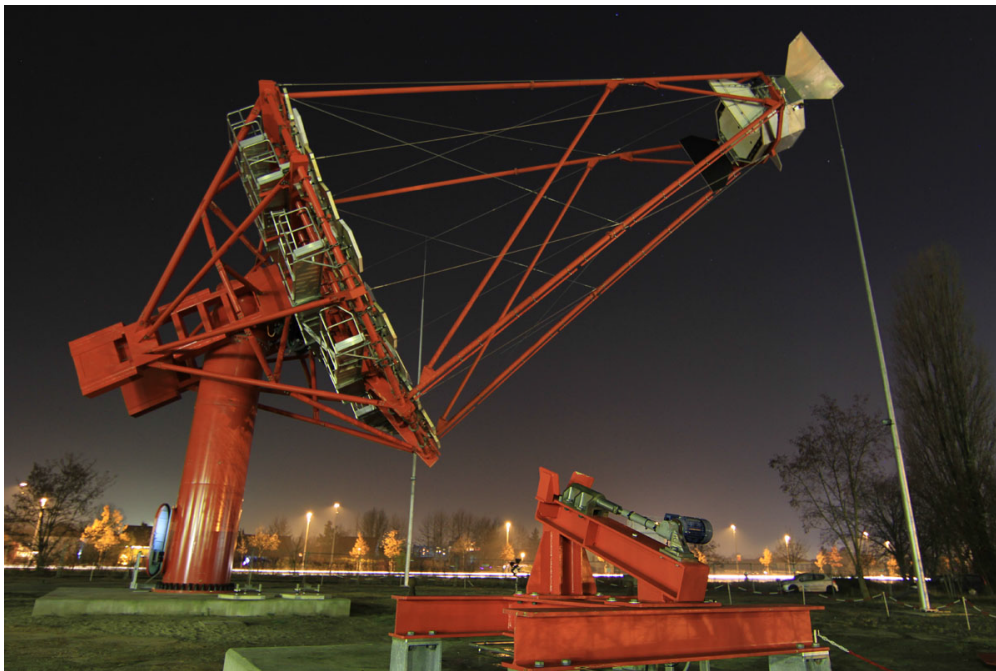


Fig. 1.19 Picture of the MST prototype. Credit to the CTA consortium.



Fig. 1.20 Picture of the SST-1M prototype structure (left; without mirror) and of the ASTRI telescope (right). Credit to the respective collaborations.

Telescope Elements (GATE) and the Compact High Energy Camera (CHEC) projects. GATE concentrates on the feasibility of such a complex telescope structure and in sec. 1.5.1 I give an extended introduction on its features. CHEC instead tries to explore for the first time the possibilities offered by a dual-mirror structure in terms of a high performance, compact form camera. Funding is in place for completion of 2 prototypes and 3 pre-production cameras. The first two prototypes have very similar mechanics and electronics, but very different photosensors. The first, CHEC-M, has Multi Anode PhotoMultipliers (MAPMs) and the second, CHEC-S, will have Silicon PhotoMultipliers (SiPMs). I focused my work on the testing, commissioning, integration and software development of CHEC-M, so in this thesis, if not expressly specified, the term camera and CHEC refers to CHEC-M. In sec. 1.5.2 I introduce the main architecture of CHEC-M, and I provide more details on the sub-components to which my work had contributed. In chapter 7 I briefly describe how the architecture of CHEC-S is evolving thanks to the lessons learned during the prototyping of the MAPM based camera. The GCT collaboration aims to provide 35 cameras as an in-kind contribution towards the construction of CTA. SiPM are very robust, don't require supply of high voltage, nor a vacuum, so they are by all means more suited than MAPM to work for many years in harsh environments like the one in which CTA will be deployed. Furthermore a very attractive feature of this type of photosensor is the possibility to be exposed to bright light without danger of critical failure of the detector, as

in the case of the fragile MAPMs. This could possibly reflect in an extended duty cycle of the array, with observation during full Moon nights, as proved to be feasible by the FACT project [56]. These factors, together with the recently proved technology readiness and steady improvements of the SiPM would probably drive the decision of the GCT sub-consortium to propose a SiPM based, rather than MAPM camera. Commissioning and full assessment of the performance of both of the prototypes is necessary to make an informed decision.

1.5.1 The structure prototype: GATE

The GATE telescope structure is a prototype proposed for the SST array of CTA by the research group of Observatoire de Paris. It is a dual-mirror Schwarzschild-Couder (SC) design based on preliminary studies developed at the University of Durham. The SC optical design has never been successfully implemented before in gamma-ray astronomy, where traditionally a one-mirror Davis-Cotton design is commonly used. The telescope optics use a primary mirror of diameter 4 m, a secondary mirror of diameter 2 m, a focal length of 2.3 m and a focal ratio of 0.57 resulting in a spherical focal plane with a radius of curvature 1.0 m (see Fig. 1.21). The primary mirror (M1) is tessellated and consists of six identical panels whereas the secondary mirror (M2) is monolithic.

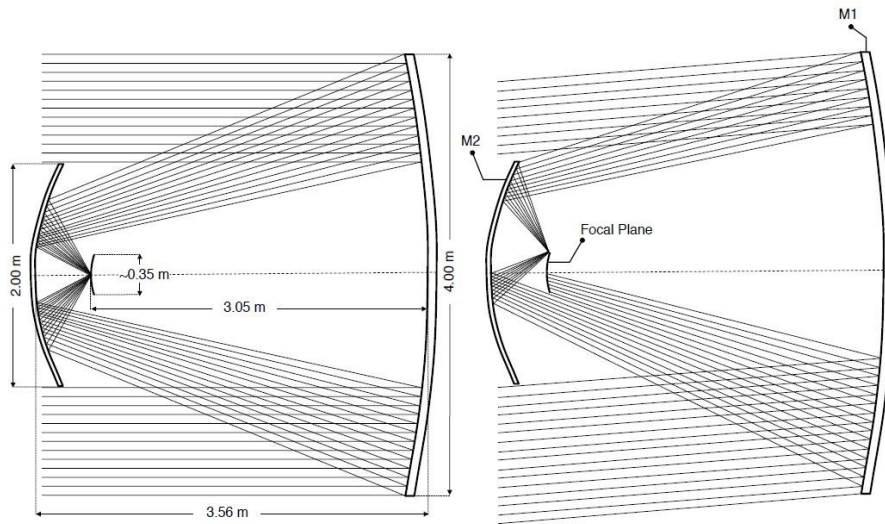


Fig. 1.21 Optics of the GCT . On-axis case (*left*) and at a field angle of 4.5° (*right*).

The M1 of the very first prototype is composed of 6 circular individual mirrors, that provide similar overall optics. This choice for the first proof-of-concept prototype has been made because the manufacture of the M1 petals requires the development of a dedicated special sized slumping/coating chamber, into which investment is justified only by the production of a certain number of structures. The mirrors are constructed using either



Fig. 1.22 Picture of the prototype telescope structure at the Observatoire de Paris in Meudon, France. Four black machined dummies substitute the, at that time, missing mirrors.

polished and coated aluminum or glass (under investigation). Drive motors allow motion in the altitude and azimuth (alt-az) directions and are attached to the optical assembly and counterweight support structure. The M1 is supported with an independent structure from the mast holding the M2, to avoid stresses on the secondary from influencing the shape of the primary. The M1 support structure can rotate about the telescope's axis, so the mirrors can be easily installed from ground level. A locking mechanism ensures the necessary stability of the system, once in place. The weight of the camera is supported by the structure of the secondary and installation and maintenance of the camera are easily performed thanks to a swiveling mount. Almost all the elements of the GATE structure are made of carbon steel. The total weight is ~ 7.8 tons, which puts GATE among the lightest structures of the proposed design for the SST. The red (RAL 3016) colour of the telescope is the best compromise between the reduction of solar radiation heating and the absorption of the background stray light in the observed wavelength. The complete structure of the first prototype shown in Fig. 1.22 is hosted at the Observatoire de Paris in Meudon, France. At the time the picture was taken⁷ only 2 out of 6 of the dishes were already manufactured. Black machined dummies were mounted in their stead. The entire telescope can be enclosed inside a shelter to reduce exposure to harsh environmental conditions of the desert. Fig. 1.23 shows the shelter partially open.

⁷December 2015



Fig. 1.23 Prototype structure at the Observatoire de Paris in Meudon, France. Shelter partially open.

1.5.2 The camera prototype: CHEC-M

A CAD image of CHEC-M is shown in Figure 1.24 showing the principal external components, whilst Figure 1.25 shows the internal electronics architecture for the camera. The camera is designed to record flashes of Cherenkov light lasting from a few ns to a few tens of ns, with typical image width and length of $\sim 0.2^\circ \times 1.0^\circ$. The small focal length of the telescope implies that an approximately 0.2° angular pixel size is achievable with pixels of physical dimensions of 6 to 7 mm, while the dual-mirror optics ensure that the point spread function (PSF) of the telescope is below 6 mm up to field angles of 4.5° , as shown in Fig. 1.26. A field of view (FoV) of 8° (again required by CTA for the SSTs) can therefore be covered with a camera of diameter about 0.4 m, composed of 2048 pixels (see Fig. 1.27).

CHEC-M is designed to provide full waveform information in every event for all of its 2048 pixels. It is based on 32 camera modules each containing a 64-channel Hamamatsu H10966 MAPM attached via a shaping preamplifier board to a front-end electronics (FEE) module called TARGET providing digitization and level-zero triggering. Chapter 2 is dedicated to a full description of the modules, with details on my contribution to their testing, commissioning and integration in the full system. The modules can slide inside the camera on rails in an aluminum internal rack and pulled into a backplane PCB by means of a screw at the end of the FEE modules. See Fig. 1.28. The front of the modules are connected to the output of a preamplifier with individually shielded ribbon cables to match the different physical geometries of the internal mechanical stand-off and the curved focal plane. Holes in a plane plate allow connections between the MAPM and the front of the preamplifier. The focal plane plate for the CHEC-M prototype was machined in the

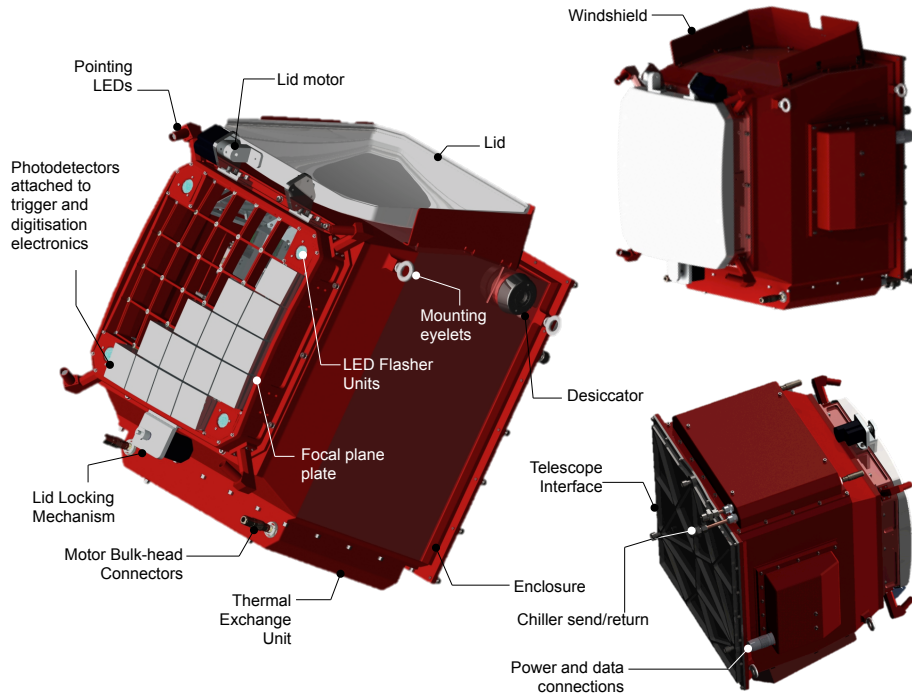


Fig. 1.24 A detailed overview of the GCT camera. The CAD model shown is for the prototype camera equipped with MAPMs (CHEC-M).

workshops of the the University of Oxford with the precision required to align the position of the MAPM with an accuracy of better than 0.35 mm.

The TARGET modules are interfaced to the back end electronics via a 40 pin connector to the backplane that routes the data to two Data Acquisition (DACQ) boards. Each of which are a custom built White Rabbit [69] switches and serialize to an external PC the bulk data of 16 of the FEEs coming via a Samtec ribbon cable, capable of a transfer rate of 16×1 Gbps. The DACQ boards interfaces all communication to the camera: bulk data, control and monitoring signal from all the components. This is implemented via four optical fibres capable of 1 Gbps each, two for each DACQ. The backplane also has the important role of trigger decision making. In chapter 3 I provide detailed description of its functionalities and my contribution to the camera prototype development with my work on the backplane commissioning process. Four LED flasher units are at the corners of the plane plate. They house ten UV-peaked LEDs each and they illuminate the camera focal plane by reflection onto the secondary mirror of the GCT telescope. Their range of illumination is from 0.1 to 1000 photoelectrons and they serve to calibrate the camera [70]. The system is designed to be fully enclosed to avoid intrusion of dust, dirt, water or any other external intrusion. The only part of the camera being exposed to the outside world is the focal plane. The tiny gaps between MAPM modules are sealed and a lid system

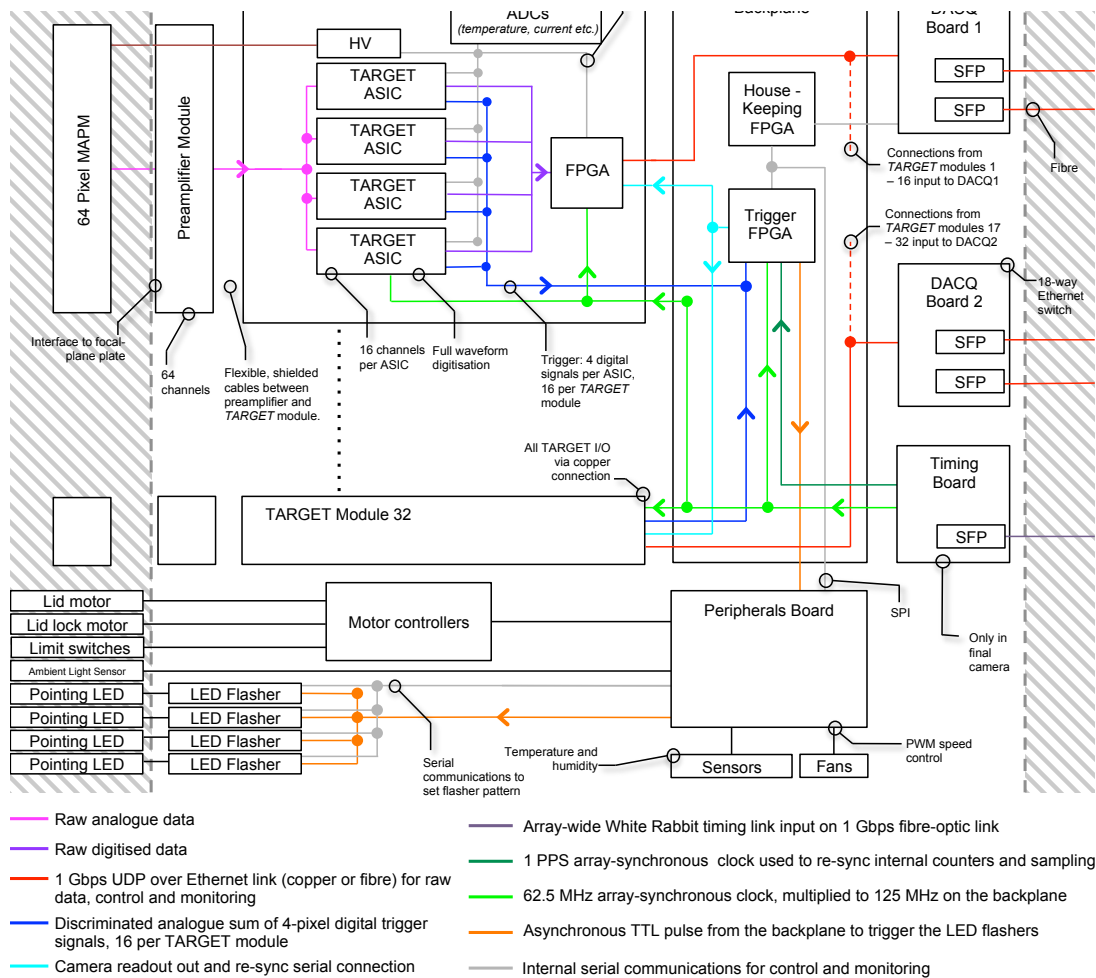


Fig. 1.25 A schematic showing the logical elements of the GCT camera, the communication between those elements, the raw data flow through the camera, the trigger architecture and the clock distribution scheme. Power distribution is excluded for simplicity

provides protection from the elements outside of observation time. The lid can be opened and closed by two motors controlled by a Peripherals Board (PB) that communicates to the external world through the backplane and then finally the DACQ. The PB is also in charge of control and monitoring of the LED flashers, a set of internal sensors (temperature, humidity, etc.) and four (plus 4 spare) fans that circulate air inside the camera with the aid of a set of mechanical baffles. The ~ 450 W of heat generated by the electronics are extracted from a chilled plate on the side of the camera. A commercially available chiller circulates cold water through a heat sink. The camera is powered by a single 12 V DC power supplier, mounted at the rear of the secondary mirror. A set of environmental tests were performed to assess the suitability of the design for exposure to the elements. This included testing impact, water ingress, temperature cycling (from -25°C to $+40^{\circ}\text{C}$), aging under UV exposure and wind tunnel. As for the CTA requirements, the camera lid was found to operate in wind speeds up to a maximum of 50 km/h, but a small amount of water

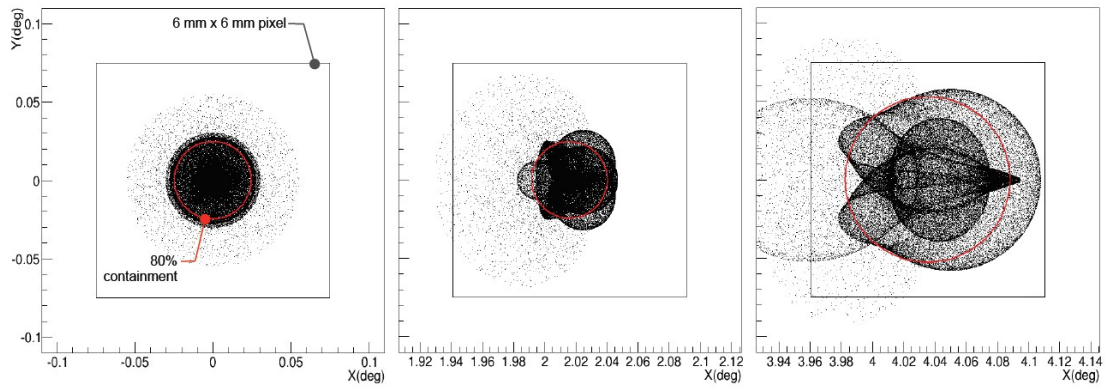


Fig. 1.26 The Point Spread Function (PSF) as simulated using sim-telarray [68]. From left to right respectively, for field angles of 0° , 2° and 4° . The size of the squared pixel of $6\text{ mm} \times 6\text{ mm}$ is drawn. The red circle represent the radius containing 80% of the total energy.

ingress around the lid seal led to a design revision of the lid seal for the CHEC-S prototype and further camera (see chapter 7).

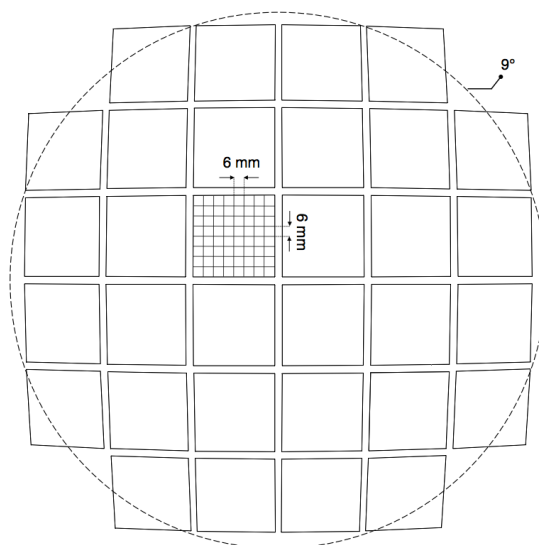


Fig. 1.27 View of the focal plane of CHEC-M. 32 modules with 64-channels each, for a total of 2048 pixels. The field of view covered is roughly 9°.

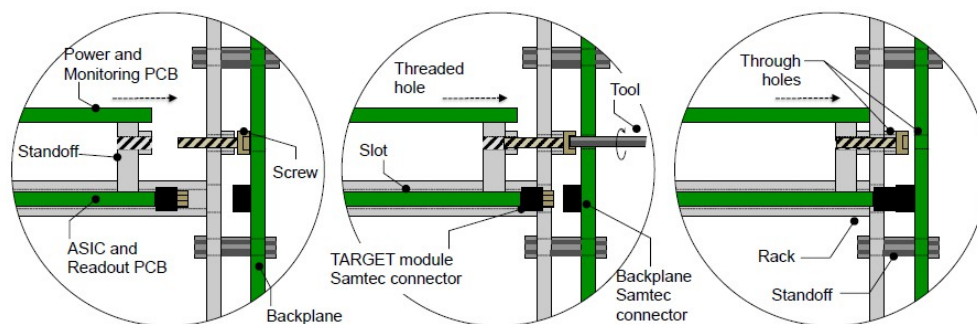


Fig. 1.28 Connection procedure to secure the TARGET module in place against the backplane. Each module is slide inside the camera on rail machined in the aluminum rack. A crew pulled back the module and ensure stable connection between the module and the backplane.

Chapter 2

Front end electronics: TARGET

In this chapter I provide details on the heart of the front end electronics, the TARGET module. I describe my work in relation to the early commissioning phase of the module and optimization of some of its operational parameters. Over the course of the years many versions were developed of these electronics, always improving from the lesson learned from the previous generation. CHEC-M adopted the TARGET version 5 and, if not otherwise specified, I implicitly refer to it. As reported in chapter 7, the other two versions are under development and one of them will likely be used in CHEC-S and in following camera prototypes. In the second half of the chapter I introduce my contribution towards the phase of integration process with the DACQ boards. These two components together comprise the minimal building block of the data chain in the camera. They were the first elements to be tested together.

2.1 TARGET module

Each of the 32 TARGET modules in the camera is composed of six PCBs. See Fig. 2.1 and Fig. 2.2. Two long boards are mounted parallel to each other at a distance of few cm. Four other smaller PCBs at the front of the module are interposed perpendicularly between the other two boards. Each of these four front-most PCBs interfaces with a shaping preamplifier via ribbon cables and provides 16 channels input for the TARGET application-specific integrated circuit (ASIC) it hosts. See sec. 2.2 for more details on the feature of the ASIC.

One of the two long PCB has an on-board transformer and serves the purpose of high voltage generation to be distributed to the photosensors. The supplied HV ranges from 750 V to 1100 V, which corresponds to a selectable gain of the MAPM from $\sim 4 \times 10^4$ to $\sim 6 \times 10^5$, with nominal chosen operation at 8×10^4 . The supplied HV value can be controlled with an FPGA on the second long PCB. This Xilinx Spartan-6 can also control a series of sensors on the board (temperature, current drawn, etc.) and implements the

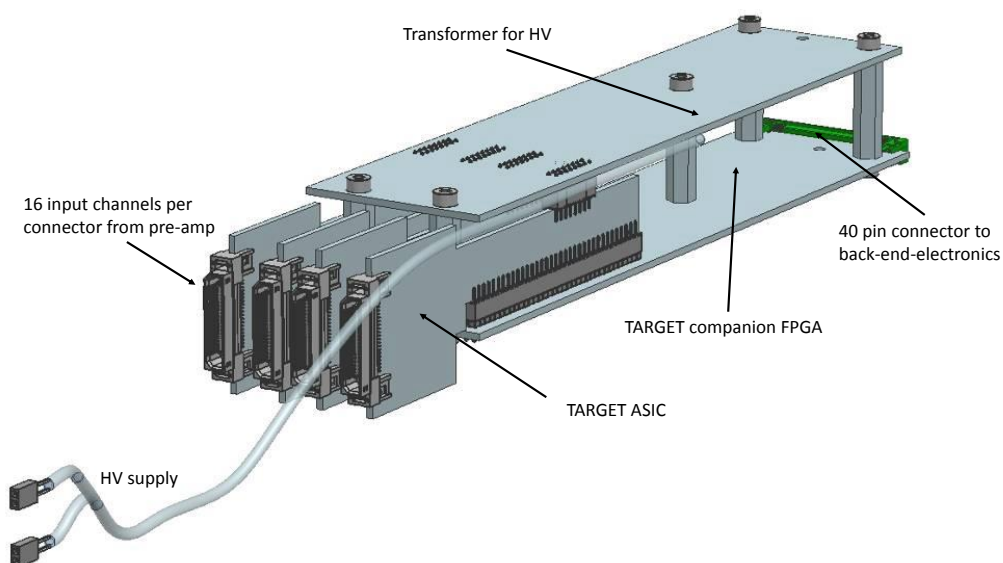


Fig. 2.1 3D rendering model of the TARGET module. *From the TARGET Interface Control Document (TARGET ICD hereinafter).*

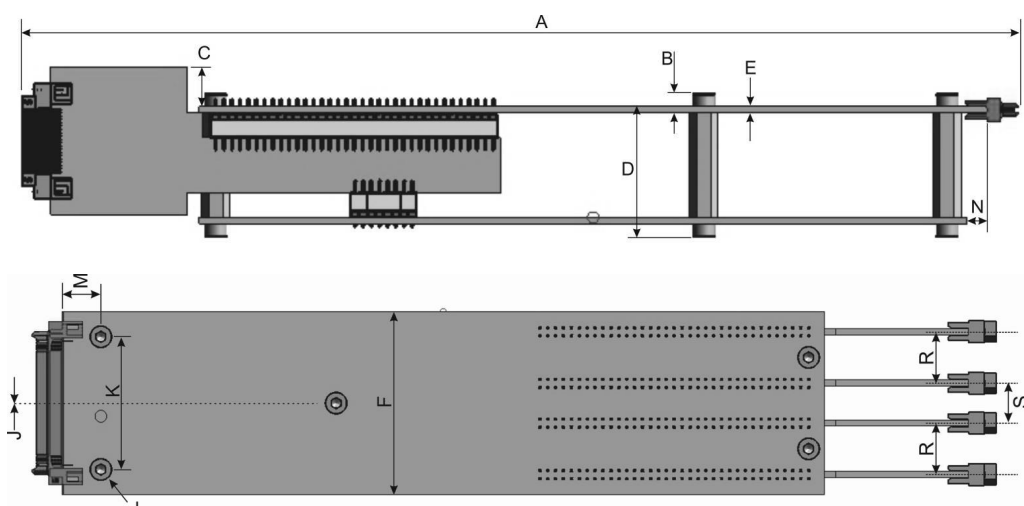


Fig. 2.2 Dimension of the TARGET module. A:244 mm, B:5 mm, C:10 mm, D:31.7 mm, E:1.55 mm, F:46 mm, J:0 mm, K:33.4 mm, L:2.92 mm, M:9.4 mm, N:5 mm, R:13 mm, S:10 mm. *From the TARGET ICD.*

communication based on UDP protocol to the external world via high-speed serial link routed through the Backplane to either one of the DACQ boards. When the Backplane decides to trigger the read out of the camera, it sends to the FPGA on the TARGET module a serial message called TACK. See sec. 3.1 for more details on the trigger logic. At this time the FPGA sends a message to the ASICs to digitize and readout a part of their analog buffer. The segment length to be read is settable in blocks of 32 ns, in normal operation the value is set to 96 ns. A TACK always contains a 64 bit number expressing the time in nanoseconds elapsed from a counter synchronized between TARGET and the Backplane. Based on the difference between this relative timestamp and a local counter (increments of 8 ns) the FPGA ask the ASICs to start digitization from the position in the buffer containing the data at the time which the trigger arrived. A settable look-back time adjusts for deterministic delay due to signal processing. The data readout from the 64 channels (16×4 ASICs) associated to a module are serialized and sent to the back end electronics. The module requires a power supply input of +12 V. Immediately after powering up, the drawn current is ~ 300 mA, after initialization of the ASICs and during operation the current drawn is approximately 600 mA. Fig. 2.3 shows a picture of the TARGET module assembled with preamplifier and MAPM.

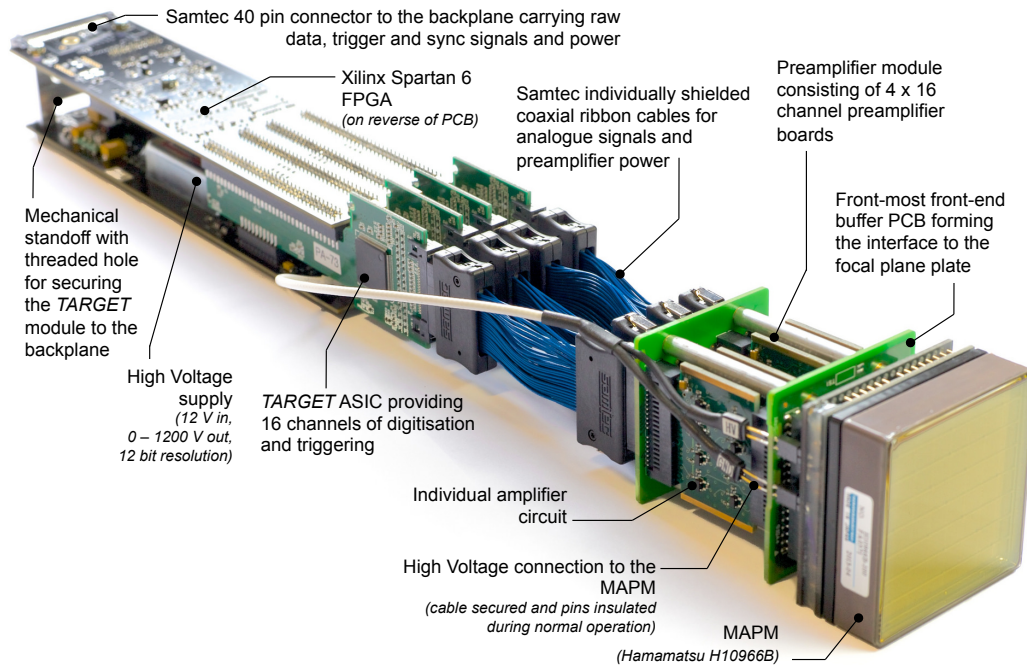


Fig. 2.3 Picture of a front end electronics modules, comprising a MAPM block, a shaping preamplifier connected via ribbon cables to a TARGET module. *Photo credit to Prof. Akira Okumura.*

2.2 TARGET ASIC

TARGET is an ASIC initially developed at SLAC to find a good performance solution to reduce the cost of multi-channel digitizing electronics in preparation for the next generation IACT observatories. It serves two purposes, data digitization and level-zero trigger signal generation. It accepts 16 input channels, in each of which the signal is split into two signal processing lines.

Trigger line The 16 inputs are divided into four groups, each containing 4 neighbors pixels forming a so called super-pixel. The analog sum of the signals from the four channels forming a super-pixel are summed in an inverting summing amplifier and fed to a comparator. When the signal level is greater than the applied threshold a pulse is generated in a one-shot. The threshold of the comparator and the width of the pulse are settable, along with a set of other parameters regulating this level-zero trigger chain. In sec. 2.3.2 I describe my work in the optimization of some of these parameters. Each ASIC account for four level-zero trigger signals, for a total of 16 per module fed directly to the Backplane. There the decision to trigger the readout of all the camera is taken based on these 512 signals (16×32 modules).

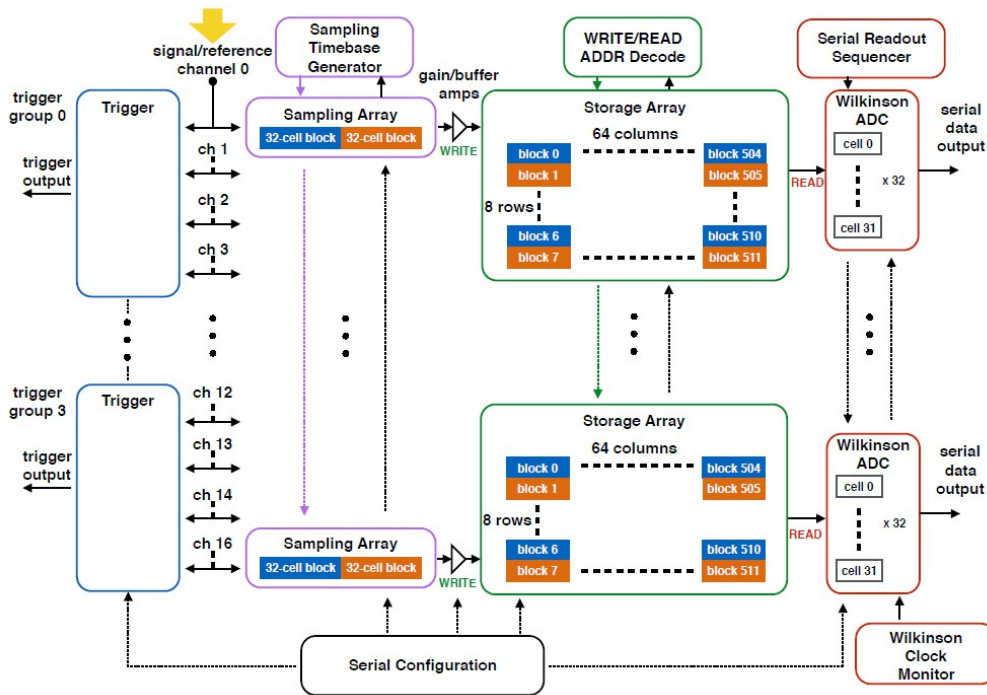


Fig. 2.4 Functional block diagram of the TARGET ASIC. From [71].

Data line The continuous sampling of the input at 1 GSa/s is provided by a two-stage ping-pong architecture as shown in Fig. 2.4. The first low capacity stage is composed

of two Switched Capacitor Array (SCA) with 32 cells each. A series of analog switches connects the input alternatively to either one of the blocks at regular intervals as provided by a timebase generator. This clocking signal is provided by the companion FPGA on the TARGET module. While an SCA is sampling, the contents of the other is transferred to a deep buffer of 512 similar SCAs for a total of 16,384 cells. With a sampling speed of 1 GSa/s this means a buffer of roughly $16\ \mu\text{s}$. When the companion FPGA issues the readout command any number of consecutive 32-sample blocks can be digitized with a 12-bit Wilkinson ADC and sent for readout. Normally the signal from an air-shower is well contained within 100 ns, so usually waveforms of 3 blocks (96 ns) are read.

2.3 Commissioning

Before assembling the whole camera, it is of vital importance to test each component separately. In this section I focus on the test bench I used for a single TARGET module. Please refer to [71] for an exhaustive compendium of the performance tests of the TARGET5 ASIC addressed by the TARGET developer group. For the tests I performed, the TARGET module was slightly modified to operate in stand-alone mode. Data lines don't run through a copper connection to the Backplane, but rather to a SFP copper transceiver connected to the PC via a SFP to ethernet media converter. In the camera the TARGET modules will start readout when they receive a TACK serial message from the Backplane. This special version of the TARGET module can accept external trigger pulses of few Volts through a Bayonet Neill–Concelman (BNC) cable soldered to a pin in the PCB. Please refer to Fig. 2.5 for a schematic view of the lab set up.

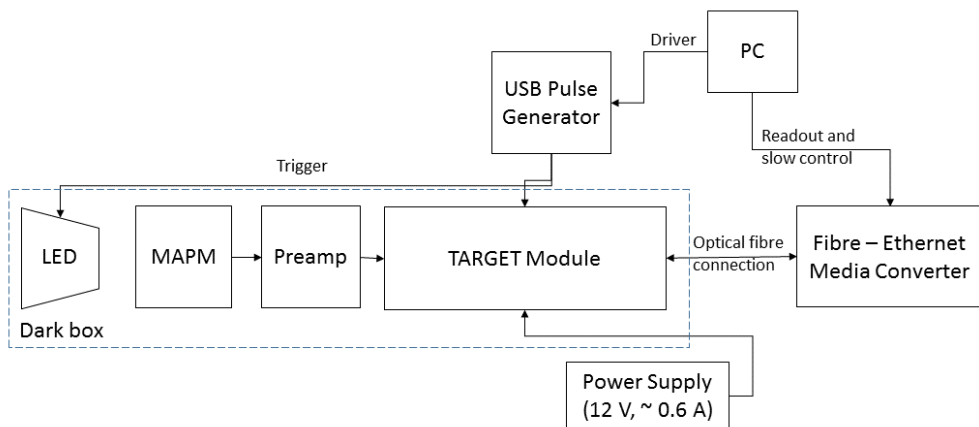


Fig. 2.5 Schematic view of test bench set up.

Pulses of Cherenkov light from a gamma-ray initiated shower typically last only few nanoseconds with a spectrum peaked in the blue at typical observatory altitudes (after atmospheric UV absorption). In the lab, I used a LED capable of producing a similar flash

of light on the rising edge of an external trigger signal. This is provided by an inexpensive portable USB waveform generator operated with a user friendly interface on a laptop. The same signal is fed to the TARGET module external trigger input to provide readout synchronization. To correct for delays in the electronics the adjustable look-back time is set (the optimal value was found to be around 400 nanoseconds) to find the position of the light pulse inside the $16\mu\text{s}$ buffer previously mentioned in section 2.1. MAPMs are capable of detecting a single photo-electron and thus are extremely sensitive and easily damaged by bright light, so the whole set up (obviously excluding PC and power supply) need to be in a dark box to shield it from environmental light present in the lab. A set of filter wheels can reduce the light intensity to test performance of the device at low illumination levels. A typical uncalibrated waveform acquired with this lab test bench and an average illumination level of few p.e. is shown in Fig. 2.6.

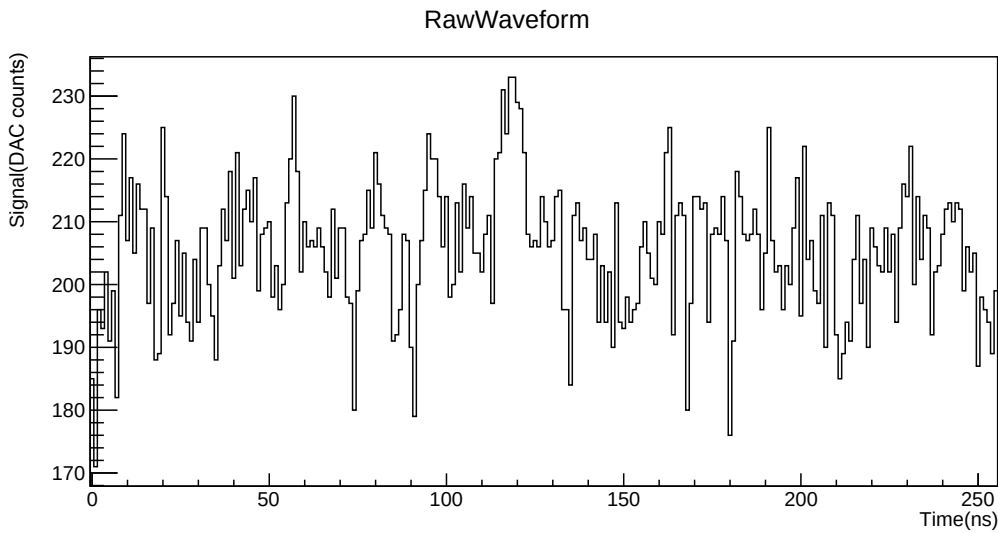


Fig. 2.6 Raw waveform data as acquired from a TARGET stand-alone module on the test bench. Illumination level of few p.e.

2.3.1 Calibration

At this very low illumination is very difficult, if not impossible, to distinguish the signal from the noise. The TARGET sampling ASIC has roughly 16 thousands capacitors and each sample in the waveform is stored in one of them. The response to the pedestal varies significantly from each of them. The information concerning which capacitor each sample was associated with is stored in the raw waveform data packet transmitted from the on-module FPGA, so a calibration procedure can take place. The pedestal value is sampled with an external random trigger in the absence of any light signal in the box with enough events to ensure each capacitor is hit at least 10 times. This pedestal per capacitor data is used to calibrate the raw waveform. To plot waveforms expressed in

Volts, one has to find the DC transfer function of the digitizer ASIC. This is measured by varying the pedestal voltage applied to shift the baseline. The level of the baseline in the ADC compared to applied bias in Volts provides the required conversion factor. The TARGET ASIC performance can be optimized by varying many parameters. For the transfer function linearity and dynamic range one of the most important is the ISEL setting, which regulates the speed of the ramp capacitor charging current, i.e. the slew rate of the Wilkinson ramp. Varying this parameter it is possible to increase the time required for digitization, simultaneously improving the voltage resolution. In Fig. 2.7 the measured transfer function of one ASIC channel for two different values of ISEL is shown. In principle this could be very dependent on the cell hit by the sample, but this is experimentally found to not be the case. A single transfer function per channel is sufficient to calibrate the front end electronics.

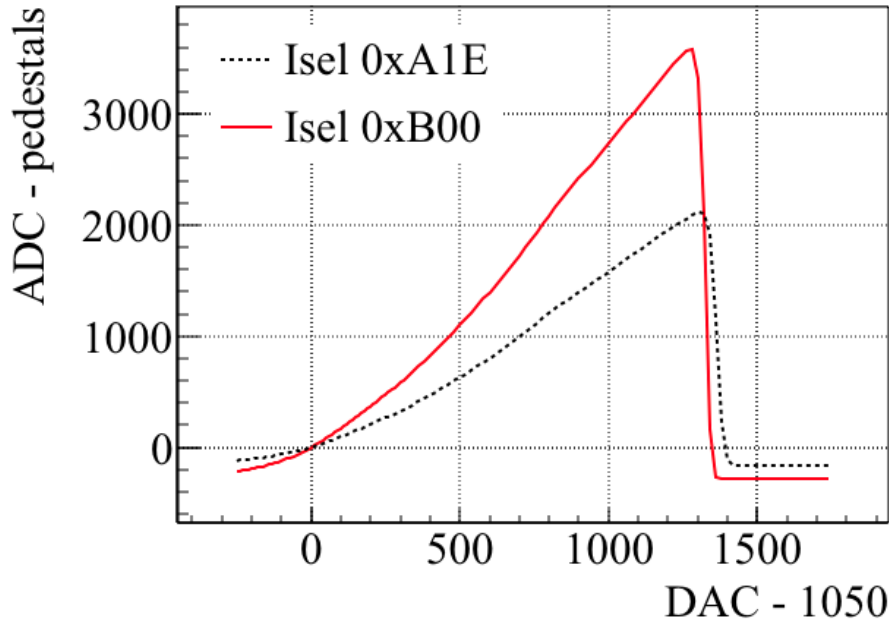


Fig. 2.7 Transfer function for one of the channel of a TARGET ASIC for value of ISEL.

After pedestal subtraction and calibration in Volts the waveform presented in Fig. 2.6 is reduced to Fig. 2.8. Clearly the light pulse at low illumination levels is now visible and the RMS noise is reduced down to roughly 1 mV. Thus allowing single p.e. measurement, for which the expected signal, taking into account the gain provided by the preamplifier, is about 4 mV.

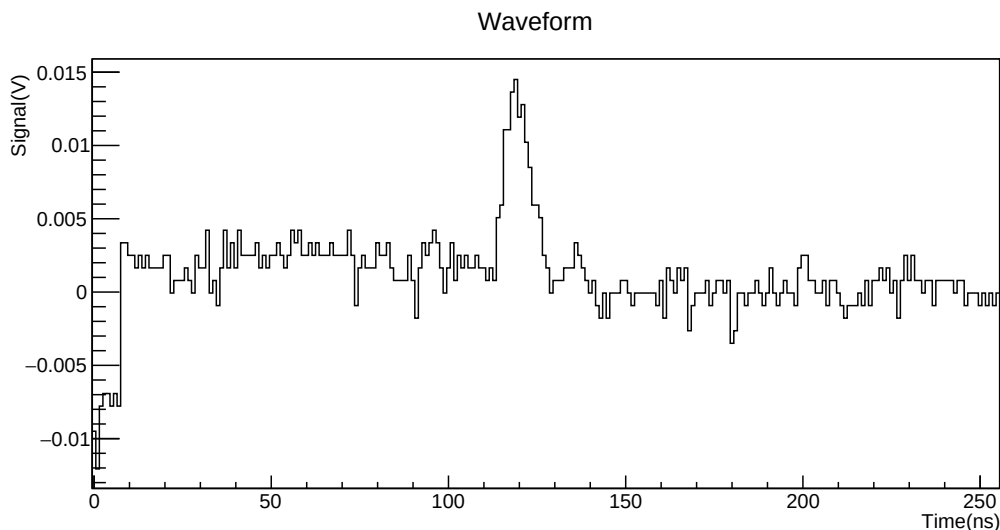


Fig. 2.8 Same waveform of 2.6 after pedestal subtraction and signal calibration to Volts.

2.3.2 Triggering chain

In this section I describe the procedure I followed to tune two of the most important parameters of the level-zero trigger signal generated from the TARGET ASIC: PMTRef4 and Wbias. Although the internal trigger functionalities of the TARGET module are not relevant until inclusion of the Backplane in the system, they should be tested separately in advance. In Fig. 2.9 I show the settable parameters relevant to discriminate the super-pixel signal. With Vofs1 and Vofs2, it is possible to adjust very coarsely the gain of an individual channel, but the main actors in the chain are Thresh and PMTref4. The former sets the reference voltage for the comparator and the latter for the analog sum of the signal from the four adjacent channels forming a super-pixel. Both are controlled by a 12-bit DAC and can be adjusted separately, but they are interlaced. The goal of tuning such values is to avoid issuing false positive triggers due to noise, but only on a signal level higher than the one corresponding few p.e. illumination. Detailed MonteCarlo investigations are necessary to identify the best working point in relation to the both the performance of the camera and the physics involved in the process of the air-shower development.

The procedure I followed in the lab was to fix Thresh to about a quarter of its maximum value and to scan the values of PMTRef4, until the noise level would cause triggers. Later PMTRef4 can be fixed and only Thresh has to be changed to finely adjust the reference level of the comparator. The spread among different channels is minimal. To reduce the amount of generated configuration data, only one curve for the most noisy channel per module is taken into account. The setting Thresh is the best parameter for the fine adjustment at the super-pixel level. The exact same measurement can be repeated on a super-pixel channel basis, especially if future TARGET ASIC versions show a larger scatter in the value to be set. I fitted the data with a bilinear function. In Fig. 2.10 I report

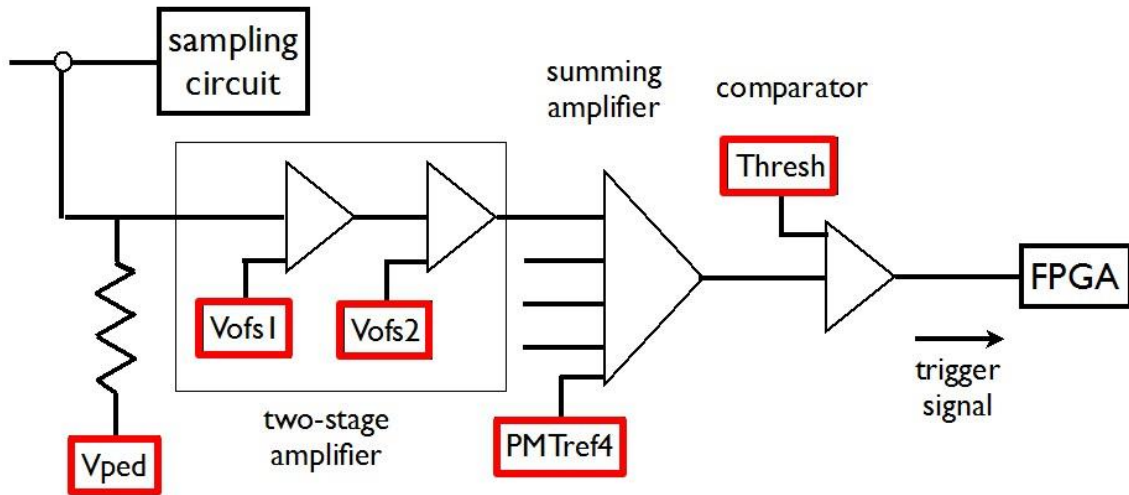


Fig. 2.9 Schematics view of the electronics relevant for triggering features of the TARGET module. Highlighted tunable parameters.

the results of my measurement in relation to the pedestal voltage applied (V_{ped}) for each module in the camera. These curves are used during the configuration of the camera to set the default PMT_{ref4} value in relation to the chosen V_{ped} . In Fig. 2.11, I show an example of the fit for one of the modules.

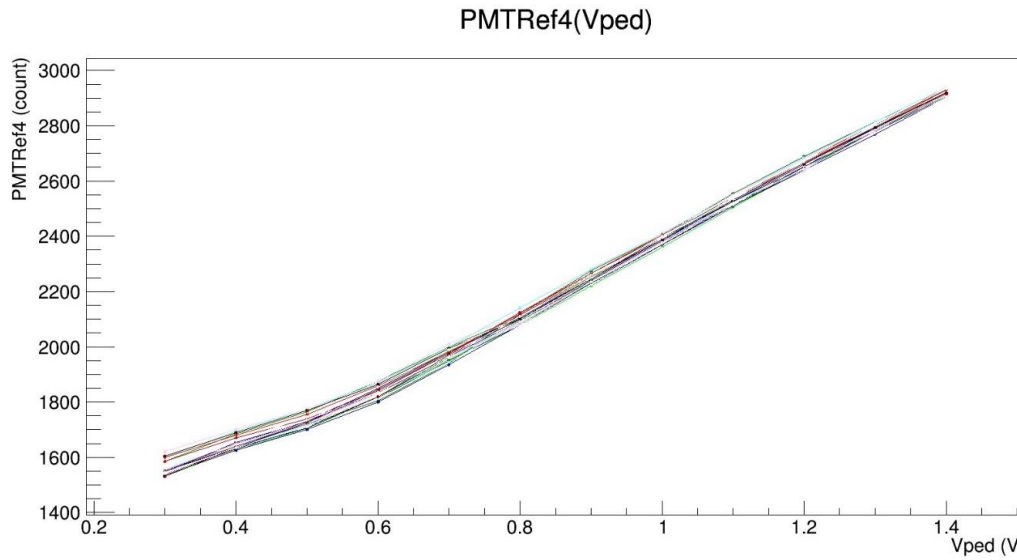


Fig. 2.10 Minimum value of PMT_{ref4} that causes triggers on the noise. Different lines show each module in camera.

Another important setting of the TARGET ASIC for the trigger chain is the width of the trigger output signal. This defines the coincidence window for the Backplane to find a signal over threshold in two adjacent super-pixels. A dedicated MonteCarlo investigation is necessary to identify the optimal value for this parameter to achieve the best trigger

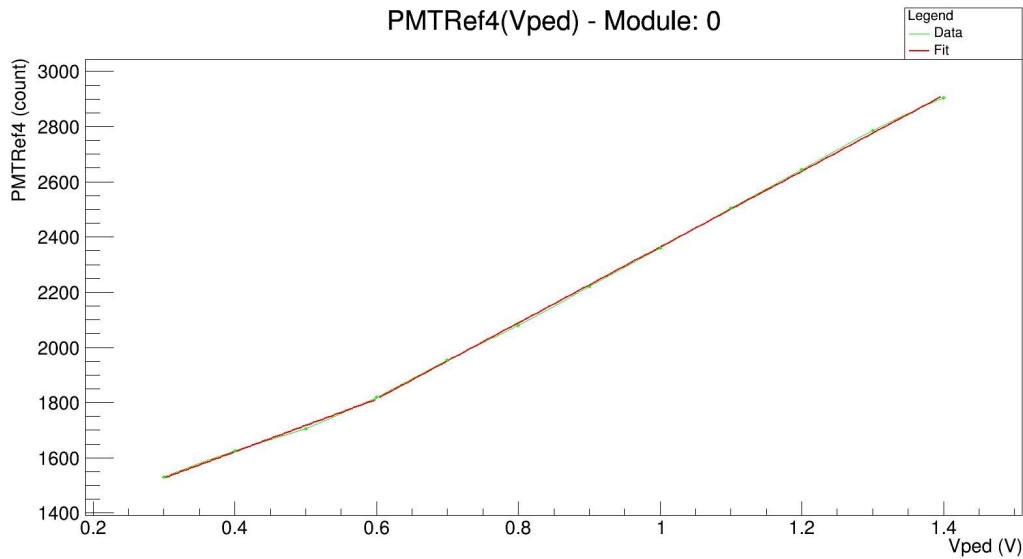


Fig. 2.11 Bilinear fit of PMTRef4 in function of VPed for one of the module.

performance. Here I focus on the limitations of the hardware in terms of this width and the calibration of the 12-bit DAC that controls it. I stimulated with an electrical pulse the input of two adjacent channels belonging to the same super-pixel to ensure triggers. With an oscilloscope probe I measured the width of the 2 V trigger output signal. The measure was repeated for other channels, leading to consistent results. Fig. 2.12 shows the relation between Wbias and the trigger output width. The signal becomes less stable for very short pulses around and below 10 ns.

2.4 Integration with the DACQ boards

The physical interface between the DACQ boards and the TARGET modules are the serial data links running through the Backplane. The Backplane delivery date was delayed by many months due to its extremely complex and interconnected routing layout. Therefore a proto-backplane was built for the purpose of performing initial testing on the combination of the TARGET modules and the DACQ boards. The proto-backplane had the same geometrical factor as the Backplane, but missed any functionalities of the original; if not for data lines routing from the TARGET modules to the two Samtec flexible cables interfacing the DACQs. Power to the FEE was distributed from a PSU to a pin on the rear of the proto-backplane for each FEE. The clock for the TARGET was generated and distributed from an external tester board equipped with an FPGA. The front end electronics modules, complete with preamplifier and photosensors, were hosted in an aluminum rack with the two DACQ boards on top as shown in Fig. 2.13. The system was placed in a dark box where a laser with a diffuser could illuminate the focal plane of the camera. The light source could produce sharp peaks lasting about ~ 200 picoseconds. In Fig. 2.14 I show

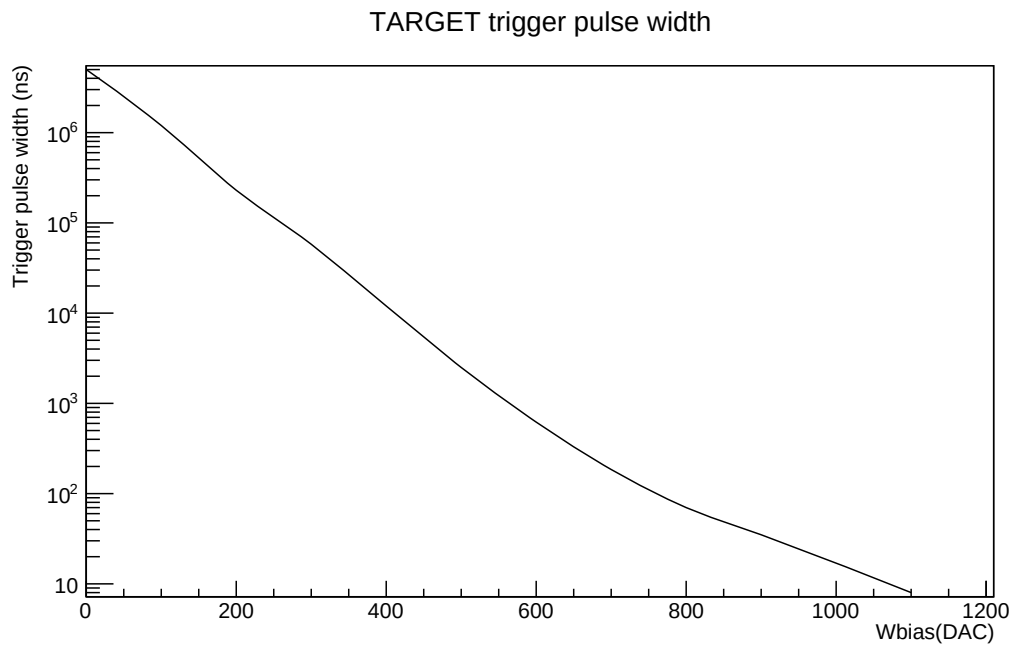


Fig. 2.12 Calibration of the TARGET ASIC trigger pulse width in relation to the W_{bias} parameter.

the relative illumination intensity on the camera focal plane. The measurements are of the average peak height of a reference silicon photomultiplier sensor moved to five different positions in front of the camera. Without the triggering features of the real Backplane, the only way to record the events was to use the same signal from a pulse generator¹ to trigger the laser and the tester board, which would then fan the signal out to all the TARGET modules. To account for delays in the different lines, an appropriate look-back time had to be set for the TARGET modules to find the signal in their buffer.

2.4.1 Communications

Auto-negotiation features had to be removed from the firmware of the DACQ board, otherwise no communications could be established to the TARGET modules that don't support this feature. Another behavior was first encountered when integrating the two components. After a TARGET module was powered-up, attempts to establish any communications failed about 50% of the time. A deeper analysis of the issue showed that commands attempting to write to a register of the FPGA always succeeded were acknowledge by the TARGET. Any attempt to read a register resulted in error code "RX INVALID CODE" on the DACQ board. Cycling the power to either the TARGET module or the DACQ to which it was connected would sometimes solve the problem. This issue was generated from a phase polarity difference between the DACQ and the TARGET module, due to

¹Agilent 81180A

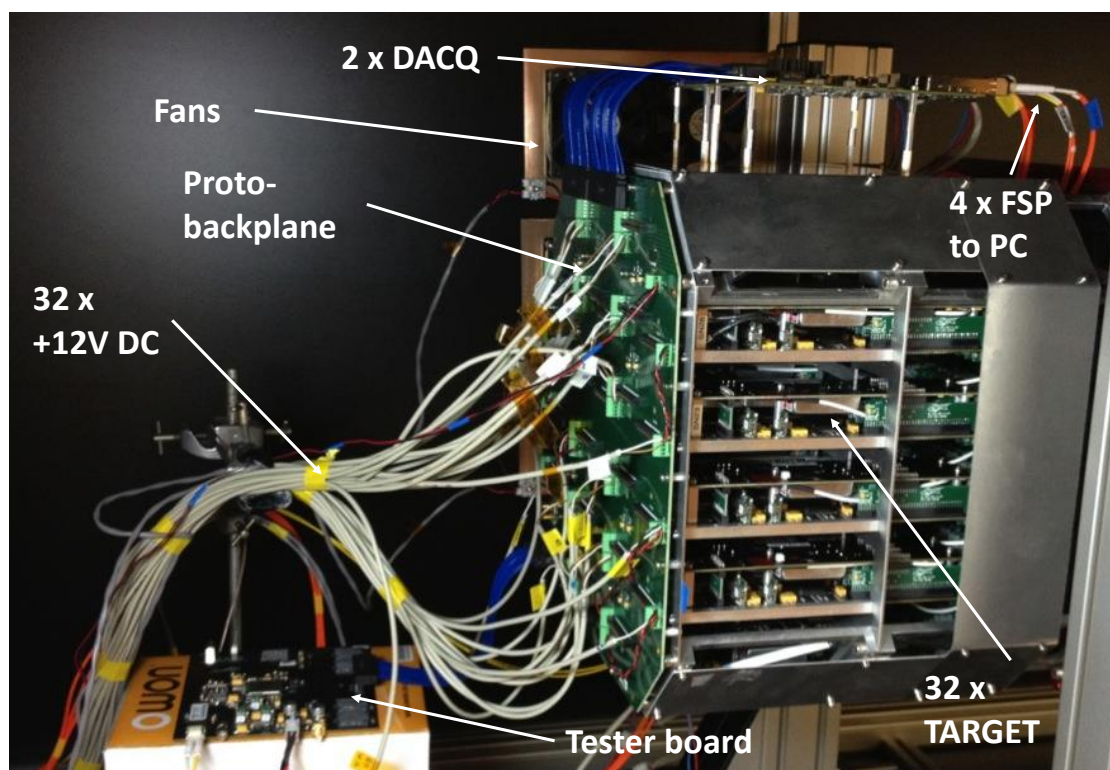


Fig. 2.13 Laboratory set up at the University of Leicester for the commissioning of the

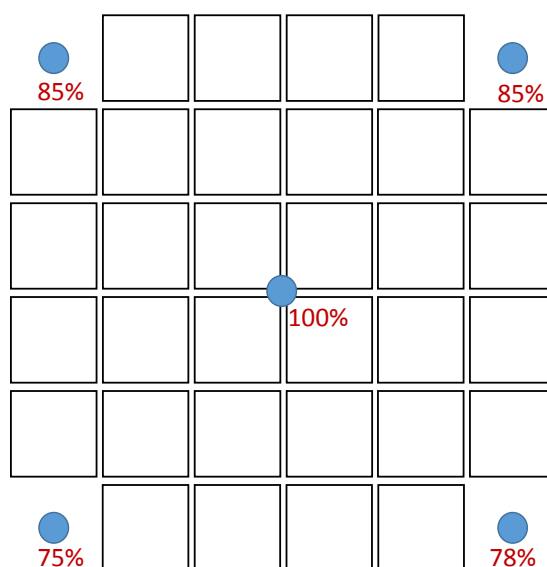


Fig. 2.14 Level of illumination on the focal plane provided by the laser and diffuser light source inside the dark box during commissioning of the TARGET + proto-backplane +DACQs system. Percentage is expressed relative to peak height as measured with a reference SiPM. The positions used for the measurement represented by the blue dots.

the different frequency the two are running at (8 ns clock for TARGET, 16 ns clock for DACQ). This depends on the phase difference found at boot-up. A register in the TARGET FPGA is now used to set the polarity to respond to read/write commands. In the libCHEC library (see chapter 4) an auto-detecting phase feature is implemented. A read request is issued, no response is received 50% of the time. In this case a write command is sent to change the phase. This doesn't fail because write commands are always received by the modules. After communications are established no instability is observed, even if it is clear that the implementation of the communications on the TARGET firmware is faulty. This is probably due to an inappropriate custom implementation of the ethernet protocol. A standard ethernet core was not used because the module development is shared with the Schwarzschild-Couder telescope (SCT) group [61], which needs to use the Pretty Good Protocol (PGP) due to higher data rate to be achieved. An easy way to avoid the issues is implemented in the software, so investigation to identify the root cause continues, but with a very low priority.

2.4.2 Data Rate

It was finally possible to reliably establish communications between the DACQ boards and the TARGET modules. Initially data rate tests were performed with only one DACQ and one module. CTA requirements for the SST cameras is to be able to register events with an average rate of 300 events/s, and a goal of 600. The test performed in the lab easily met the requirements. The same results were obtained when using 8 modules per DACQ boards (half camera focal plane populated). No readout could be achieved when all the 32 modules were used. "RX Overruns" errors could be seen logging to the DACQ via a debug port. The boards would freeze and, after entering this state, a power cycle was necessary. After a series of tests the root of the cause was discovered. The buffer size on the DACQ board was not deep enough to hold an event from the full camera. The firmware of the TARGET modules was modified to allow a settable delay for the TARGET FPGA to wait before sending data to the DACQ boards. Choosing different delay times for each module on a DACQ board it was possible to stagger the packets sent to avoid overflowing of the buffer on the DACQs. Experimentally, a minimum delay of 18 μ s between modules allow for stable readout of the camera at a frequency of 500 Hz without packet losses. This issue is still under further investigation. The buffer size was increased and 2 separate Virtual LAN (VLAN) per DACQ were introduced. This led to a minimum settable delay between TARGET modules of 1 μ s, but did not entirely solve the problem. Increasing further the buffer size on the board led to instability of the synthesis of the firmware. As described in the conclusion of this thesis, a new physical DACQ board will be introduced for future cameras, where the buffer size will be enough to hold more than an entire event.

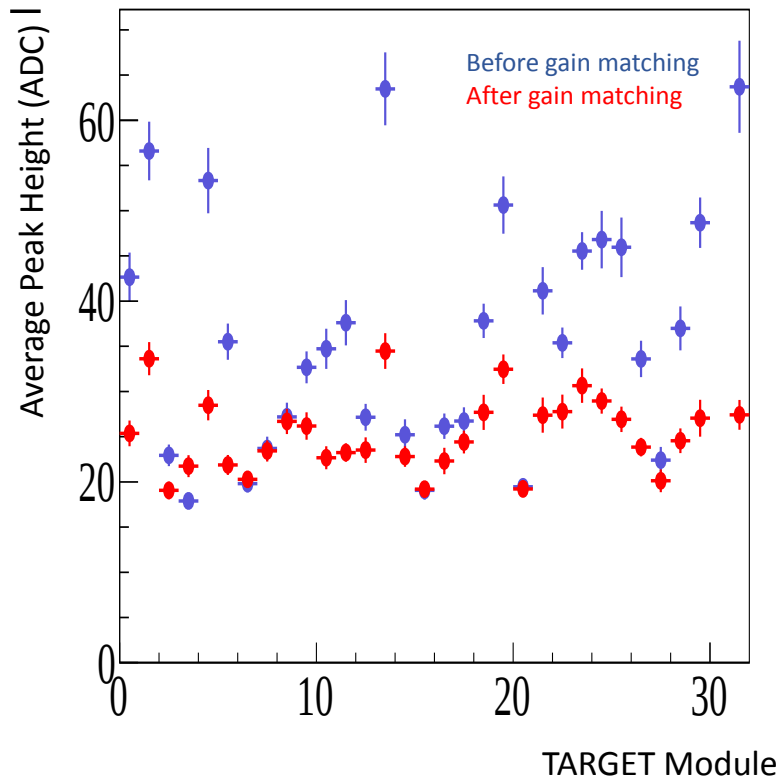


Fig. 2.15 Mean peak height in a module. Blue circles show this before any gain matching, where all modules were supplied with HV of 1100 V. The red circles show points where the HV was varied to uniform the gain across the camera. Here, the RMS decreases from $\sim 50\%$ to 16%

2.4.3 Performance

A minimum set up of the camera was achieved. Stable data taking could be performed to further analyze the performance of the camera, with the caveat that no trigger functionalities could be tested, especially to prove the prototype could register light intensity similar to an event from an air-shower. Before acquiring data at low illumination a flat fielding of the camera was required. The first very rough attempt at equalizing the gain was to match the highest gain MAPM with the lowest gain pre-amp. Then the high voltage supplied to the module was adjusted. Unfortunately all the 64 channels in a MAPM share the same supplied HV, so no further intra-module gain regulation can be applied. An RMS of the order of 10% is to be expected within an MAPM as declared by manufacturer. A different value of the HV can be supplied to different modules to even the gain as much as possible. In Fig. 2.15 I show the mean peak height in a module when each module is supplied with the same (1100 V) high voltage and after gain matching. The RMS is reduced from $\sim 50\%$ to 16%. Reducing further this value would improve little without a more even illumination, please refer to Fig. 2.14.

The illumination level can be adjusted with a set of filter wheels mounted in front of the light source in a dark box and controlled remotely as part of the libCHEC software library package (see chapter 4). Several data runs were acquired with the full camera triggered at 500 Hz, with different illumination levels. Fig. 2.16 shows the peak height spectrum in a pixel for a run with a very dim illumination. The data are fitted with a double Gaussian convoluted with a Poisson distribution as in equation 2.1

$$P(x) = \sum_{n=0}^{\infty} P_{\text{Poisson}}(n, \lambda) \times \text{Gauss}(x, \bar{x}_n, \sigma_n) \quad (2.1)$$

$$\propto \frac{1}{\text{PedWid}\sqrt{2\pi}} e^{-\left(\frac{x-\text{Ped}}{\sqrt{2}\text{PedWid}}\right)^2} + e^{-\lambda} \frac{1}{\text{SPEWid}\sqrt{2\pi}} e^{-\left(\frac{x-\text{SPE}}{\sqrt{2}\text{SPEWid}}\right)^2},$$

where x is the peak height of a pulse, $P_{\text{Poisson}}(n, \lambda)$ the Poisson distribution for n p.e., $\bar{x}_n$, σ_n respectively the mean and sigma of the Gaussian distribution for n p.e. and n the number of p.e. (here the sum was truncated at $n = 1$). The fit returns an average illumination level of ~ 0.9 photo-electrons, an RMS noise level of ~ 1.07 ADC and a distinct single p.e. peak at ~ 3.5 ADC. This measurement can be used to calibrate the data to the most relevant unit of photo-electrons. This measurement obviously depends on the gain of the photosensors, hence the HV supplied. A measurement for each intended supplied HV has to be performed. An extrapolation of a $\sim \times 3$ gain factor for each 100 V increase of the HV can be used for rough estimates, but not for proper calibration. In this thesis I choose to use the p.e. unit only when such a calibration set is available.

A set of MonteCarlo simulations from an internal note to the group showed that for a camera based on MAPM the optimal FWHM of the waveform of any channel is between 5.5 and 10.5 ns. In Fig. 2.17 I report the distribution of the pulse FWHM as recorded through the entire electronics chain. Two light sources were used during the test and commissioning phase, and the width of their pulses is convoluted with the signal shape. When using a laser generating pulses of light lasting ~ 200 ps the FWHM is 5.4 ns. Using the calibration LED flasher developed by the group [70], the signal has a FWHM of 7.5 ns. These values perfectly match the range of values suggested by the MonteCarlo simulations study.

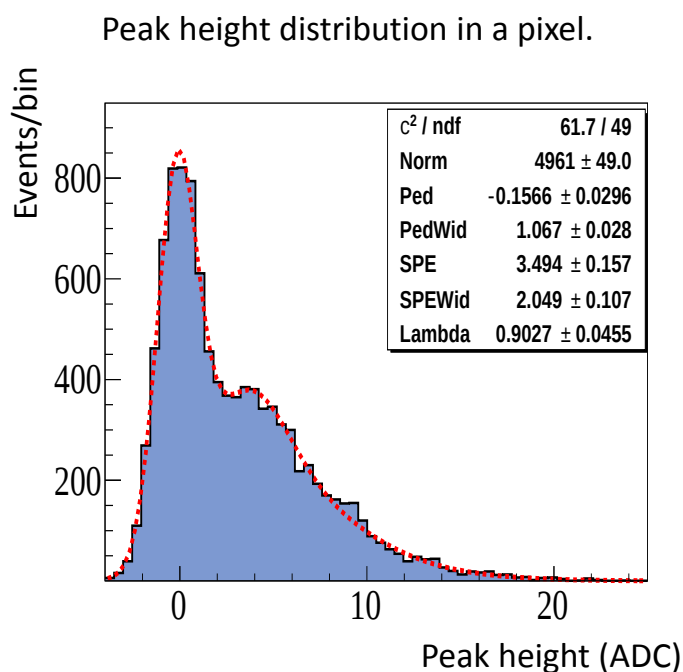


Fig. 2.16 Peak height distribution in a pixel. High voltage supplied to the module of 1100 V. Very low illumination level, fit return ~ 0.9 p.e.

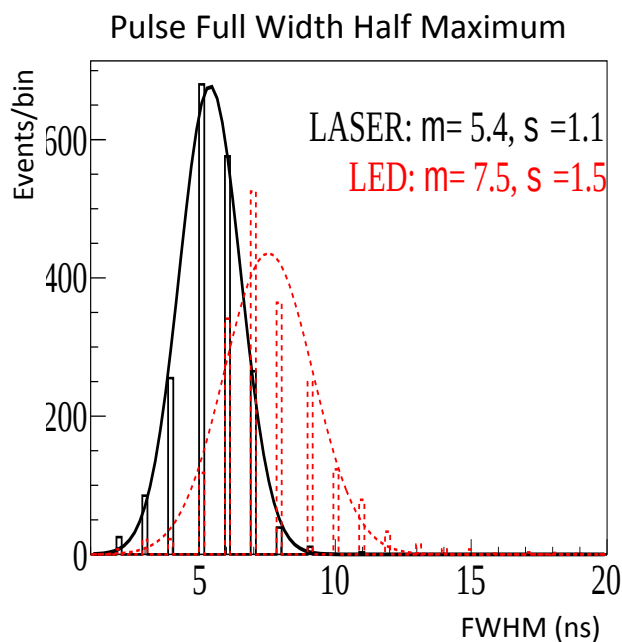


Fig. 2.17 Distribution of the pulse width in the camera measured as the Full Width Half Maximum (FWHM). Two light sources used, (*black*) a diffused laser emitting pulses of ~ 200 ps and (*red, dashed*) the GCT LED calibration flasher, with an intrinsic emitted pulse width of 4-5 ns

Chapter 3

Back end electronics: Backplane

The Backplane is the vibrant heart of the trigger chain of the camera. It is developed in collaboration with academic and industrial partners in the US. It will be used for the GCT, but also for the Schwarzschild-Couder Telescope (SCT). A design proposed for the MSTs array of CTA. Fig. 3.1 shows a picture of the Backplane. In this chapter I give a detailed description of two of its main components, a Trigger FPGA (sec. 3.1) and a Housekeeping companion FPGA (sec. 3.2).

I move then to a full description of the commissioning of the Backplane in the lab and integration within the camera that I performed at the Laboratory of the University of Leicester (sec. 3.3). The Backplane completes, together with the DACQ boards, the TARGET modules, pre-amplifier and photosensors, the minimum system of a camera for multi-TeV gamma-ray astronomy.

3.1 Trigger FPGA

One of the main functions of the Backplane is its key role in the trigger chain. As already discussed in details in sec. 2.2 in each TARGET ASIC the analog signals of a group of neighboring pixels, 2 by 2, is summed to form a so called super-pixel (SP). This is compared in a discriminator and, if over the threshold, the ASIC sends a low-voltage differential signal (LVDS) directly to the Backplane, bypassing the on-module TARGET FPGA. See Fig. 3.2 for a visual definition of the concept of pixel and super-pixel.

Each TARGET module contributes to 16 SPs, level zero trigger lines. The 512 signals are gathered on the Backplane in a central FPGA dedicated to triggering tasks (TFPGA). When the TFPGA receives the over-threshold signal from 2 neighbor super-pixels (including diagonals) during a coincidence window, it generates a serial TACK message and initiates the readout of the camera. The width of the coincidence time window is determined by the overlap of input trigger signals from the FEE (typically 10-30 ns) and can be regulated (see sec: 2.3.2). The neighboring SP trigger logic is illustrated in Fig. 3.3.

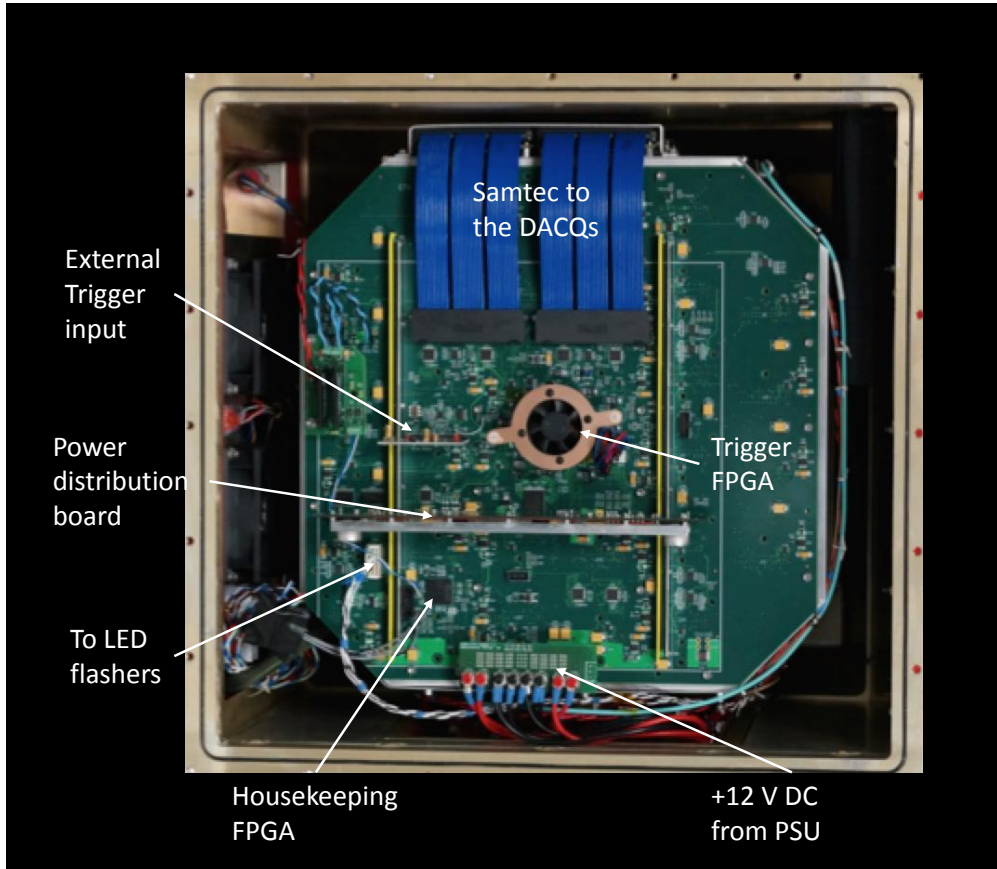


Fig. 3.1 Picture of the Backplane inside the camera enclosure. High-lighten some of its major components. *Photo credit to Prof. Akira Okumura.*

A TACK message always contains the 64 bit timestamp in nanosecond of the trigger decision from the Backplane. This is sent to the TARGET FPGA on board of all modules via controlled impedance, time matched LVDS pairs. When a TARGET module receives a TACK message it compares its content with its own local counter and decides how many nanoseconds to look back into its buffer of $16 \mu\text{s}$ to start digitization of the interesting part of the buffer that contains the waveform of the signal from the photosensors. This mechanism needs an initial synchronization of the counter on the TFPGA keeping the time that gets copied in the TACK and similar counter on the TARGET FPGA. This mechanism is implemented with a special TACK message called SYNC, which holds the 64-bit value at which all the FPGAs involved have to start counting. Also the jitter of the two counters and the jitter of the delay necessary to form and dispatch the TACK message have to be negligible. The TFPGA has to be very fast and has to handle the many inputs from all the super-pixels in the camera. A Xilinx XC6VLX550T in a 1760 pin BGA package is adequate to the task. The system aims to achieve 1 ns precision, so the Backplane de-skews, to under 1 ns, the 512 LVDS with fixed delays in increments of 25 ps implemented in on-board IO buffer in the TFPGA. For this task a very stable clock has to be provided from

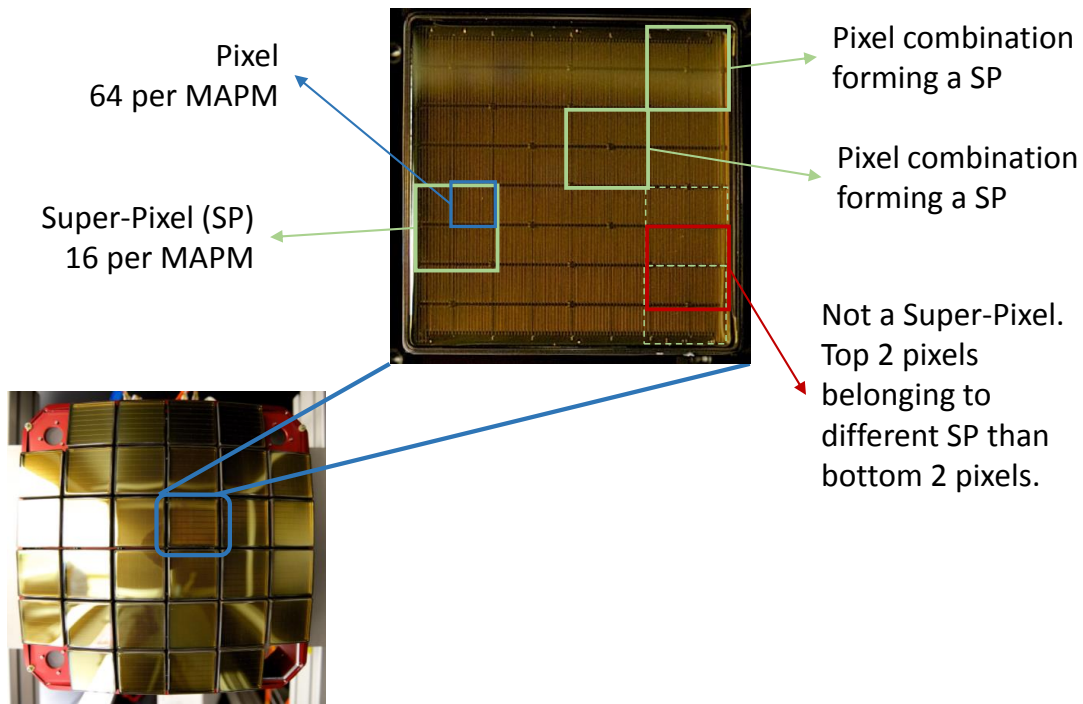


Fig. 3.2 Visual definition of the meaning of pixel and super-pixel (SP). In green example of set of 4 pixels effectively grouped in a SP. In red a combination of 4 pixels not matching to a SP. In this example the top 2 pixels belong to a different SP than the bottom 2. The definition of a super-pixel is not flexible and it is hard-wired in the TARGET ASIC.

one of the DACQ boards. An oscillator at 62.5 MHz on the DACQ feeds the Backplane, that multiplies the frequency within a quad clock generator to generate a 250 MHz clock for the TFPGA and a 125 MHz clock to be distributed to the TARGET modules. The TFPGA fabric runs on a 250 MHz clock, so the local counter for the generation of the TACK message is incremented in steps of 4 ns, which is not sufficient to provide the required event time tagging accuracy of 1 ns. In order to achieve this ambitious precision the 512 super-pixel trigger signals are piped into a ISERDES register of the high speed IO block of the Virtex 6 clocking at 500 MHz in dual data rate (DDR) mode, virtually running at 1 GHz. Each of the 512 lines are connected to 4 trigger outputs to the TFPGA with a phase delay of 1 ns between them creating four phase groups from A to D (see Fig. 3.4). This process provides 2048 inputs to the TFPGA where a combinatorial logic looks for coincidence within the same phase group and neighbouring pixels. The timestamp t_{TACK} for the TACK message is calculated from the counter with 4 ns accuracy $t_{4ns_Counter}$ according to

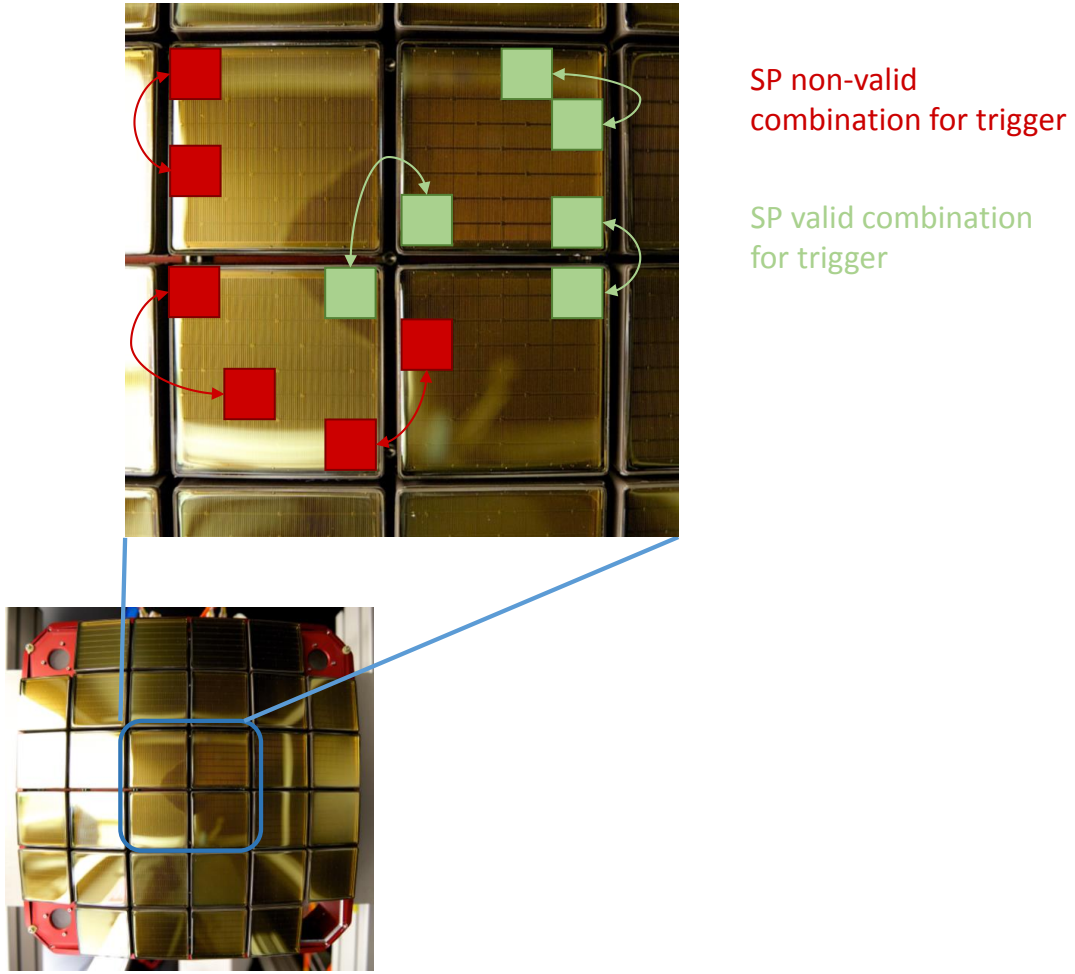


Fig. 3.3 Visual explanation of trigger logic of the neighboring SP. In green examples of SP couples that are considered neighbors and therefore can potentially trigger the camera readout when both are over threshold.

$$t_{TACK} = t_{4ns_Counter} - t_{delay} - \begin{cases} 3, & \text{if phase A} \\ 2, & \text{if phase B} \\ 1, & \text{if phase C} \\ 0, & \text{if phase D} \end{cases}, \quad (3.1)$$

with t_{delay} a deterministic delay to account for the time required for the signal processing. This term is unimportant because the TARGET module needs a defined loop-back time to compensate all the delays in the chain to find the signal in their buffer, so only one value has to be specified that takes into account the whole process.

For obvious commissioning and debugging reasons it is possible to ask the TFPGA to create a TACK and generate a camera trigger from an external command coming from the

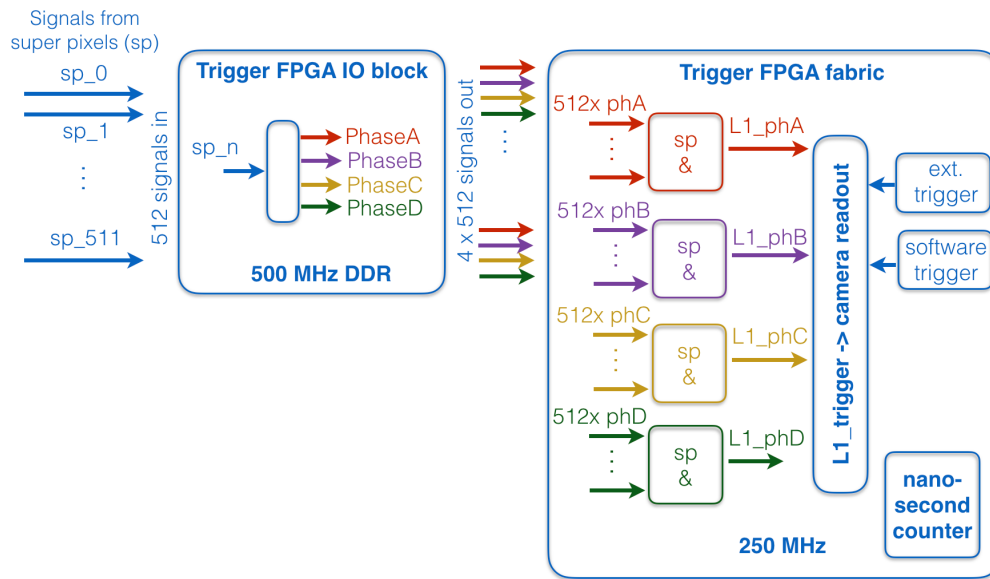


Fig. 3.4 Timing of the trigger chain. *From the Backplane Interface Control Document.*

software or an hardware wired signal. The latter could be used by the SCT group for an inter-telescope trigger signal.

3.2 Housekeeping FPGA

The first element to come live on the Backplane when the main 12 V DC line is supplied to the camera is the housekeeping Actel A3P400 FPGA (HKFPGA). The HKFPGA handles the slow control, monitoring and communication of the Backplane. Among its tasks are also to manage the 12 V DC supply to the TARGET modules and the SI5338 phase programming to tweak alignment of the 125 MHz of their clocks. The communication to the HKFPGA are implemented via one of the DACQ using a full duplex synchronous clocked serial stream based on serial peripherals interface (SPI). The HKFPGA communicates to the TFPGA in a similar way. The former passes the slow control of the latter to the same DACQ board, that bridges to the external PC. The DACQ board acts as the SPI Master, communication starts when it asserts a select signal (SSEL). Then it generates a 16-shift clock (SCK) with pulses of width of about 200 ns and send 16 bits of data starting with MSB on the MOSI line. The transmission is on the positive edge and the sampling on the negative edge. The SPI message is a fixed length message with eleven words of 16 bits each. The message structure consist of: a start of message word followed by a command word, eight data words and an end of message word. The HKFPGA replies on the MISO line with the echo of the start of message and command words, eight data words and the

echo of the end of message word. In Fig. 3.5 a block diagram of the implementation of the communications between the DACQ and the HKFPGA is shown.

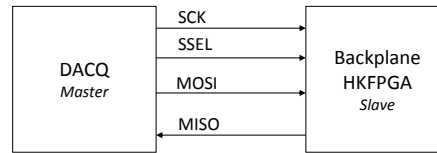


Fig. 3.5 Block diagram of the SPI communications between the DACQ and the HKFPGA. Similar protocol is used between the HKFPGA and the TFPGA.

The HKFPGA also has to deliver SPI messages to the Peripherals Board (PB). From the Backplane, through the PB, four LVCMOS 0-3.3 V run to the LED flashers in each corner of the camera focal plane. When commanded, the HKFPGA can send pulses to one or all of the calibration flashers and a delayed signal to trigger the TFPGA to start readout of the camera. While these lines transparently run through the Backplane, the pattern of LEDs to be used has to be selected in advance with a distinct command to the PB.

3.3 Commissioning

The Backplane for the first camera prototype was developed at the Washington University in St. Louis, where a minimal set of integrity tests was performed before delivery to the laboratory at the University of Leicester. There I integrated the Backplane in the camera and carried further extensive tests with the help of a colleague each from one of the other two institutes. Before delivery to the GCT group, the American colleagues used a dummy load circuit to simulate the TARGET module, to verify proper distribution of the 12 V DC supply from the power board on the Backplane and the clock. During this phase the clock distribution chip for one of the module slots malfunctioned. The chip could be replaced, but the risk of introducing further and more critical faults was considered too high to justify replacement at that time, considering the very long leading time from the industrial partner to manufacture such a complex interconnected device and the delay in the overall schedule it may have caused. None of the functionalities of the rest of the module in the camera was impaired, so it was chosen to operate the camera with 31 out of 32 TARGETs. The SPI interface was tested with an ARDUINO connected to a debug port, not via the DACQ board.

In Fig. 3.6 is the set up at the laboratory of University of Leicester. An aluminum rack hold the DACQ boards, the Backplane and the 32 modules in place.

The whole structure is kept in a dark box equipped with fan for cooling of the electronics and a diffuse light source. A laser emits light at wavelength in near ultraviolet, similar

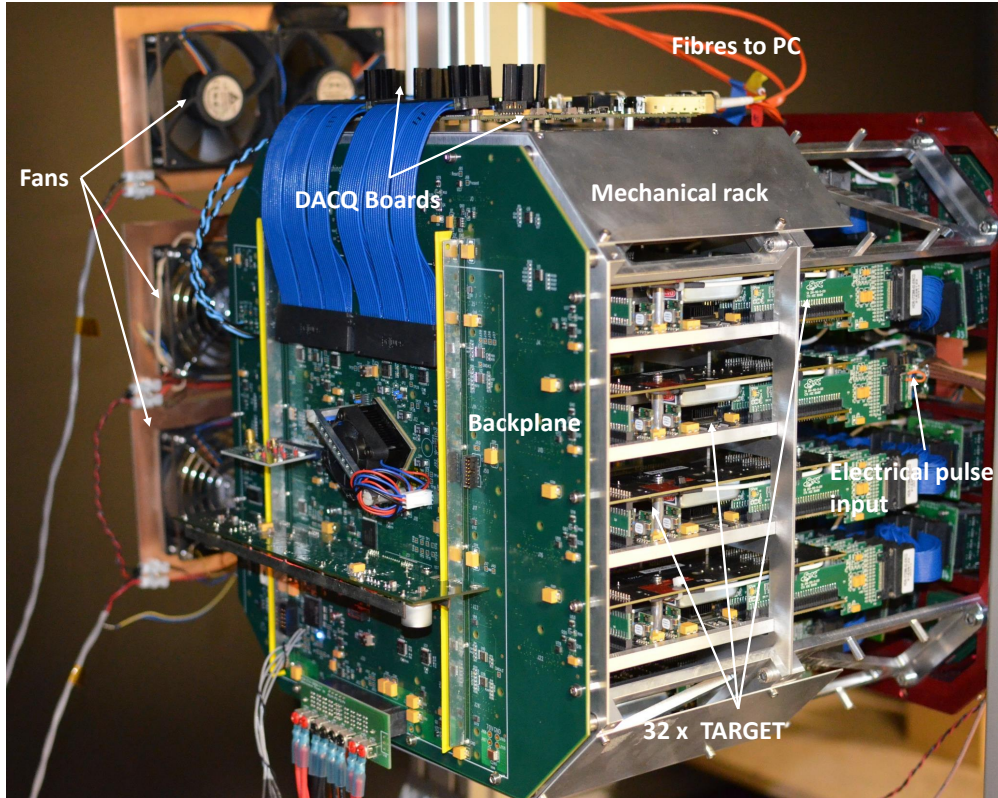


Fig. 3.6 Set up at the University of Leicester for the commissioning of the Backplane and its integration in the camera. The camera is inside a dark box containing also a diffused laser, which can't be seen in the picture.

to the Cherenkov light the camera has to observe. The light is then diffused with a spare diffuser from the calibration flashers unit developed by the group. In Fig. 3.7 I report the uniformity of the light as measured by a reference silicon photomultiplier detector momentarily accommodated at the center of each photosensor of the camera.

3.3.1 Power distribution & Comms

In the lab, a PSU provided 5 V to a set of fans and a separate high current PSU supply 12 V DC to the Backplane. The DACQ boards and the TARGET modules receive a 12 Volt DC supply from the power distribution board on the Backplane. The DACQ boot up sequence shows peak in the drawn current. During commissioning of the Backplane, its power board wasn't capable of providing the sufficient power, so the DACQ boards were supplied directly from the PSU.

As described in more details in sec. 4.1.1 and sec. 4.1.2 I wrote all the necessary software components to implement the communication to the Backplane through a bridging server on the micro-processor on one of the DACQ boards. Although every command seemed to be received by the Backplane, the replies from the HKFPGA were corrupted

Laser Uniformity Across CHEC-M

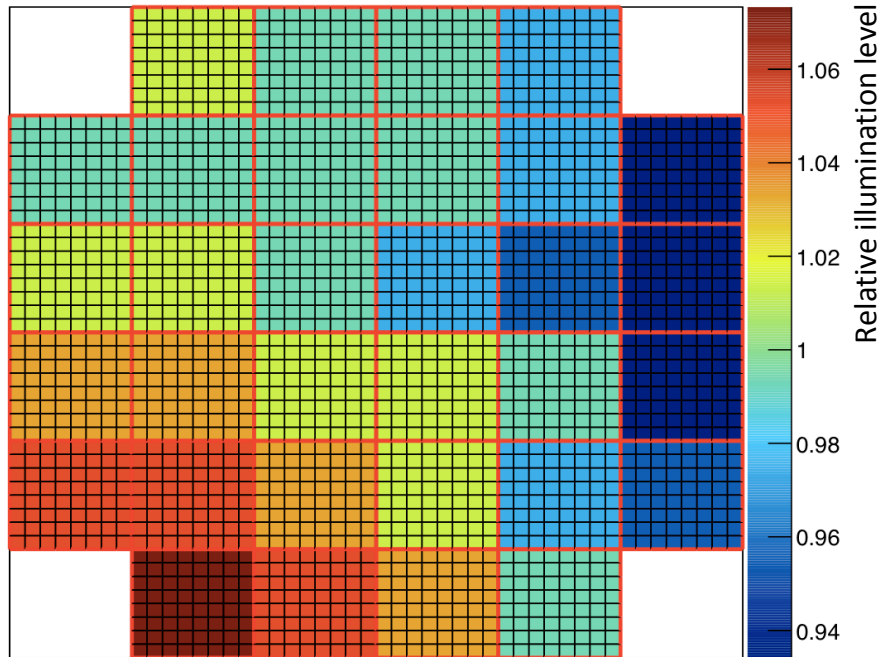


Fig. 3.7 Illumination uniformity of the diffused laser on the focal plane of the camera in the dark box. Measurements are taken as the relative mean peak height of a reference silicon photomultiplier positioned at the center of each module.

almost 10% of the time. This behavior had never been observed using an ARDUINO connected to the debug port of the Backplane and was probably due to a fault in the bridging chain. I introduced a forced sleep of 10 ms between commands to limit the rate of the communication, and this helped to reduce the rate of corrupted data to below one percent.

After both the Backplane and the DACQ are running and configured, a command can be issued to the HKFPGA to control the distribution of the 12 V DC line to the slots hosting the front end electronics. The TARGET modules are switched-on one by one, with a pause in the sequence between modules of a few hundreds milliseconds to minimize the current drawn spikes. Only after all the modules are connected to the 12 V line do the initializations of their FPGA and ASICs begin, with an associated increase in the power consumption (see sec. 2.1). I implemented a very conservative and slow boot-up sequence, waiting for the current drawn by each module to stabilize, before booting the next one. Nevertheless the 12 V DC supply line from the Backplane failed very often. Upon failure, the supplied voltage drops enough that all the previously booted modules enter in an unknown state, requiring re-boot. Increasing the supplied voltage to 12.2 V helped very little, just slightly reducing the failure rate. This required a very long sequence of boot-up and resets with the necessary help of operator intervention, with an additional

stress on the hardware components. Typically starting the system from cold would take up to 1 hour.

3.3.2 Trigger chain

The most important functionalities introduced by the integration of the Backplane in the camera is the ability to trigger the system internally with a patch of light shining on 2 adjacent super-pixels. In the early commissioning days it was important to be able to monitor with the oscilloscope a few test points on the rear of the Backplane during operation. This contrasts with the impossibility to operate the camera outside a light tight dark box. A bright light level would certainly break the very sensitive multi-anode photomultiplier photosensors. It was therefore chosen to operate with no high voltage supplied to the MAPM and provide the input signal to the FEE by other means. A boxcar signal of 1 V, 30 ns wide was injected directly into two channels of one of the TARGET module belonging to two neighbors super-pixel. It's possible to see on the right of Fig. 3.6 the wires connected to the front end of a module. This strategy allowed to test and debug the proof of concept of the trigger chain, with safe operation of the camera under bright ambient light.

SYNC

The trigger logic requires all the modules to run a counter with 8 ns precision. All of them have to start at the same time and from the same number, so that it can be compared with the timestamp contained in a TACK message. To synchronize all the modules, the Backplane can issue a special TACK message called SYNC. Its timestamp will be the starting number for the counter in each TARGET and for the Backplane TFPGA counter itself. Every module keeps track of whether they are synced or not in a bit of a specific register depending on the version number of the TARGET and its FPGA firmware (bit 0 of register 17 for TARGET 5). A module that didn't previously receive a SYNC would ignore any other type of TACK. At first none of the modules could be synced, due to a failure from the Backplane side. After shifting by four the 64 bits timestamp in the SYNC all the modules could be synchronized. This shift is probably derived from a condition race between the synchronous and asynchronous part of the trigger logic in the TFPGA and varies with different synthesis of its firmware. A successful value for the last three significant bits can be either 0 or 4. No further detailed investigation followed on this issue because a simple workaround can be implemented on the software side, where one value and then, if necessary, the other is used.

TACK generation

After successfully achieving synchronization of the whole system a pulse was sent to the module with the input of the TARGET ASIC connected to a pulse generator. The DACQ board instantly crashed and a power cycle was necessary. Note that any communication with the Backplane is via the DACQ, so it was interrupted. After re-boot of the DACQ boards the communications to the Backplane were established once more and the number of triggers issued by the Backplane in the span of couple of seconds was of the order of tens of thousands. The module was therefore trying to readout at more than a 10 kHz rate, and this caused overflow of the buffer on the DACQ and its consequent freezing.

By probing a test point on the rear of the Backplane, it became clear that, after $\sim 14 \mu\text{s}$, a second spurious TACK message was sent from the FEE module (see Fig. 3.8). The inspection of the available test points on the TARGET showed that some of the lines pick-up a burst of noise when the TARGET FPGA readout after receiving a TACK. This noise, apparently originating from pin “SMPLSEL3_S1”, causes another trigger and a feed-back loop starts. The problem was resolved with a hold off time on the TFPGA

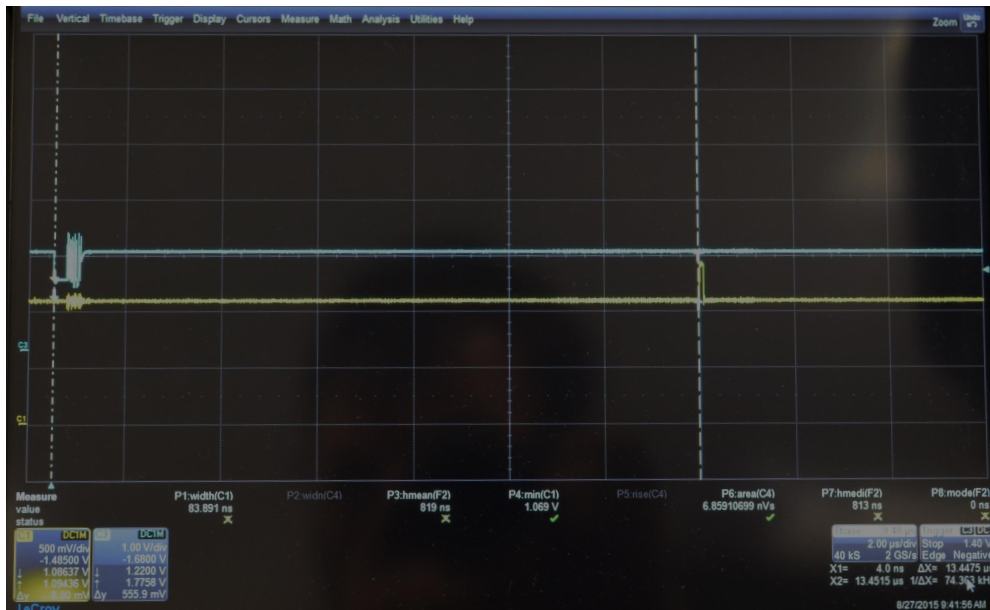


Fig. 3.8 Feed back loop effect between the Backplane and the TARGET module. In blue (top) the first TACK signal send by the Backplane and in yellow (bottom) the line driven by the TARGET module. After $\sim 14 \mu\text{s}$ a second trigger pulse is sent by the module. In this test the Backplane is made to ignore the signal from the TARGET and the first TACK was generate on command from the software. So no second TACK is visible on the blue channel.

trigger logic of $70 \mu\text{s}$, well after all the tail of the spurious secondary trigger signals from the front end electronics. The look-back time for the TARGET modules in their buffer

is determined by a fixed time due to signal processing and routing. With a sweep of this adjustable parameter I found this delay time to be ~ 700 ns.

First light with self-triggering feature

At this point the system achieved a sustained control rate of events using an internal trigger on one of the modules. Next, the camera was enclosed in the dark box, the HV was supplied to the photosensors and the focal plane was illuminated with the diffused light of the laser. Fig. 3.9 shows a non calibrated plot of the very first light recorded with the use of the internal trigger. The Figure shows the non-calibrated mean waveform after pedestal subtraction in each module. The graphs are arranged following the geometrical disposition on the focal plane of the corresponding module. Module 0 is top-left and module 31 is bottom-right. Some modules are missing from the plot for different reasons:

- Module 13: after numerous attempt couldn't power up the module without the 12V supply to drop, excluded from the run.
- Module 17: after numerous attempt couldn't sync the module, excluded from the run.
- Module 30: clock distribution chip on the Backplane not functioning.

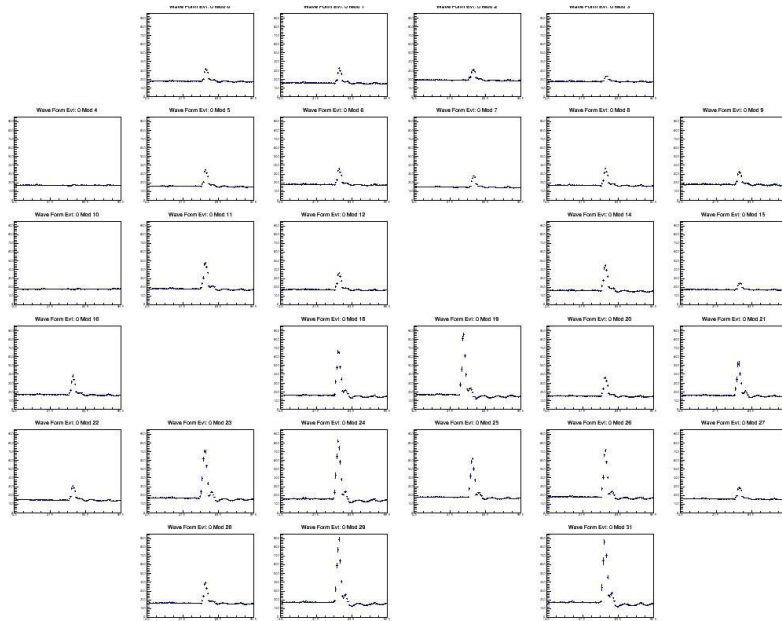


Fig. 3.9 The very first event recorded using self triggering capability of the camera. Data acquired in a dark box, using a diffused laser pulsed at 500 Hz. Each graph shows the mean waveform in a module. Module 0 is top-left, module 31 is bottom-right. Data are non calibrated only pedestal subtracted. Missing modules: 13 power not supplied, 17 not synced, 30 no clock.

Trigger Map

The TFPGA allows any super-pixel trigger input to be removed from the combinatorial logic to consider only patches of the camera. For example, a very bright star could illuminate a pixel for long enough to let the camera trigger on spurious events, dominated by the NSB. Or, simply, it could be necessary to mask off a faulty channel due to a malfunction of the part of the photosensor, pre-amplifier or TARGET ASIC. With an SPI command the hit pattern of the super-pixels that generated the triggers can be queried. The next step of the commissioning of the trigger chain was to confirm the trigger map logic was as designed (see sec. 3.1).

Two tests are necessary. Firstly, it must be checked that the combinatorial logic gives a match between the correct identity number of the super-pixels. Secondly, it needs to be verified that the numbering of the super-pixels in a module corresponding to the physical pixel group of the photosensors. To perform these two tests the camera was illuminated with uniform light, bright enough to ensure trigger even at high threshold. This setup ensures the camera would not trigger on noise, because the threshold is well above it, and the number of triggers would match one-to-one to the number of pulses of light generated by the laser.

Test1 - trigger logic map The test focused for simplicity on module number 6 and its neighbors. At first I set the trigger mask off for every super-pixel, i.e. I removed them all from the combinatorial logic. Then I enabled super-pixel (SP) pairs one by one to check which combination issued triggers. Procedure:

1. Module 6 - Enable SP 0
2. Enable Module 0 - SP 0
3. Send 5 pulses of light
4. Check number of triggers (should be 5 if neighbors SP, 0 if not)
5. Check hit pattern (should match the two SPs enabled)
6. Disable Module 0 - SP 0
7. Repeat from point 2 for Module 0 - SP 1 to 15
8. Repeat from point 2 for Module 1 to 31
9. Repeat from point 1 for Module 6 - SP 1 to 15

All and only neighbors super-pixels generated triggers, and the returned hit pattern always matched with the enabled patch. This test confirmed that the trigger logic map matched the designed one. This results are valid under the assumption of the physical correspondence

of the identity number of super-pixels as in Fig. 3.10.

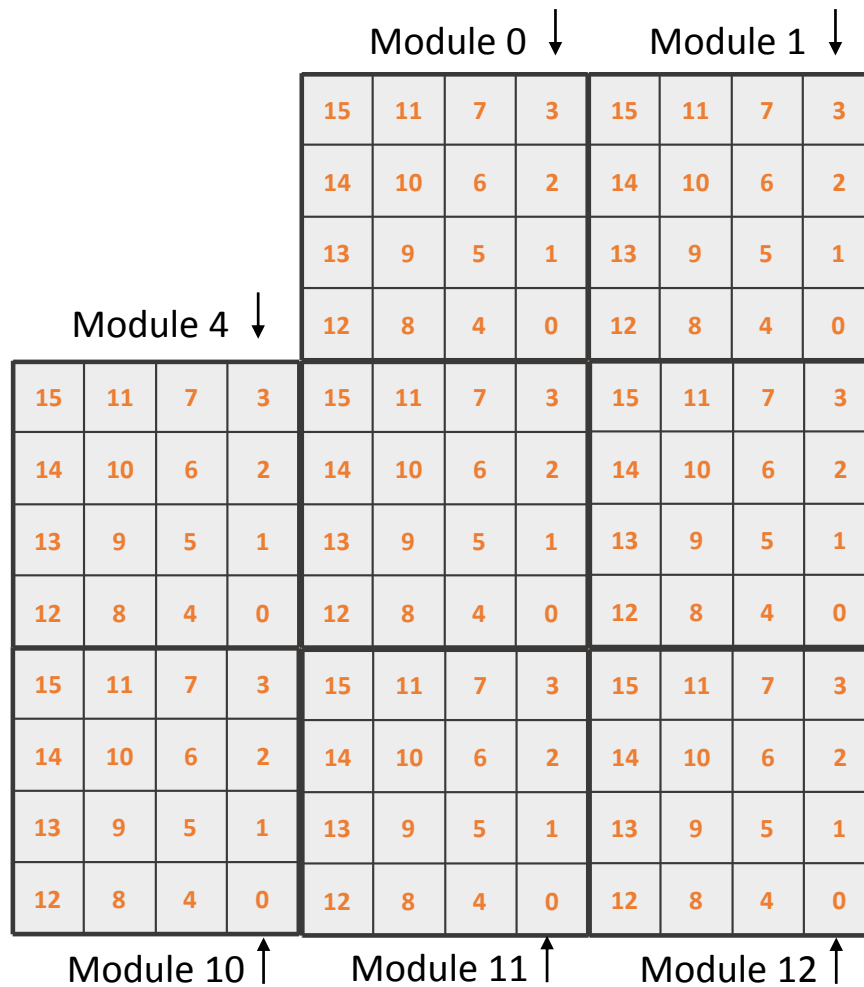


Fig. 3.10 Diagram including the top-left quarter segment of the camera. In orange the super-pixel identity number map as inferred from Test1 on the trigger logic map. The camera was illuminated uniformly and super-pixels trigger channel enabled one coupled at a time. This is the only consistent map with the test result.

Test2 - physical match to trigger mask map To check the physical matching of the trigger map of Fig. 3.10 I applied a plastic thick cover with a hole that allows light to shine only on 4 neighbours on one of the corners (can be changed with orientation of the cover). I applied the cover with the hole in the upper-left corner of module 6, and enabled all of the super-pixels (see Fig. 3.11). I expected the hit pattern to show triggers from module 6, super-pixels 15-14-11-10. Instead the BP reported hits from SPs 0-1-4-5. I performed a variant of this test to exclude a miss-match between the hit pattern super-pixel numbering and the trigger logic super-pixel trigger line numbering. Leaving the hole in the same position, I enabled only SPs 15-14-11-10. If trigger logic was consistent with Fig. 3.10,

but the hit pattern reversed, the camera should then trigger, and report hit pattern 0-1-4-5. The result was no trigger, while enabling SP 0-1-4-5 the number of trigger matched the pulses issued by the diffused laser. Results obtained repeating the test rotating the cover were consistent. The layout of the physical identity numbering of the super-pixels was clearly like shown in Fig. 3.11.

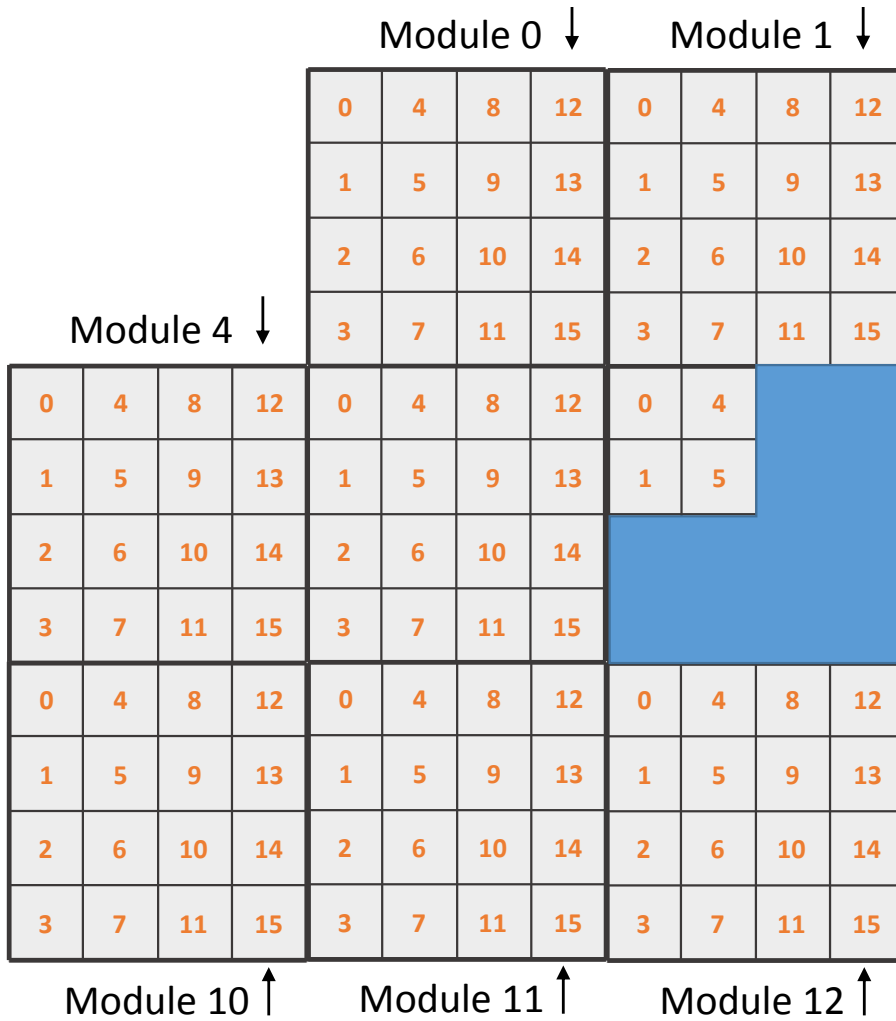


Fig. 3.11 Diagram including the top-left quarter segment of the camera. In orange the super-pixel identity number map as inferred from Test2 on the trigger logic map. The camera was illuminated uniformly and all the SPs trigger channel of module 6 (in the middle right in this Figure) were allowed to participate to trigger decision. A plastic cover (darkened area) with a hole covered the photosensors as described in Test2 to verify physical match to trigger mask map. The cover was rotated to all the four relevant position and this is the only consistent map with the test result.

The conclusion of the two tests was a miss-match of the numbering orientation of the super-pixels, which led to the correct trigger logic within a module, but a wrong neighbour

matching for inter-modules super-pixels. An additional test reported triggers for patches as shown in Fig. 3.12. The error was fixed in the TFPGA trigger map logic and the tests repeated to finally confirm the correct trigger map logic. Any future version of the Backplane or TARGET schematics or firmware must be checked against this set of tests.

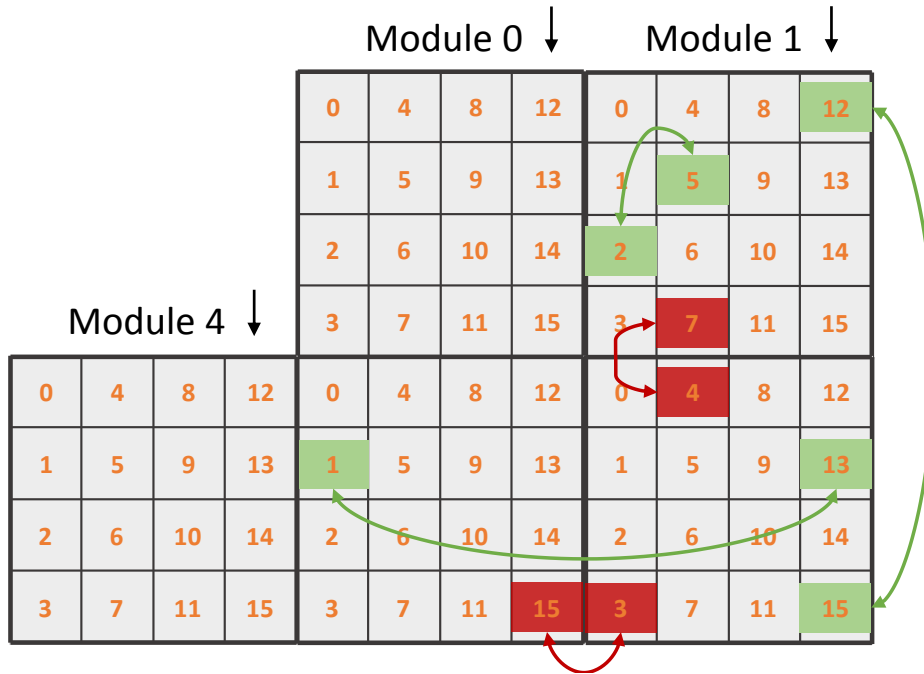


Fig. 3.12 Diagram including a segment of the camera. In green examples of super-pixel couples erroneously paired as neighbours in the first version of the TFPGA firmware. In red couples that should have been paired, but were not.

Time resolution

It is a CTA requirement for the SST camera to have a timing resolution of <2 ns. In Fig. 3.13 the distribution of the peak arrival time as recorded with the camera prototype in the lab. The light source is a diffused laser with pulses of ~ 200 ps. The graph shows a resolution of less than a nanosecond, conforming to the CTA requirements.

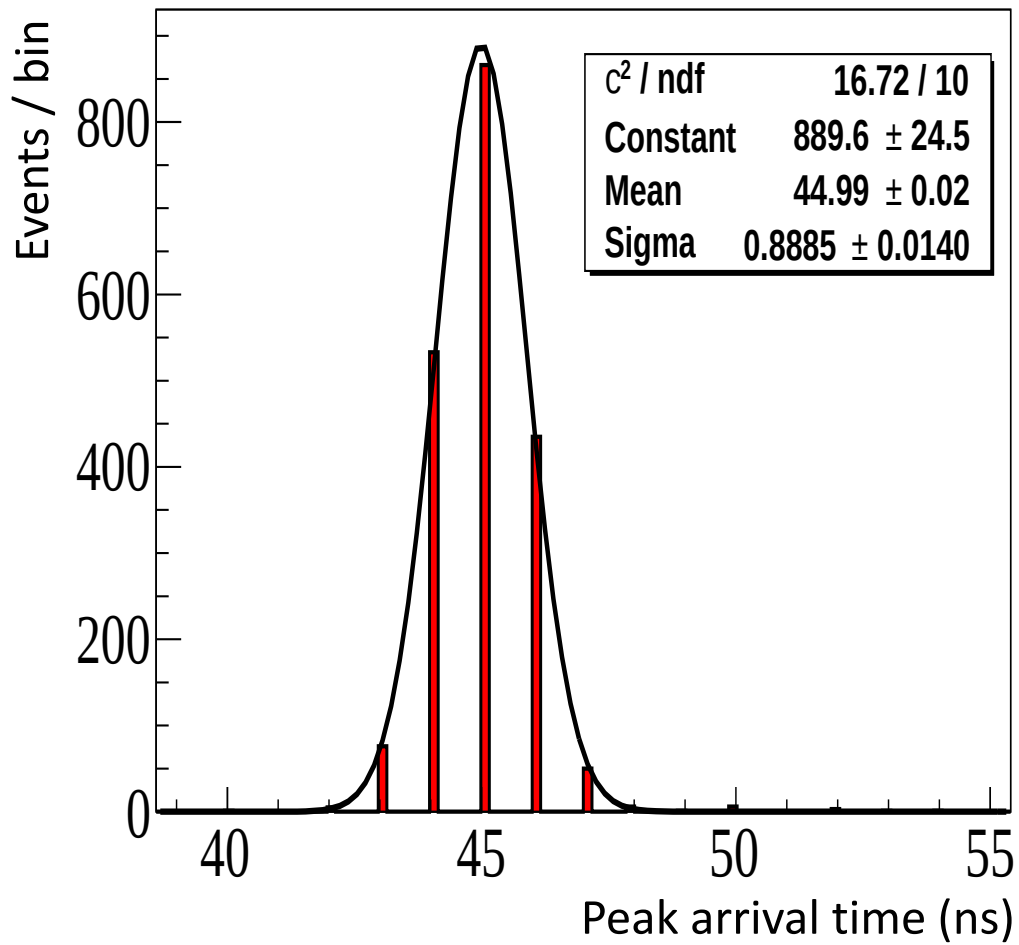


Fig. 3.13 Distribution of peak arrival times in the camera. Data was recorded with a diffused laser producing flashes of light lasting ~ 200 ps. A superimposed Gaussian fit shows a resolution of better than a nanosecond.

Chapter 4

Software development for data acquisition and control

A very complex system such as a Cherenkov camera, composed mainly of custom-made electronics, needs a significant amount of custom software ranging from tasks to handle communication protocols with the hardware to high level scripts and user friendly interfaces to operate the camera. The software has to be very robust, reliable and easy to maintain because the camera is expected to operate in a remote environment for many years. At the same time the code has to be flexible enough to allow for future upgrades without need of any major restructuring to maintain retro-compatibility. In this chapter I present the libCHEC library which was developed to address all the above mentioned requirements. The overall development of libCHEC was led by me, with the help of a small group of GCT colleagues as described in the declaration of authorship. I give particular attention to the elements of libCHEC that I wrote myself.

The necessity of a single comprehensive and reliable library was clear during the commissioning phase of the many hardware components of the camera, and their integration in the full system. From then, libCHEC constantly evolved, following the changes in the hardware and firmware, and implementing solutions for many of the issues encountered in the testing of the custom-made electronics. The code described here is the latest implementation¹ and I leave for sec.7.1.3 a discussion for future work on the code and its incorporation within the whole CTA array control software complex.

This chapter is divided in two sections that provide details on each of the most relevant components I developed for the libCHEC software architecture presented in Fig. 4.1. In the first section I focus only on the very core and most critical classes. In the second section I give explicit examples of how the parts come together into one system of a few high level processes that allow solid operation of the camera. The library itself is composed of many

¹As of Summer 2016

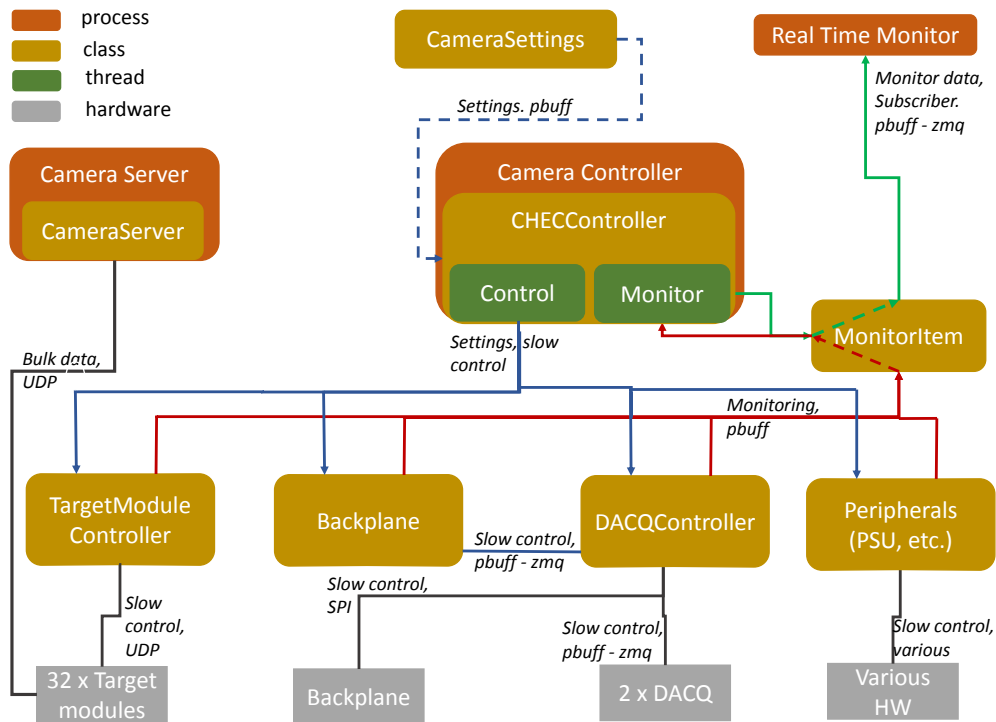


Fig. 4.1 Software architecture.

thousands lines of code, but I quote only short extracts where relevant as examples for the reader.

4.1 libCHEC core

In this section I present the low-level drivers and the controllers for the three cardinal, most complex, custom-made components of the camera: the TARGET modules (4.1.3), the Backplane (4.1.1) and the DACQ boards (4.1.2). The whole architecture of libCHEC also required the development of some auxiliary classes, the most important to store and load configurations in a common fashion (4.1.4), and a homogeneous structure to implement monitoring and automatic reactions among the many different components of the system (4.1.5). The highest-level classes of this chapter are the prime ones to handle the camera: a server class (4.1.6) for data acquisition and event building and a controller at camera level (4.1.7) for the slow control and reliable operation of the entire system.

The libCHEC library is written in C++11 and I tried to keep to a minimum any dependencies on external libraries, particularly for ease of long-term maintenance—usually the largest part of the lifetime cost of any software package. Nonetheless, some tasks are flawlessly and effortlessly achieved with the use of a few third-party open-source

codes. libCHEC relies on ZeroMQ² as an inter-process transport layer, and google protocol buffer³ for message serialisation, storage of settings and common monitoring data structure. The target operating system is Scientific Linux 6.5⁴ with compiler gcc 4.9.2⁵.

4.1.1 Backplane

As described in sec. 3.2 the communications to the Backplane housekeeping FPGA are implemented via SPI. The physical connection is through one of the DACQ boards on one of the Samtec cables. All communication to the Backplane must therefore be via the DACQ board, where a bridging server runs on the DAQC ARM microprocessor, and forwards relevant SPI commands to the Backplane. The DACQ then waits for replies from the Backplane HKFPGA and forwards them to the invoker of the command. The `Backplane` class needs a pointer to the controller of the DACQ (Code below, line 3) to which it is physically connected to implement this bridging mechanism.

```

1 class Backplane {
2 private:
3     boost::shared_ptr<DACQController> fDACQController;
4     bool send_spi(uint16_t(&Message)[11], uint16_t(&Data)[11],
5                 bool IsVerbose = false);
6
7 public:
8     explicit Backplane(boost::shared_ptr<DACQController> pDACQController);
9     virtual ~Backplane(){};
10
11     bool Send_Calibration_Trigger();
12     bool Read_time_of_last_trigger(uint64_t& triggerntime);
13     [...]
14 };

```

Code 4.1 Extract of Backplane class header. Constructor, destructor, example of few methods.

An SPI message to the Backplane is always comprised of eleven 16-bit words. I implemented the message exchange in *send_spi* function reported below on the `Backplane` side and in the *SendSpiCommand* (line 6) function of the `DACQController` class for the DACQ side (see sec. 4.1.2). Multi-thread safety is provided by the implementation of the latter.

```

1 bool Backplane::send_spi(uint16_t(&Message)[11], uint16_t(&Data)[11],
2                          bool IsVerbose) {

```

²<https://zeromq.org/>

³<https://developers.google.com/protocol-buffers/>

⁴<https://www.scientificlinux.org/>

⁵<https://gcc.gnu.org/gcc-4.9/>

```

3  SPIMessage cmd;
4  for (unsigned int i = 0; i < 11; ++i) cmd.add_data(Message[i]);
5  SPIMessage reply;
6  if (!fDACQController->SendSpiCommand(cmd, reply))
7      return false;
8  else {
9      for (unsigned int i = 0; i < 11; ++i) Data[i] = reply.data(i);
10     if (IsVerbose)
11         for (unsigned int i = 0; i < 11; ++i)
12             std::cout << std::hex << Message[i] << " " << Data[i]
13                 << std::dec << std::endl;
14     usleep(10*1000); //~10ms
15     return true;
16 }
17 }

```

Code 4.2 Implementation of the send_spi command, from the [Backplane](#) class source file.

The external library ZeroMQ is used as transport layer between the [DACQController](#) and the server running on the ARM micro-processor. The serialisation of the data is performed with the [SPIMessage](#) class (line 3), generated automatically with the external library google protobuf. I provide more details in sec. 4.1.2. To limit the rate of the SPI messages to a level sustainable by the hardware chain, the process has to sleep for 10 ms at line 14. The specific implementation of the firmware demands that a command addressing the HKFPGA has to start with the keyword SPI_SOM_HKFPGA (definition below, line 1) and to end with SPI_EOM_HKFPGA (line 2). When a message starts with SPI_SOM_TFPGA (line 3) the HKFPGA redirects it to the trigger FPGA. Similarly, the command has to finish with the keyword SPI_EOM_TFPGA (line 4). I defined these special 16 bit keywords in the [Backplane](#) class header with human readable names so that, should the firmware version request an update of the values encoded for specific commands, only a few lines of code would be required to be modified, a task easily achievable even by non-experts.

```

1 #define SPI_SOM_HKFPGA 0xeb90 // Start of Message HKFPGA
2 #define SPI_EOM_HKFPGA 0xeb09 // End of Message HKFPGA
3 #define SPI_SOM_TFPGA 0xeb91 // Start of Message TFPGA
4 #define SPI_EOM_TFPGA 0xeb0a // End of Message TFPGA
5 #define BP_NOT_USED 0x0000 // Not used
6 [...]
7 #define SPI_READ_TRIGGER_NSTIMER_TFPGA 0x0700 //Command Word
8 [...]

```

Code 4.3 Extract of [Backplane](#) class header. Example of keyword.

Below is a simple example, where the function *Read_64_bit_nanosecond_time* implements the SPI command to request the number of triggers (32 bit) and the time of the last trigger in nanoseconds (64 bit).

```

1 bool Backplane::Read_64_bit_nanosecond_time(uint64_t& nstime,
2                                             uint32_t& triggers) {
3     uint16_t Message[11], Data[11];
4     Message[0] = SPI_SOM_TFPGA; //Start of Message
5     Message[1] = SPI_READ_nsTimer_TFPGA; //Command word
6     Message[2] = BP_NOT_USED;
7     Message[3] = BP_NOT_USED;
8     Message[4] = BP_NOT_USED;
9     Message[5] = BP_NOT_USED;
10    Message[6] = BP_NOT_USED;
11    Message[7] = BP_NOT_USED;
12    Message[8] = BP_NOT_USED;
13    Message[9] = BP_NOT_USED;
14    Message[10] = SPI_EOM_TFPGA; //End of Message
15    bool result = send_spi(Message, Data);
16    nstime = 0;
17    nstime = (((uint64_t)Data[2] << 48) | ((uint64_t)Data[3] << 32) |
18             ((uint64_t)Data[4] << 16) | ((uint64_t)Data[5]));
19    triggers = ((Data[6] << 16) | Data[7]) - 1; // TFPGA adds one extra
20                                                // on reset
21    return result;
22 }

```

Code 4.4 Example of the implementation of a method of the *Backplane* class.

In the example a *Message* of 11 words of 16 bits each is composed (lines from 4 to 14) and then passed to the function *send_spi* (line 15) which will send the command and copy in the second argument *Data* the reply from the Backplane. In this example the first word is *SPI_SOM_TFPGA* (line 4), so the command is meant for the TFPGA. The second word encodes the specific command (line 5). This specific command does not require additional parameters, so the rest of the message is just padded with a repeated unused word (lines from 6 to 13). The reply *Data* is also always 11 words of 16 bits, of which the first two and last one are echos of the command words. The data itself is contained in the eight words in between, encoded in a data structure that depends on the command issued. In the example above the 64 bits of time information from the last trigger are contained in the first four words of the data-carrying section (line 17, *Data*[2]→MSB, *Data*[5]→LSB). The counter for the trigger number has 32 bits, of which MSB are copied in *Data*[6] and the LSB in *Data*[7]. One count is subtracted, because the counter always starts from 1 after a reset signal to the TFPGA (line 19).

4.1.2 DACQController

This class implements the slow control—monitoring of the DACQ boards, and communications with the DACQ ARM micro-processor, through the server on each DACQ. This transport layer is provided by the external library ZeroMQ and carries the message between the `DACQController` and the server on the micro-processor. Another external library, google protobuf, was chosen for the message structure and data serialisation over the ZeroMQ sockets. These two libraries are open-source, robust, broadly used, very often in combination, and widely-supported by the community.

```

1 bool DACQController::SendAndReceive(Query& pQuery ,
2                                     Query_QueryType pType){
3     std::lock_guard<std::recursive_mutex> lock(fDACQMessageMutex);
4     if (!fRequestSocket.SendMessage(pQuery)) {
5         GERROR() << "Could not send message: " + pQuery.DebugString();
6         return false;
7     }
8     if (!fRequestSocket.ReceiveMessage(pQuery)) {
9         GERROR() << "Could not receive response for message: " +
10                pQuery.DebugString();
11         return false;
12     }
13     if (pQuery.type() == Query::ERR) {
14         GERROR() << "Error on DACQ board: " + pQuery.error().message();
15         return false;
16     }
17     assert(pQuery.type() == pType);
18     return true;
19 }

```

Code 4.5 Implementation of the *SendAndReceive* method of the `DACQController` class.

In Code 4.5 I report the implementation of the *SendAndReceive* method, which is the only one in the class that communicates to the server on the boards. The required multithread safety is provided by the private class member recursive mutex *fDACQMessageMutex* that prevents simultaneous asynchronous accesses. I chose this particular mutex because allows multiple locking inside recursive functions, avoiding deadlocks and preserving multi-thread safety, under the assumption that no function locking the mutex spawns a new thread. The use of *lock_guard* (line 3) ensures deadlock avoidance, because the mutex is released when the guarded lock is destroyed at the end of the function that created it. The `Query` class, passed as a parameter to the *SendAndReceive* method (Code 4.5, line 2) is auto-generated with google protobuf. My choice of the data type structure from the .proto file used to compile the `Query` class is shown in Code 4.6.

```

1 message SPIMessage {
2     repeated uint32 Data = 1;

```



```

3 }
4 message Query {
5     enum QueryType {
6         ERR = 1;
7         RTU = 2;
8         SLC = 3;
9         RRM = 4;
10        VLA = 5;
11        LED = 6;
12        SPI = 7;
13        RBT = 666;
14        ALV = 667;
15    }
16    required QueryType Type = 1;
17    optional ErrorMessage Error = 2;
18    optional RTU_Entries RtuEntries = 3;
19    optional SlowControlData SlowControl = 4;
20    optional MAC_Addresses MACs = 5;
21    optional VLAN_Entries VlanEntries = 6;
22    optional int32 LedMask = 7;
23    optional SPIMessage SpiMessage = 8;
24 }
25

```

Code 4.6 Extract of .proto file with the definition used to compile the `Query` and `SPIMessage` class with the google protobuf external library.

All functionalities of the `DACQController` are implemented by calling the `SendAndReceive` method, specifying a particular Query type to send the intended command or request the desired data. The different parameters for a specific command are passed with an optional type in the `Query` message (Code 4.6, line from 17 to 23). The server on the ARM micro-processor recognizes the type of command and acts appropriately. In Code 4.7 the SPI bridging functionalities of one of the DACQs are shown, with the Backplane side implemented by sending a `Query` with QueryType set to “SPI” (line 5) and the content of the SPI message in either direction set by the optional `SPIMessage` type (lines 6, 8).

```

1 bool DACQController::SendSpiCommand(const SPIMessage& pCommand,
2                                     SPIMessage& pReply) {
3     assert(pCommand.data_size() == 11u);
4     Query query;
5     query.set_type(Query::SPI);
6     query.mutable_spimessage()->CopyFrom(pCommand);
7     if (SendAndReceive(query, Query::SPI)) {
8         pReply.CopyFrom(query.spimessage());
9         return true;
10    } else
11        return false;

```

```
12 }
13
```

Code 4.7 Implementation of the *SendSpiCommand*.

4.1.3 TARGET

TargetDriver

For the low-level communication with the front-end electronics modules libCHEC is linked against an external library, TargetDriver, developed by the group and widely employed by the broader TARGET user community. The communications are implemented in the **TClient** class and use UDP packets sent over raw sockets. Two ASCII definition files (in the form of flat tables) are used to assign parameter values for each setting of the FPGA and the four ASICs. These parameters are: a name string, the bit position and length in the register and its address, a minimum, maximum and default value and, when appropriate, linear calibration parameters for conversion of the ADC count into physical units (for example Volt for applied pedestal bias). The **TargetModule** class inherits from the **TClient** class and then implements the three core functions that allow it to read and write a setting of the FPGA (Code 4.8, lines 3, 4) or ASICs (line 5), providing as parameters the name of the setting in the form of a string and the value to assign.

```
1 class TargetModule : public TClient {
2 public:
3     int WriteSetting(std::string name, uint32_t val);
4     int ReadSetting(std::string name, uint32_t& val);
5     int WriteASICSetting(std::string name, uint16_t asic, uint16_t val,
6                          bool individualASIC = false);
7 [...]
8 }
```

Code 4.8 Extract of the **TargetModule** class header of the TargetDriver library. Three main core functions are declared.

Calling the *Initialise()* method of the **TargetModule** class sets all the registers to the default values as specified in the definition files. The TargetDriver library has been designed to work with all the different TARGET module versions and relies on no external packages for ease of installation and use and to minimize the amount of future support required.

In the software architecture I designed, two separate executables handle the slow control/monitoring and the bulk raw data flow. Thus the firmware of the FEE was modified to have two settable port numbers for the respective functions. All modules send data to the port where the camera server is listening, while the control signals are necessarily kept on separate ports.

TargetModuleController

Each TARGET module needs different settings to match its unique characteristics, e.g. the precise high-voltage value to be supplied to the photosensor, and the trigger thresholds to equalize performance across the focal plane. TargetDriver itself does not have any awareness of the identity of each particular TARGET module, so a controller is needed to distribute configurations and commands to all the modules in an appropriate way. The `TargetModuleController` class I developed owns the pointer to an instance of a `TargetModule` for each module in the camera within `fTargetModuleMap` (Code 4.9, line 15). During the commissioning and testing phase, all 32 modules were not always used, or even physically present in the camera, so the construction and allocation in the map of the correct number of instances is performed in the `Config()` method (Code 4.10). The identity of the modules connected, and their unique configurations, are specified in a set of camera-level settings files as described in 4.1.4, which are passed at construction time to the `TargetModuleController` via the pointer `fCamera` (line 11). These parameters are then applied by the `Initialise` method (line 15), that can be called again at any point during execution, to reset all the module settings to default.

```

1 class TargetModuleController {
2
3 private:
4     typedef boost::shared_ptr<TargetDriver::TargetModule>
5                                     TargetModule_ptr;
6     typedef std::map<uint32_t, TargetModule_ptr> TargetModuleMap;
7     Camera_ptr fCamera;
8     TargetModuleMap fTargetModuleMap;
9
10 public:
11     TargetModuleController(const Camera_ptr& pCamera);
12     virtual ~TargetModuleController() {}
13
14     void Config();
15     bool Initialise(bool IsReset = false);
16     [...]
17 }
```

Code 4.9 Extract of the `TargetModuleController` class header.

```

1 void TargetModuleController::Config() {
2     std::lock_guard<std::recursive_mutex> lock(fTargetMutex);
3     //Loop on all the module expected to be in the camera
4     for (ModuleMap_cit module = fCamera->beginModule(),
5          modEnd = fCamera->endModule();
6          module != modEnd; ++module) {
7         //Instance of a T5 Module
```

```

8     TargetModule_ptr Module(new TargetDriver::TargetModule(
9         "TargetDriver/configFiles/TM5_FPGA_Firmware0xFEDA003D.def",
10        "TargetDriver/configFiles/TM5_ASIC.def", index));
11
12    //Attempt to establish comms with module
13    int stat = Module->EstablishSlowControlLink(
14        module->second->GetCameraControllerIpAddress(),
15        module->second->GetModuleIpAddress());
16
17    //If succesfull add pointer to the map of the controller
18    if (stat == TC_OK)
19        fTargetModuleMap.insert(
20            std::pair<uint32_t, TargetModule_ptr>(module->first, Module));
21    else
22        GERROR() << "Module: " << module->first << " "
23            << Module->ReturnCodeToString(stat);
24    }
25 }

```

Code 4.10 Implementation of the *Config()* method, from the *TargetModuleController* class source file.

The *TargetModuleController* class implements wrapper methods to set a common value to all the modules that are available (Code 4.11). This was often used during commissioning in the lab, for example during a run when one wants to measure the transfer function, the applied pedestal bias is increased for all the modules during the run (as described in sec. 2.3.1). The method *CheckSettingForAll* provides a direct way to check whether all the modules have the same expected value for a particular setting, and is often used to check if every single module is synced (a setting referring to a particular bit in the register; LSB of 0x17 for Target5 module version).

```

1  bool WriteSettingToAll(const char* setting, uint32_t value);
2  bool WriteASICSettingToAll(const char* setting, uint32_t value);
3  bool CheckSettingForAll(const char* setting, uint32_t value);

```

Code 4.11 Extract of the *TargetModuleController* class header. Example of method of the class.

Similarly to the case of the DACQ, to ensure multi-thread safety the access to the pointer of the *TargetModules* has to be protected with a mutex (Code 4.12, line 4). My choice of using recursive mutex and *lock_guard* are motivated by the same reason as stated in sec. 4.1.2. An example as used in the *TargetModuleController* class is shown in Code 4.12.

```

1  class TargetModuleController {
2
3  private:

```

```

4  std::recursive_mutex fTargetMutex;
5  }
6
7  bool TargetModuleController::WriteSettingToAll(const char *setting ,
8                                                  uint32_t value) {
9      GDEBUG() << "--> Writing Setting " << setting << " = " << value
10         << " to all TARGET modules";
11      std::lock_guard<std::recursive_mutex> lock(fTargetMutex);
12      fAllOK = true;
13      for (TargetModuleMap_it module = fTargetModuleMap.begin(),
14           end = fTargetModuleMap.end();
15           module != end; ++module) {
16          WriteSetting(module, setting, value);
17      }
18      return fAllOK;
19 }

```

Code 4.12 Implementation of the *WriteSettingToAll*, as an example on how thread-safety is ensured within the class.

4.1.4 Camera Settings

A complex software structure like the one provided by libCHEC needs a robust, easy and flexible way to store, load and parse configuration files with the settings for the many parameters in the system. In this section I provide details on the structure I chose for the camera settings as mentioned in other sections of this chapter. Configuration files are changed very often during commissioning, so they have to be flexible enough to allow quick modifications even from non-experts on the software architecture. The data structure has to be human readable, easy and quick to write, read to/from disk, parse and transmit between processes. For this task I chose google protobuf to implement configuration files because not only it satisfies all these requirements, but optional parameters can be added at will if the need arises at a later time, without concerns for full retro-compatibility. Code 4.13 is a non-complete extract from the .proto file to generate the necessary classes for the network configuration and some of the parameters configuration of the modules and the camera.

```

1  message ModuleConfig {
2      required uint32 Slot = 1;
3      optional Location Position = 2;
4      optional uint32 IPAddressSuffix = 3;
5      optional uint32 PhotosensorID = 4;
6      optional uint64 SerialNumber = 5;
7      optional string MACAddress = 6;
8      optional Board DACQ = 7;

```

```
9   optional Port Uplink = 8;
10  optional Port Downlink = 9;
11  repeated PixelConfig Pixels = 10;
12  repeated SuperPixelConfig SuperPixels = 11;
13 }
14
15 message UplinkConfig {
16   required Port Uplink = 1;
17   optional Interface Network = 2;
18   optional Vlan Vlan = 3;
19   optional uint32 Subnet = 4;
20   optional uint32 IPAddressSuffix = 5;
21   optional string PortMACAddress = 6;
22   optional string InterfaceMACAddress = 7;
23 }
24
25 message BoardConfig {
26   required Board DACQ = 1;
27   optional uint32 RequestSocket = 2;
28   optional uint32 PublishSocket = 3;
29   optional uint32 ThreadSocket = 4;
30   repeated UplinkConfig Uplinks = 5;
31 }
32
33 message SuperPixelSetting {
34   required uint32 index = 1;
35   optional uint32 Threshold = 2;
36 }
37
38 message TargetSettings {
39   required uint32 Slot = 1;
40   optional uint32 HV = 2;
41   optional uint32 PmRefIntercept1 = 3;
42   optional uint32 PmRefCoeff1 = 4;
43   optional uint32 PmRefIntercept2 = 5;
44   optional uint32 PmRefCoeff2 = 6;
45   repeated SuperPixelSetting SuperPixel = 7;
46 }
47
48 message CameraSettings {
49   optional uint32 WaveformsPerPacket = 1;
50   optional uint32 WaveformBlocks = 2;
51   optional uint32 TriggerDelay = 3;
52   optional uint32 BufferSize = 4;
53   optional float BuildTimeout = 5;
54   optional float WatcherSleep = 6;
```

```
55 repeated TargetSettings TargetSettings = 7;  
56 }
```

Code 4.13 Extract of the .proto file to generate the necessary classes for Settings with google protobuf.

In Code 4.14 I give example extracts from the files containing the necessary information to set the network configuration for the camera. (Only one DACQ board and the two TARGET modules in slot number 1 and 0 are shown). Typically the first operation of any process is to read these files and propagate the information to the highest level controllers that will disseminate the settings to the nested lower level classes. The structure of the settings as a message allows for easy propagation to other processes as well when necessary.

```
1 Version: CHEC_M  
2 FEEType: TARGET_5  
3 PSType: MAPM  
4 IPAddressPrefix: "192.168"  
5 CameraServerIPSuffix: 1  
6 CameraControllerIPSuffix: 1  
7 Boards {  
8   DACQ: DACQ2  
9   RequestSocket: 5557  
10  PublishSocket: 5558  
11  ThreadSocket: 2  
12  Uplinks {  
13    Uplink: wr0  
14    Network: eth3  
15    Subnet: 12  
16    Vlan: Vlan1  
17    IPAddressSuffix: 2  
18    PortMACAddress: "02:34:56:78:9E:00"  
19    InterfaceMACAddress: "68:05:CA:26:39:04"  
20  }  
21  Uplinks {  
22    Uplink: wr1  
23    Network: eth4  
24    Subnet: 13  
25    Vlan: Vlan2  
26    IPAddressSuffix: 2  
27    PortMACAddress: "02:34:56:78:9E:01"  
28    InterfaceMACAddress: "68:05:CA:26:39:05"  
29  }  
30 }  
31  
32 Modules {  
33   Slot: 0  
34   IPAddressSuffix: 48
```



```

35   SerialNumber: 0
36   MACAddress: "08:00:56:00:03:30"
37   DACQ: DACQ2
38   Uplink: wr1
39   Downlink: wr17
40 }
41 Modules {
42   Slot: 1
43   IPAddressSuffix: 135
44   SerialNumber: 0
45   MACAddress: "08:00:56:00:03:87"
46   DACQ: DACQ2
47   Uplink: wr1
48   Downlink: wr13
49 }

```

Code 4.14 Extract of one of the configuration files to provide example of their structure.

4.1.5 MonitorItem

Similarly for the slow control we require a flexible, human readable and homogenous way to arrange and present the data from many different devices, each with its own native data structure. For slow control we do have to possibility of saving files in binary format to save space, but reading and parsing of the files still has to be quick and easy. The data has to be able to be serialised and passed easily to other threads, processes or even other machine on the same network. Again I chose google protobuf which provides all the necessary functionality required for this task. The `MonitorItem` class is automatically generated from the .proto file reported in Code 4.15, where all the monitor field types are specified.

```

1 message LastValue {
2   required string LastValue = 1;
3   required LastValueType LastValueType = 2;
4 }
5
6 message SubDevice {
7   required string SubDeviceType = 1;
8   required uint32 SubDeviceID = 2;
9 }
10
11 message MonitorItem {
12   required Device Device = 1;
13   required Parameter Parameter = 2;
14   optional SubDevice SubDevice = 3;
15   optional LastValue LastValue = 5;
16   optional TimeStamp TimeStamp = 8;

```

```

17 optional uint32 ErrCode = 9;
18 }

```

Code 4.15 Extract of the .proto file for generation of the `MonitorItem` class that specify its structure.

A `MonitorItem` always refers to a specific Device (enum, line 12) and Parameter (enum, line 13). The hierarchy of the device may require that subdevices are specified by type and ID (lines 14, 14), as in the case of TARGET where each module is seen as a SubDevice of the `TargetModuleController` with the Slot number as its identifier. A `MonitorItem` usually carries the last known value (lines 1, 15), which is saved as a string and properly converted, when necessary using the information of the original type (line 3). For example, the temperature read from a sensor would be double, while the status of some components might be better expressed by a bool. A timestamp from the CPU clock in seconds and nanoseconds (C++11 chrono precise clocks) is left as an optional field (line 16). An error code can be added if appropriate (line 17).

Every device produces its own data structure following the appropriate hierarchy, which has to be converted to the common `MonitorItem` format in the respective controller class. In Code 4.16 I report how this is done for the front electronics modules in `TargetModuleController`. I chose this specific case as an example because it is compact and easy to read due to the TARGET module data structure of the setting. This allows any parameter value to be read via a common function (sec. 4.1.3), which just uses a map between a name string and a parameter enum (Code 4.16, line 24).

```

1 void TargetModuleController::Monitor(CameraMonitor &MonitorArray ,
2                                     enum QueryParameter QueryParameter) {
3     // For multi-thread safety
4     std::lock_guard<std::recursive_mutex> lock(fTargetMutex);
5
6     //Loop on all the Target Modules
7     for (TargetModuleMap_cit module = fTargetModuleMap.begin(),
8          modEnd = fTargetModuleMap.end();
9          module != modEnd; ++module) {
10
11         float val;
12         std::string value_string;
13
14         // Loop on all the parameter associated with query
15         for (unsigned int i = 0; i < kQueryToParameterMap[QueryParameter]
16              .size(); ++i) {
17
18             //Creation of an instance of a MonitorItem,
19             //and the relevant fields are assigned
20             MonitorItem monitoritem;
21             monitoritem.set_device(Device::TM);

```

```

22     monitoritem.set_parameter(kQueryToParameterMap[QueryParameter]
23     .at(i));
24     monitoritem.set_errcode(module->second->ReadSettingCalibrated(
25         kParameterToSetting[kQueryToParameterMap[QueryParameter]
26         .at(i)], val));
27     std::stringstream Value;
28     Value << std::setprecision(4) << val;
29     if (kQueryToTypeMap[QueryParameter] != LASTVALUE_STRING)
30         CTA::SST::CHEC::Util::FillLastValue(*monitoritem
31             .mutable_lastvalue(), Value.str(),
32             kQueryToTypeMap[QueryParameter]);
33     else
34         CTA::SST::CHEC::Util::FillLastValue(*monitoritem
35             .mutable_lastvalue(), value_string,
36             LastValueType::LASTVALUE_STRING);
37
38     //Each Module Slot is seen as a SubDevice of the
39     //TargetModuleController.
40     CTA::SST::CHEC::Util::FillSubDevice(*monitoritem
41         .mutable_subdevice(),
42         "Slot: ", (module->first));
43
44     //MonitorItem timestamped
45     Time::GetUnixTimeStamp().FillTimeStamp(
46         *monitoritem.mutable_timestamp());
47
48     //The information contained in the new MonitorItem are copied
49     //in the MonitorArray passed by reference
50     MonitorItem *monit = MonitorArray.add_monitoritem();
51     monit->CopyFrom(monitoritem);
52 }
53 }
54 }

```

Code 4.16 Implementantion of the `TargetMonitorController Monitor()` method, as example on how the different component controllers compose a `MonitorItem` based on their native data structure.

Every time a parameter of any of the devices is read, and a `MonitorItem` is created, it's checked against a set of automated reactions taken from a human-readable and easy-to-edit file. Once more I chose google protobuf to implement the `Reaction` class (Code 4.17).

```

1 enum ReactionToTrigger {
2     DECREASE_TEMPERATURE = 0;
3     SHUT_DOWN = 1;
4     POWER_DOWN_MODULE = 2;
5     POWER_CYCLE_DACQ=3;

```

```

6 [...]
7 }
8 enum Condition {
9     MORE_THAN = 0;
10    LESS_THAN = 1;
11    EQUAL = 2;
12    DIFFERENT = 3;
13 }
14 message Reaction {
15     required Condition Condition = 1;
16     required LastValue LastValue = 2;
17     optional LogSeverity LogSeverity = 3 [default = INFO];
18     optional ReactionToTrigger ReactionToTrigger = 4;
19     repeated Parameter Parameter = 5;
20 }

```

Code 4.17 Extract of the .proto file for generation of the **Reaction** class that specify its structure.

Every reaction contains a reference value (Code 4.17, line 16) and details of how it should be compared (lines 8, 15) with a **MonitorItem**; specifically, which Parameters should be referred to (line 19). Optionally a different LogSeverity than the conservative default INFO (line 17) can be specified, and a specific reaction function mapped with a ReactionToTrigger enum (line 18). The high-level handling of the generic **MonitorItems** and **Reactions** for all the camera components are under the **CHECController** class, more details of which are given in sec. 4.1.7.

4.1.6 CameraServer

The **CameraServer** class is the basic object for the continuously-running server process, which acts on commands received from a second process that is in charge of the control of the camera. The latter process hosts a **CHECController** instance. When requested, **CameraServer** starts listening on a specific data port for UDP packets from the front-end electronics, builds the events and saves them to a FITS file. The idea of keeping the two processes separate derives from the difference in importance of their functions. While an unexpected behaviour of the server could result in corrupted data, a malfunctioning of the camera controller could severely affect the safety of the system itself. By keeping the server on another process, its influence on the camera survivability is kept to a minimum.

```

1 class CameraServer {
2
3     private:
4         DataListener* fListener;
5         EventFileWriter* fWriter;
6         Buffer* fBuffer;

```

```

7
8  bool Init (RunConfigMessage& pConfig);
9  void StartRun (RunConfigMessage& pConfig);
10 void StopRun ();
11 void KillThreads ();
12 void FillStatistics (RunConfigMessage& pMessage);
13
14 public:
15  void RemoteControl ();
16 }

```

Code 4.18 Extract of the `CameraServer` header with definition of the most relevant class methods.

The `DataListener` (Code 4.18, line 4) is a class specifically developed for receiving UDP packets from the bulk data stream of TARGET modules, therefore it naturally inherits from the base class `TClient` from the TargetDriver library (see sec. 4.1.3), which uses raw sockets comms. Data are queued in a ring buffer (line 6) where a set of three indexes point to the positions in the buffer for (i) the next event to be read from the buffer and written to disk, (ii) the last event being built and (iii) the next available slot to start building a new event. Obviously the last index will never go past the first, and hence events do not get dropped and overwritten. The buffer depth and computing power of an off-the-shelf PC equipped with an solid-state hard drive (greater read/write speed than conventional HDD) proved to be sufficient to meet the requirements on the CTA goal data rate for the SSTs. The number of UDP packets per built event can be changed and is specified in the camera-level settings. The `EventFileWriter` (line 5) is used to save data to a FITS file with an appropriate header that includes all the settings for the run. The camera server is one key component for the commissioning of the camera and the gathering of the data necessary for performance analysis, but in the near future every camera in CTA will use the same data acquisition process to stream data to the common CTA pipeline. This will be provided by the CTA central DAQ working group.

```

1 void CameraServer::RemoteControl() {
2
3  //Establish connection to a process running a CHECController instance
4  zmq::context_t context(1);
5  ZMQ::Socket REP(context, ZMQ::mReply);
6  REP.AddConnection(
7      ZMQ::GetTcpSocketConnection(ZMQ::tBind, "*", SERVERPORT, -1, -1));
8  if (!REP.Connect()) {
9      GERROR() << "Could not bind reply socket";
10     return;
11 }
12
13 //Loop waiting for commands

```

```
14 while (true) {
15     RunConfigMessage m;
16     if (!REP.ReceiveMessage(m))
17         GERROR() << "Failed to receive request" << std::endl;
18
19     //Acknowledge the command
20     RunConfigMessage Acknowledgement;
21     Acknowledgement.set_messagetype(ACKNOWLEDGE);
22     std::cout << "CameraServer message received: "
23         << RunControlMessageType_Name(m.messagetype())
24         << std::endl;
25
26     //Parse the message and execute the appropriate instruction
27     switch (m.messagetype()) {
28         case INIT:
29             if (fInitialised) KillThreads();
30             Init(m);
31             break;
32         case RUNSTART:
33             StartRun(m);
34             break;
35         case RUNSTOP:
36             StopRun();
37             break;
38         case STATISTICS:
39             if (fInitialised)
40                 FillStatistics(Acknowledgement);
41             else
42                 cout
43                     << " You tried to FillStatistics when the CS wasn't
44                     initialised"<< endl;
45             break;
46         case RESET:
47             KillThreads();
48             break;
49         case TERMINATE:
50             KillThreads();
51             return;
52         default:
53             break;
54     }
55     if (!REP.SendMessage(Acknowledgement))
56         GERROR() << "Failed to send reply" << std::endl;
57 }
```

58 }

Code 4.19 Implementation of the entry point to a `CameraServer` object, the *RemoteControl* method.

The standard entry point to the `CameraServer` class is the method *RemoteControl()* (Code 4.19), that establishes a connection to a process hosting a `CHECController` and waits for commands. In this way a single `CameraServer` object can be left always running and it will be handled, like another physical device, by the main camera controller. I chose to implement the inter-process communications with the external library ZeroMQ because it provides a set of robust and easy-to-use sockets based on a wide choice of different communication patterns. Here I used a non-blocking version of the request-reply pattern. After proper initialisation of the socket and establishing connection (line 8), the `CameraServer` will always wait for Request (line 16), then send a reply to acknowledge the command (line 21). The process sending the request won't be blocked by a missed reply, so in case of camera server failure it will wait only a limited small amount of time and report the missing connection with the server. All the necessary network information to establish this connection is contained in a common configuration file accessed in a fashion described in sec. 4.1.4, and the `RunConfigMessages`, once exchanged, are serialised with google protobuf. The messages sent from the controller include all the necessary information and parameters needed by the `CameraServer`, like run number, other header information, desired buffer size to be allocated, etc.

4.1.7 CHECController

I developed the `CHECController` class to be the heart of the software library operating the camera. This section presents a detailed description of all the major features of the class.

```

1 class CHECController {
2
3     private:
4         // Controller of the TARGET modules.
5         TargetModuleController fTargetModuleController;
6
7         // Controller of the DACQ boards.
8         DACQBoardController fDACQBoardController;
9
10        // Controller of the Backplane
11        typedef std::shared_ptr<Backplane> BackplanePtr;
12        BackplanePtr fBackplaneController;
13
14    public:
15
16        CHECController(const Camera_ptr& pCamera);

```



```

17  virtual ~CHECController();
18  // Load the configuration for software / hardware
19  void Config();
20  // Control power distribution to the Target modules
21  void PowerONModules();
22  void PowerOFFModules();
23  // Initialise the hardware with the configuration previously loaded
24  void Init_Hardware();
25  // Reset SYNC, Send SYNC,
26  // if failed repeat with different SYNC start time
27  bool SYNC();
28  // Start/Stop a new Run
29  void StartRun(int run_num, std::map<std::string, std::string>
30                runParams);
31  void StopRun();
32  // Preparing for a clean exit, proper de-allocation, thread joining
33  void Stop(bool ResetTM =true);
34 }

```

Code 4.20 Extract from the **CHECController** class header with the definition of few of the main methods.

A **CHECController** owns a pointer to a **TargetModuleController** (Code 4.20, line 5, see also sec. 4.1.3), a **DACQBoardController** (line 8, see also sec. 4.1.2) and a **Backplane** (line 12, see also sec. 4.1.1). These pointers are allocated during the execution of the *Config()* method (Code 4.20, line 19). All the necessary configurations are propagated with *Init_Hardware()* (line 24) to the lower-level controllers and drivers from a pointer to a set of settings as described in sec. 4.1.4. The controller of the camera is also in charge of communicating with the process that hosts the **CameraServer** listening for data.

```

1  zmq::context_t fContext;
2  ZMQ::Socket fRequest;
3
4  bool CS_Init();
5  bool CS_StartRun(const RunHeader& pHeader, bool IsData,
6                  bool IsTransferFunction, bool IsPedRun,
7                  bool IsDynamicRun, std::string CommandLine,
8                  std::string AdditionalSettings);
9  bool CS_StopRun();
10 bool CS_Stop();
11 bool CS_GetStatistics(CameraServerStatistics& pStatistics);
12 void CS_Monitor(CameraMonitor& MonitorArray);

```

Code 4.21 Extract from the **CHECController** class header with the definition of the methods implementing the possible commands to the camera server.

For each feature of the `CameraServer`, I wrote a corresponding method to invoke the necessary commands (Code 4.21). Some, like `CS_StartRun` (line 5), may have parameters that are built into the message sent over to the server. As mentioned in sec.4.1.6 the inter-process comms are implemented over a request-reply pattern with ZeroMQ. The `CHECController` side acts as the request party and waits only a limited amount of time for the reply, thus avoiding blocking situations in this safety-relevant process. The `CameraServer` is seen as another component and its health is monitored in a similar way. The necessary information and statistics, like number of events built and the status of the server, are pulled with the `CS_Monitor()` method (line 12).

```

1  QueryCameraMonitor fQueryCameraMonitor;
2  CameraReactions fReactions;
3
4  // Monitoring thread
5  virtual void Monitor();
6  void LaunchMonitor();
7
8  CameraMonitor MonitorAnItem(enum Device Device,
9                             enum QueryParameter QueryParameter,
10                             bool IsVerbose = false);

```

Code 4.22 Extract from the `CHECController` class header with the definition of the methods implementing the slow control monitoring thread.

One of the most important functions of the controller is to ensure the health of the camera by monitoring for any deviation from standard behaviour. A thread is dedicated to the sole purpose of checking the relevant parameters. These are specified in a configuration file and copied at the beginning of the process execution in `fQueryCameraMonitor` (Code 4.22, line 1). This class member contains information on each parameter of each device that has to be checked and the frequency at which this has to be done (see sec. 4.1.5). The `Monitor` thread continuously calls the method `MonitorAnItem` (see Code 4.24) at the requested frequency.

```

1  std::recursive_mutex fMonitorFileWriterMutex;
2  MonitorFileWriter fMonitorFileWriter;
3  ZMQ::Socket fPublish;
4
5  CameraMonitor CHECController::QueryAnItem(
6  enum Device Device, enum QueryParameter QueryParameter,
7                                     bool IsVerbose) {
8  CameraMonitor MonitoItemArray;
9
10 switch (Device) {
11     case TM:
12         fTargetModuleController.Monitor(MonitoItemArray, QueryParameter);
13     break;

```

```

14     case BP:
15         fBackplaneController->Monitor(MonitoItemArray, QueryParameter);
16         break;
17     case CS:
18         CS_Monitor(MonitoItemArray);
19         break;
20     [...]
21     default:
22         GERROR() << "Non valid Device: " << Device_Name(Device);
23     }
24
25     if (IsVerbose) std::cout << MonitoItemArray.DebugString()
26                     << std::endl;
27
28     std::lock_guard<std::recursive_mutex> lock(fMonitorFileWriterMutex);
29     if (MonitoItemArray.monitoritem_size() != 0) {
30         fPublish.SendMessage(MonitoItemArray);
31
32         for (int i = 0; i < MonitoItemArray.monitoritem_size(); ++i)
33             fMonitorFileWriter.Write(MonitoItemArray.monitoritem(i));
34     }
35     return MonitoItemArray;
36 }

```

Code 4.23 Implementation of the *QueryAnItem* class method, also extract from the **CHEC-Controller** class header with the definition of few private class members.

Each time a parameter of a component is monitored, the *QueryAnItem* method (Code 4.23) calls the Device specific method to read the values related to the query (line 10) and return an array of **MonitorItem** filled with the relevant slow control data (line 35). For example, when *Q_TM_TEMPERATURE* is queried, the method

```

1 fTargetModuleController.Monitor(MonitoItemArray, Q_TM_TEMPERATURE);

```

is called, and *QueryAnItem* returns the **MonitorItemArray**, which is twice size of the number of **TARGET** modules, each contributing with two on-board temperature sensors. This function also saves the **MonitorItems** (line 33) as a binary file on disk, and, if specifically requested, prints it to the screen (line 26). Because different threads could try to write to the same file simultaneously, I added a mutex for multi-thread safety (line 28). Another feature of the method is to publish all the slow control data (line 30) on a ZeroMQ socket, other processes, possibly even running on another machine, receive the queried data and report alerts or plot relevant information in real time (for an example see sec.4.2.2).

```

1     std::vector<unsigned int> CheckForReactions(CameraMonitor CM);
2     void React(MonitorItem M);
3
4 CameraMonitor CHECController::MonitorAnItem(

```

```

5     enum Device Device, enum QueryParameter QueryParameter,
6     bool IsVerbose, std::map<std::size_t, Strings>* pToFillTable) {
7     CameraMonitor CM;
8     std::vector<unsigned int> index;
9     CM = QueryAnItem(Device, QueryParameter, IsVerbose, pToFillTable);
10    if (CM.monitoritem_size() != 0) {
11        index = CheckForReactions(CM);
12        if (index.size() != 0) {
13            sleep(1);
14            CM = QueryAnItem(Device, QueryParameter, IsVerbose, pToFillTable);
15        }
16        for (unsigned int i = 0; i < index.size(); ++i)
17            React(CM.monitoritem(index.at(i)));
18    }
19    return CM;
20 }

```

Code 4.24 Implementation of the *MonitorAnItem* class method, also extract from the *CHECController* class header with the definition of the private class methods *CheckForReactions* and *React*.

After the slow control data is retrieved by *QueryAnItem* and is available inside *MonitorAnItem* (Code 4.24, line 9), it is compared using *CheckForReactions* with a set of *Reactions* (line 11, see also sec. 4.1.5) loaded from a configuration file at controller construction time. One or more abnormal parameter readings can trigger an automated response in order to ensure the camera health. If such a trigger occurs, the relevant parameters are monitored once more after one second (line 14) to double-check against a faulty read. If the second readings are consistent with the first, then the appropriate reactions are carried out with *React* (line 17).

Example Simple configuration file for *MonitorItems* to be followed up and relative *Reactions*.

```

1 QueryMonitorItem {
2     Device:TM
3     QueryParameter:Q_TM_TEMPERATURE
4     UpdateInterval:2
5 }
6 QueryMonitorItem {
7     Device:BP
8     QueryParameter:Q_BP_TRIGGER
9     UpdateInterval:10

```

10 }

Code 4.25 Simple example of a configuration file for the monitoring of two parameters, the temperature of the target modules every 2 seconds and the number of triggers every 10 seconds.

```

1 Reaction {
2   Condition: MORE_THAN
3   LastValue: {
4     LastValue : "40"
5     LastValueType: LASTVALUE_DOUBLE
6   }
7   LogSeverity: ERROR
8   Parameter: TM_TEMPERATURE_ADC_0
9   Parameter: TM_TEMPERATURE_ADC_1
10  ReactionToTrigger: POWER_DOWN_MODULE
11 }
12 Reaction {
13   Condition: DIFFERENT_THAN
14   LastValue: {
15     LastValue : "true"
16     LastValueType: LASTVALUE_BOOL
17   }
18   LogSeverity: ERROR
19   Parameter: DQ_STATUS
20   ReactionToTrigger: POWER_CYCLE_DACQ
21 }
```

Code 4.26 Simple example of a configuration file for the reactions on few abnormal situations.

In this very simple example, *MonitorAnItem* calls every 10 seconds to monitor the number of triggers and the timestamp of the last one, issued by the Backplane:

```
1 CameraMonitor CM=QueryAnItem(BP,Q_BP_TRIGGER);
```

And here, calls every two seconds to monitor the temperature sensors of the TARGET modules:

```
1 CameraMonitor CM=QueryAnItem(TM,Q_TM_TEMPERATURE);
```

Let us assume that, during one of these checks, all but one of the TARGET modules have temperatures between 28°C and 35°C, and one faulty module reports a temperature of 42°C. When the slow control data are compared against the chosen `textcolorForestGreenReactions`

```
1 std::vector<unsigned int> index = CheckForReactions(CM);
```

the temperature is found to be outside bounds by the first `Reaction` in the list (> 40 degree, Code 4.26, line 4). The indexes of the abnormal parameters in the CM array are

stored in the *index* vector. After one second those, and only those to avoid unnecessary overhead, are queried again. Suppose the sensor on the module has shifted a little and now is 43°C. Still this value is out of range, so the function associated with the reaction *POWER_DOWN_MODULE* (line 10) will be called. As the name clearly suggests, the power to the relevant module will be cut to prevent any damage to the electronics. During this process ERROR (line 7) information is displayed, saved into the slow control data file, and published on the ZeroMQ socket.

4.2 High Level processes

The classes of the library libCHEC described in this chapter provide all the essential building blocks to operate the camera in a very flexible, but yet robust, way. Many are the options I offered and explored by the team during the commissioning and performance evaluation of the camera. Here I present a minimal, but complete solution of three processes that running at the same time provide all the necessary functions to allow an user with only a minimum training to operate the camera as a stand-alone object (no interfaces with the telescope structure or the rest of the array, see sec. 7.1.3).

4.2.1 Camera Server

The camera server process serves the purpose of gathering the bulk raw data, building the events and saving them on disk. It hosts a *CameraServer* object (and optionally a *Logger*) and doesn't need to be launched multiple times for each new run, but it will instead be kept always running and waiting for commands from the camera controller process.

```
1 int main(int, char* []) {  
2     std::string logname("exampleServer.log");  
3     GetLogger().SwitchFile(logname);  
4     GetLogger().SetFilterLevel(sInfo);  
5  
6     CameraServer server;  
7     server.RemoteControl();  
8     return 0;  
9 }
```

Code 4.27 Camera server process.

When necessary, between runs, it will be asked to reset in the same way. The *RemotControl()* is the only function requested here and was explained in details in sec. 4.1.6.

4.2.2 Real Time Monitor

A very useful feature provided by the monitoring scheme I implemented is that other processes (as many as desired) can subscribe to a specific port on the network where every slow control data is published. During operation is very important for the user to be presented with the relevant information for the camera health in real time. Different users can be interested in different parameters, in Code 4.28 I describe, as reference, only one of the many possible way to exploit this very powerful system.

```

1  std::atomic_bool Continue;
2  void CheckContinue() {
3      std::cout << " Press any key to exit" << std::endl;
4      char a;
5      std::cin >> a;
6      Continue = false;}
7
8  int main(int argc, char* argv[]) {
9      //Subscribe to the port where the slow control data is published
10     zmq::context_t context(1);
11     ZMQ::Socket Subscriber(context, ZMQ::mSubscribe);
12     Subscriber.AddConnection(
13         ZMQ::GetTcpSocketConnection(ZMQ::tConnect, "127.0.0.1",
14                                     MITEM_PORT));
15     if (!Subscriber.Connect()) std::cout << "Can't connect the subscriber
16                                     socket";
17
18     // Plotting, canvas set up
19     TApplication* application =
20         new TApplication("RealTimeMonitorPlotter", &argc, argv);
21     TCanvas* c = new TCanvas("RTM", "RTM", 1000, 1000);
22     c->Divide(2, 1);
23
24     // Graph object holding the number of trigger over time
25     TGraph* grBP_Trigger = new TGraph();
26     // Array of graph objects holding the temperature values of each
27     // TARGET
28     std::vector<TGraph*> grTM_Temp;
29     for(int i=0; i<32; ++i){
30         TGraph* g = new TGraph();
31         grTM_Temp.push_back(g);}
32
33     // Drawing of an empty graph, will be later kept update with new data
34     c->cd(1);
35     grBP_Trigger->Draw("AP");
36     c->cd(2);
37     grTM_Temp[0]->Draw("AP");

```



```

38  for(int i=1;i<32;++i)
39      grTM_Temp[0]—>Draw( "SAMEP" );
40
41  double time_0=Time::GetUnixTimeStamp().GetSeconds();
42
43      std::thread ChkCont(CheckContinue);
44      Continue = true;
45      while (Continue) {
46          CameraMonitor CM;
47          Subscriber.ReceiveMessage(CM);
48
49          for (int i = 0; i < CM.monitoritem_size(); ++i) {
50              MonitorItem M = CM.monitoritem(i);
51              double time = M.timestamp().seconds() - time_0;
52              double val;
53              if (M.lastvalue() ==LASTVALUE_DOUBLE)
54                  val = std::stod(M.lastvalue().lastvalue());
55
56              // TARGET MODULE TEMP
57              if ((M.parameter() == TM_TEMPERATURE_ADC_0)||
58                  (M.parameter() == TM_TEMPERATURE_ADC_1)){
59                  int TM_Slot = M.subdevice().subdeviceid();
60                  grTM_Temp.at(TM_Slot)—>SetPoint(grTM_Temp.at(TM_Slot)—>
61                      GetN(), time / 60, val);}
62
63              if (M.parameter() == BP_TRIGGER_COUNT)
64                  grBP_Trigger—>SetPoint(grBP_Trigger—>GetN(), time / 60,
65                      val);
66          }
67
68          // Plot update
69          c—>cd(1)—>Modified();
70          c—>cd(1)—>Update();
71          c—>cd(2)—>Modified();
72          c—>cd(2)—>Update();
73  }
74  application—>Run();
75  ChkCont.join();
76  return 0;
77  }

```

Code 4.28 Minimal example of a real time monitor process to plot the temperature of the modules and the number of trigger over time as they get monitored in the camera controller process.

In this simple example a minimal usage of the ROOT external library has been adopted for plotting (lines from 19 to 39). More elaborate styles can be implemented, or even

a completely different external library can be chosen to carry out the same purpose, but the core of the process remains the same. This is where I want to focus the attention in this section. At the start of the process a ZeroMQ socket is created and subscribed to the port where the slow control data is expected to be published (line 10). *time_0* is taken as starting reference point in time (line 41). The core of the process is in the while loop starting from line 45 that can be interrupted by a key press in an auxiliary thread spawned at line 43. The process waits until it receives any slow control data (line 47). The message is in the form of an array of **MonitorItems**, that can be analysed one by one (line 49). Each message contains a timestamp that is used to determine the elapsed time since the definition of *time_0* (line 51). This process can be used to plot the value of all the data over time in a different plot, but in this very simple example I choose, for code readability, to focus only on the temperature of the TARGET modules and the number of trigger time series. The **MonitorItem** is parsed and if it contains information on module temperature (lines 57 or trigger count 63) the process updates the content of the relevant graphs. This example can be easily expanded to include any other slow control data. A set the team found very useful and used during commissioning extends this very simple script to the temperature of the DACQ boards and a colour-coded representation of the focal plane of the last recorded temperature of the TARGET modules. Thanks to the ZeroMQ publisher-subscriber pattern many different similar processes focusing on different set of parameters or with plotting style can run at the same time and all listen for the same data.

4.2.3 Camera Controller

In this section I make a minimal, but complete example on how the **CHECController** class is meant to be used in high level scripts, giving an idea on how all the element explained in this chapter come together to form the heart of the software control of the camera.

```

1 int main(int argc , char* argv[]) {
2     // Load Camera Configuration
3     Camera_ptr camera =
4         GetCameraPtr( options . GetCameraVersion() , options
5                       . GetModuleFileSuffix() ,
6                       options
7                       . GetSettingsFileSuffix() );
8
9     // INSTANCE OF CAMERA CONTROLLER
10    CHECController CameraController( camera );
11
12    // Logger initialisation
13    std::string logname( "example.log" );
14    GetLogger(). SwitchFile( logname );
15    GetLogger(). SetFilterLevel( sInfo );

```

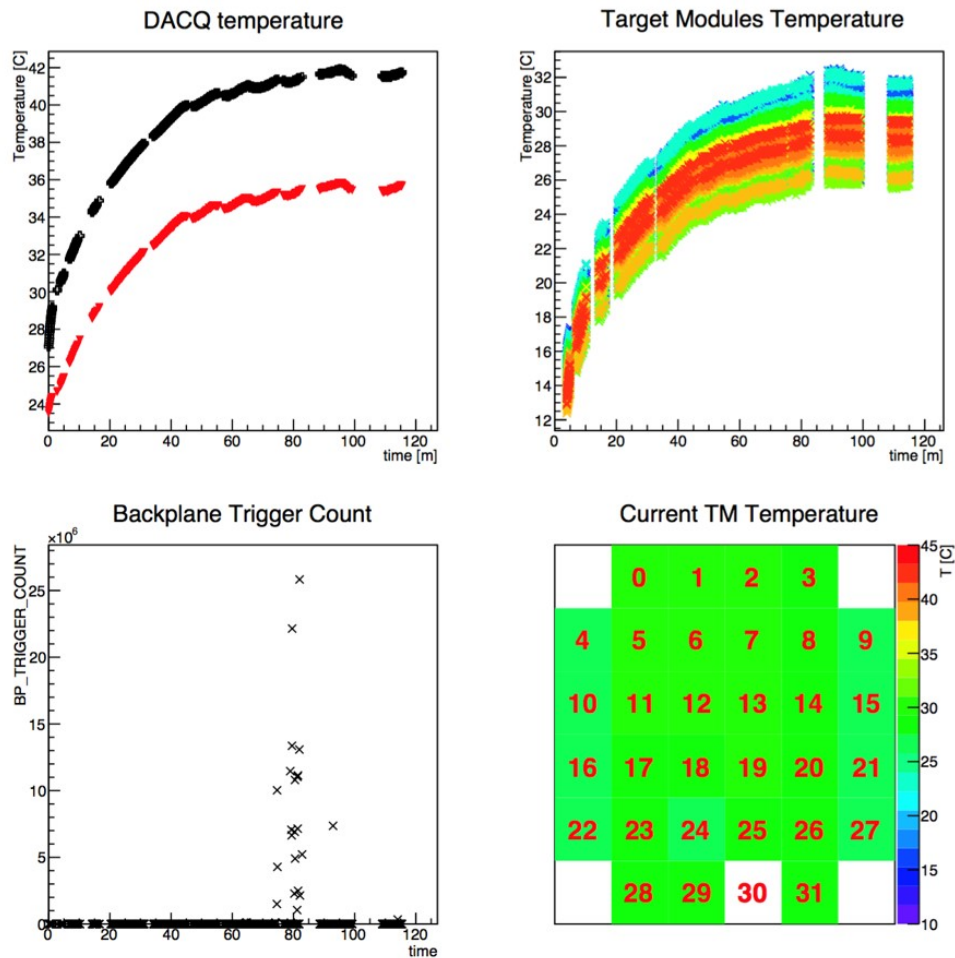


Fig. 4.2 Example of a real time monitoring of some of the most important data for slow control of the camera. Upper panel shows the temperature of the 2 DACQs (*left*) and the TARGET modules (*right*), lower left panel show the trigger count from the backplane, lower right panel shows a color-coded diagram of the focal plane of the camera with the average temperature of the modules .

```

16
17 // Configuration of the controllers
18 CameraController.Config();
19
20 //Module power up
21 CameraController.PowerONModules();
22
23 // INIT CAMERA CONTROLLER
24 CameraController.Init_Hardware();
25
26 // Start Monitoring thread
27 CameraController.LaunchMonitor();
28
29 //Start a Run lasting approx 5 min
30 std::map<std::string, std::string> runParams;
31 runParams["DESCRIPTION"] = "5 min example Run";
32 runParams["RUN_MODE"] = "DATA";
33 int runNum = 1;
34 CameraController.StartRun(runNum, runParams);
35 sleep(5* 60);
36 CameraController.StopRun();
37
38 //Reset status of camera and exit
39 CameraController.Stop();
40
41 return 0;
42 }

```

Code 4.29 Minimal example of a camera controller process. After all the necessary configurations and initialisations a single run of data taking lasting 5 minutes is performed, then the process exits.

All the necessary configuration settings are read from a set of files (line 3) and passed as the only parameter to the `CHECController` object (line 10). The global logger is set to save to the file *"example.log"* the message of level Info or greater (line 13). The method *Config()* (line 18) allocate all the resources needed for the lower level controllers and pass them the required configuration and establish connections with the entry point of the camera comms, the DACQ. At this time, the TARGET modules still do not have power, which gets distributed by the Backplane and enabled in a controlled sequence with the instruction in line 21. In line 24 all the components in the camera get ready to acquire data. The monitoring thread is spawned in line 27. When starting a new run (line 34) it is possible to add few optional parameters like a brief description, or request a specific run mode (DATA, CALIBRATION, etc.). In this example a single run of approximately 5 minutes is performed, then the camera returns to an idle state (line 36) and the software exits (line 39). It is unusual to operate the camera in this way, without any interaction

with the user. No choice is presented for when to start/stop a run or to run multiple ones. Often the way the camera is operated is to run automatically a scheduled list of runs with possibly different purposes (calibration, measurement of transfer function of front end digitization electronics, etc.). Also, the information printed on screen here is minimal and limited to lower level logging information. The example has been stripped of all those non-essential elements to focus the attention on the core features.

Chapter 5

Integration of the Camera on the Telescope

All the necessary components of the camera, from the front end electronics, to the Back-plane and the software to operate the whole system were described in the previous chapters of this thesis. The last critical component of the camera to be integrated was the Peripherals Board. The first prototype tested individually at the laboratory of the University of Liverpool suffered a fatal accidental failure and needed replacement. The time to re-order the parts and run new tests would have caused a large overrun of the planned schedule for the interface test between the camera and the telescope structure.

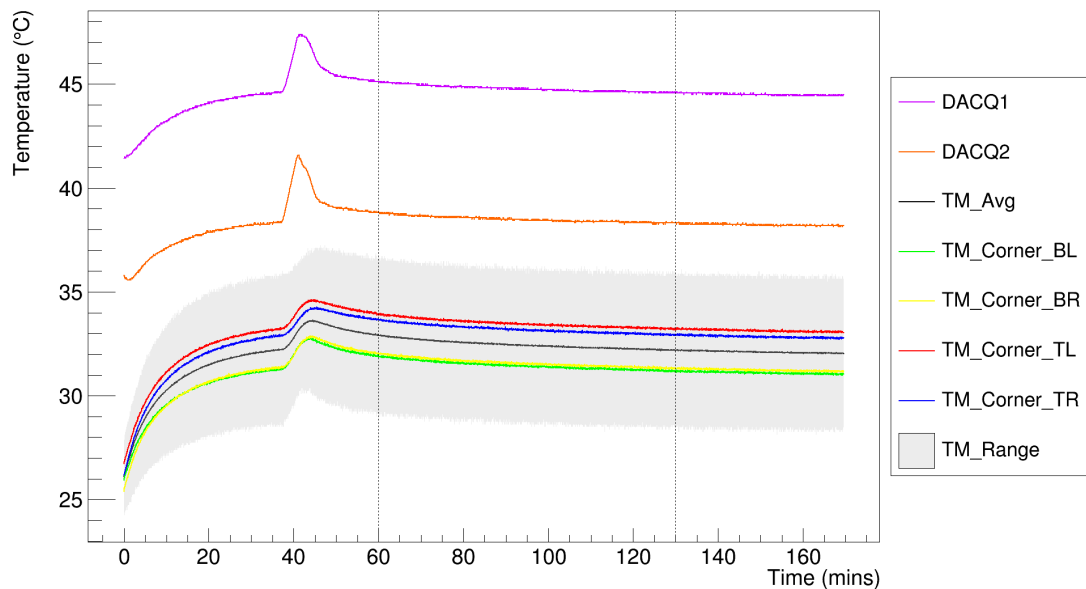


Fig. 5.1 Temperatures in the camera during a 3-hour test in the lab. The camera was fully enclosed, fan running at full speed all the time and chiller circulating water. The system reached equilibrium around 40 minutes after powering on the camera. Then the chiller was intentionally stopped for few minutes to verify the response of the camera.

The team decided to integrate the camera on the telescope if the survivability of the camera could be proven in the lab without the Peripherals Board. The camera was sealed in its enclosure, fans wired to be permanently running at full speed after power-up. A copy of the same chiller mounted on the telescope structure was connected to the cooling plate of the camera. Extensive long runs were performed and no issue was found in the camera behavior.

Fig. 5.1 shows an example of the temperatures in the system. The spike at around minute 40 is due to a test when the chiller was intentionally stopped from circulating cold water for few minutes. In winter 2015 the camera was shipped to the Observatoire de Paris in Meudon and integrated with the telescope prototype structure to test interfaces and try the end-to-end system with on sky observations. At the time only two out of the six primary mirror segments were manufactured and no further alignment was performed if not by simple visual inspection. The software to operate the motors of the telescope was not implemented yet, but the very well balanced structure allowed easy manual mobility of the telescope. Fig. 5.2 shows a picture of the prototype structure.



Fig. 5.2 The prototype telescope structure at the Observatoire de Paris in Meudon, France. The camera is mounted on the telescope.

All the mechanical interfaces were verified such as pipes for liquid circulation between the chiller and the camera, routing of the data fibers and power cables, etc. Fig. 5.3 shows the chiller mounted on the side of the telescope structure, and Fig. 5.4 the camera power supply in the cabinet on the rear of the secondary mirror.



Fig. 5.3 Chiller mounted at the side of the telescope structure.



Fig. 5.4 Inside of the electrical cabinet on the rear of the secondary mirror structure, housing the camera power supplier.

The structure was designed to easily mount and dismount the camera with the help of a movable arm that can be lowered to ground level to bolt on the camera when the telescope is in parking position. The process of mounting the camera is shown in Fig. 5.5. After practicing the operation a few times no major inconveniences were apparent. Only 3 people with minimal training can comfortably, safely and easily perform the task in less than 20 minutes. Fig. 5.6 illustrates the camera in the final position on the structure.



Fig. 5.5 Mounting procedure of the camera to the telescope structure. From left to right, top to bottom. (1) Lower the arm of the structure to host the camera to ground level. (2) Securing the camera with three bolts. (3,4) Raising the arm with the camera with the help of a winch on the rear of the secondary mirror. (5) Latching the arm with rest of the structure. (6). Securing the two horizontal support arms. These remove vibration of the camera and help stabilize the position of the focal plane with respect to the secondary mirror.

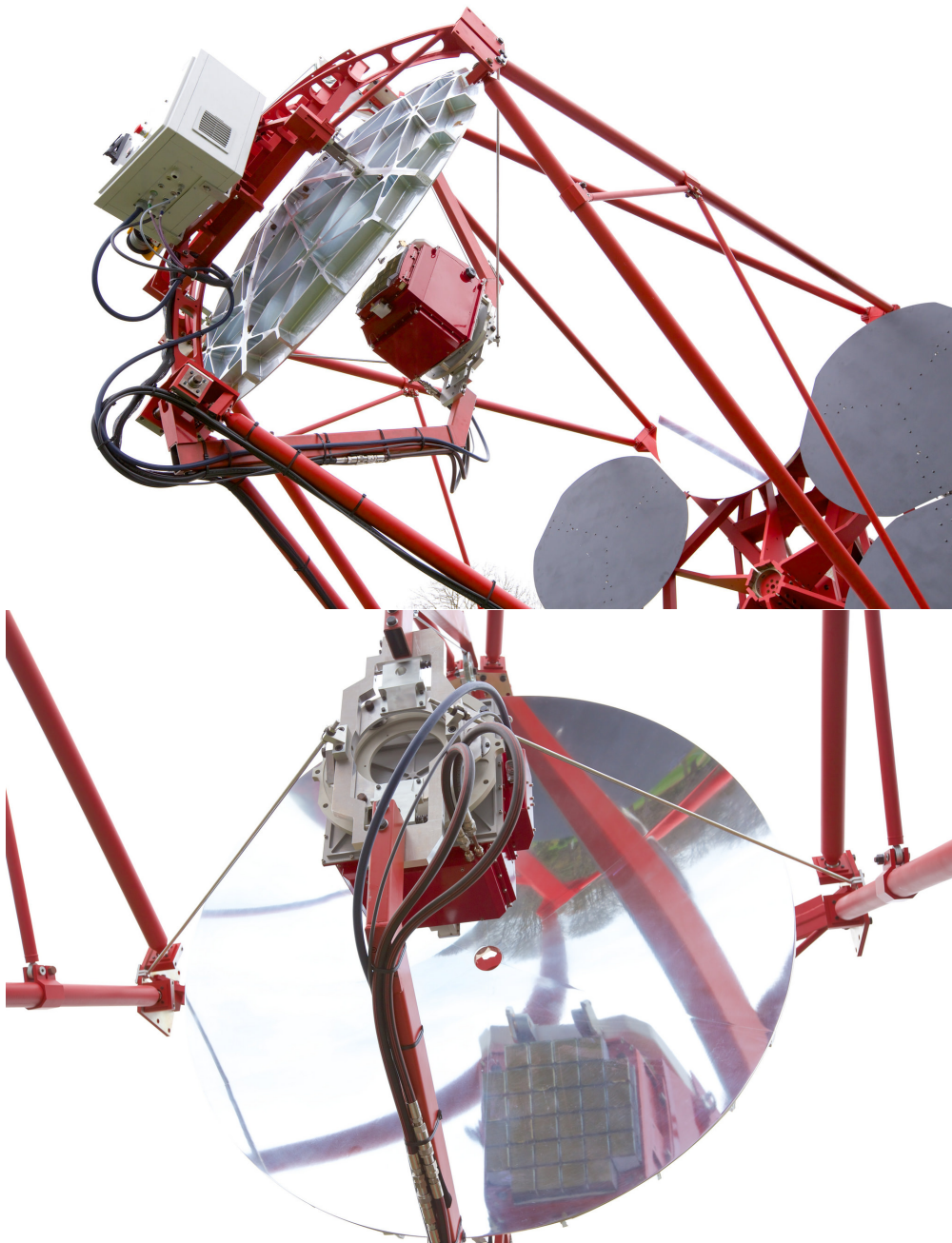


Fig. 5.6 Picture of the CHEC-M on the prototype telescope at the Observatoire de Paris, Meudon in France. (*top*) Telescope pointing at an angle of 45° above the horizon. (*bottom*) Reflection of the camera focal plane on the secondary mirror as seen from the primary mirror. The camera front looks flat.

Because the Peripherals Board was not present in the camera, the lid had to be opened and closed manually. The flashers were powered up via a 12 V to 5 V regulator and the

LED pattern fixed at power-up. As previously mentioned, the air flow was ensured by a set of fans wired to be operative permanently at full speed when powered.

As described in sec. 1.5.1, the telescope structure is protected from the environment by a shelter. The site is not very dark, even at night, due to the vicinity of the lights of the city and the light pollution from the offices on the site itself. The camera was conservatively first operated inside the closed shelter to minimize the level of NSB and tested using the 4 LED flasher units. Fig. 5.7 shows an example of an event recorded with one flasher at a time, and with all of them simultaneously. No further detailed studies on the calibration system were possible due to the missing Peripherals Board, which is needed to set different LED patterns and to regulate the calibration light intensity.

5.1 First observations on sky

The weather did not allow for observations except on one night when the sky was sufficiently clear. Unfortunately that night the Moon was almost full, but in a window of approximately 2 hours it was over the city and partially covered with clouds. The telescope was pointed away from the city and the Moon, and the shelter was partially closed to limit stray light into the mirrors. The first run was hugely dominated by spurious triggers on the noise from the very bright NSB. It was soon clear that I needed to quickly find a new operating point for the camera; different from the one optimized in the lab for the ambient light expected on the final CTA site. I reduced the high voltage supplied to the photosensors of 200 V from the gain matched value found in the lab. This means a gain reduction of roughly a factor of 3, according to the technical spread sheet provided by the MAPM manufacturer. Using this rough gain estimate I increased the threshold to about 14 p.e., aiming at triggering only on the brightest showers from cosmic-rays with a very low event rate. In five minutes, 12 events were recorded. The entire event set is in Figures 5.8 and 5.9. A second attempt to record more data was made and other 21 triggers were recorded in similar amount of observation time, but the Moon lifted from behind partial cover of a cloud and the environment became too bright. As a result, the contamination from false positive events on NSB increased significantly. The GCT team is discussing a possible data campaign in winter 2016. In all the examples here shown, only pedestal subtraction is performed. The calibration system provided by the LED flasher with full dynamic range was not yet viable due to the missing Peripherals Board. To perform a full calibration, and express the light intensity in p.e., its necessary to acquire data in the lab with the same gain regulated with the HV supplied.

It is clear that most of the events originate from a Cherenkov shower in atmosphere, from the shape and total light intensity of the image. This is confirmed with a timing analysis. In Fig. 5.10 I report the time arrival of the peak of the waveform for one of the

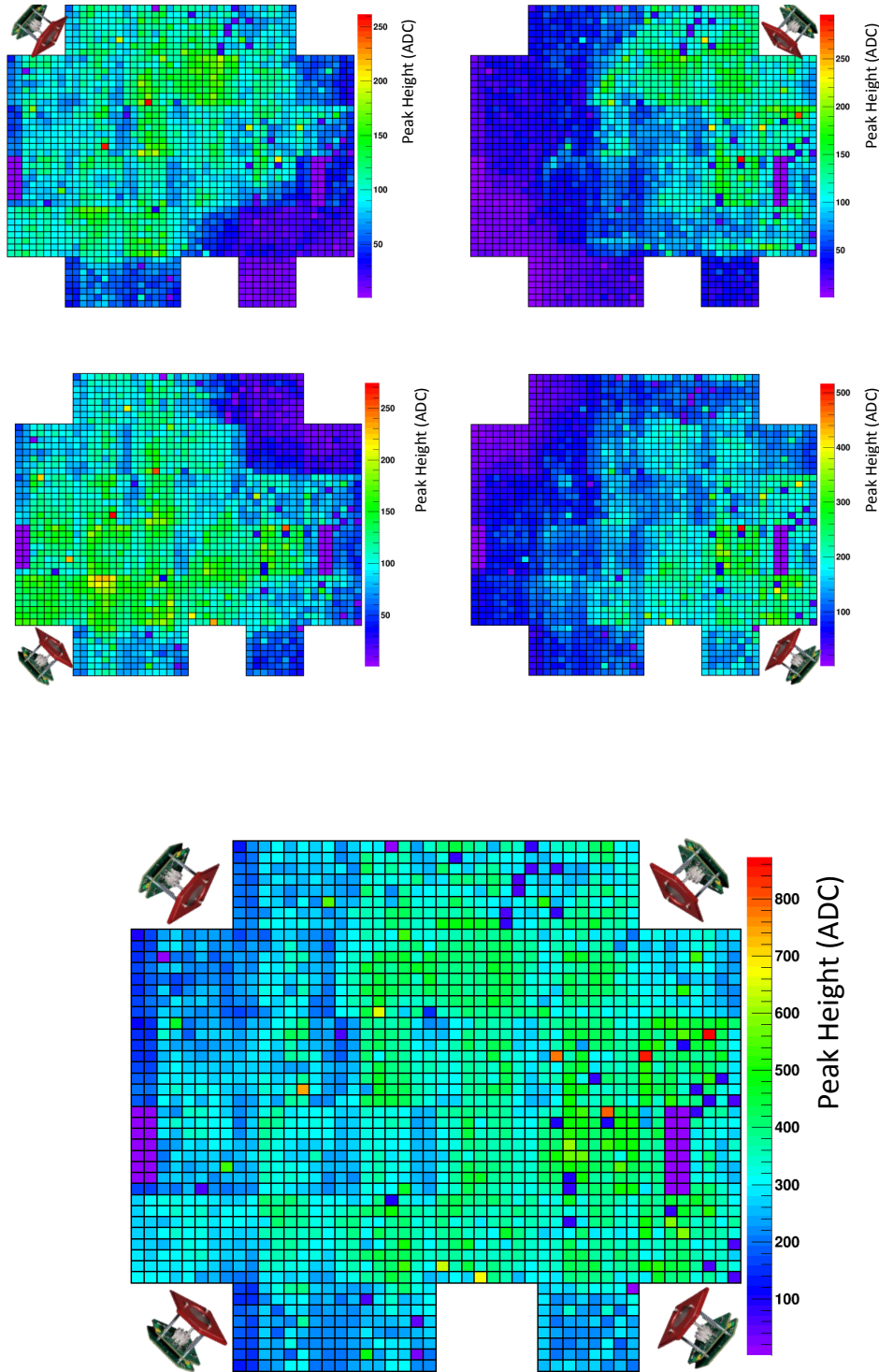


Fig. 5.7 Example of peak height distribution in the camera for events using the calibration LED flashers. *Top*: four events, each with only one LED flashing. A small image of the flasher in the corner used. *Bottom*: event with all 4 LEDs flashers in use. Because the LEDs are meant for calibration, the data are not expressed in p.e. but in ADC, after subtraction of the sample-dependent pedestal of the digitizer.

events (on the right panel) compared with the light intensity image (left panel). Clearly the signal is correlated in time, while the rest of the image shows uncorrelated noise from the NSB. For the same event, in Fig. 5.11, I highlight the time signature of the shower moving across the camera by constraining the scale to a few nanoseconds around the arrival of the peak. In Fig. 5.12 I show the waveform as recorded in two of the pixels participating in the shower development, again for the same event. A vertical line at time $t = 50$ ns is drawn to guide the eye. The chosen pixels position in the camera image is reported on the right panel. The arrival time of the peak is 4 ns apart and the shower is clearly moving from top to bottom in this image. No source of noise can realistically generate the same pattern. This argument holds for this and most of the events acquired, but for some others is less convincing. For example, the second event that I report again in Fig. 5.13 in comparison with the arrival time of the peak in the waveform. The area of the camera that generated the trigger is in the middle-right of the image, because the delays in the trigger chain are fixed, so the shower is always centered around $\sim 40 < t < \sim 60$ in the waveform. The “signal” is comparable to the level of noise in other patches of the image. Furthermore the peak arrival time shown on the right panel of Fig. 5.13 shows no strong correlation with a larger patch around the shower core.

As for the nature of the events, this collection of twelve is likely dominated by cosmic-ray initiated atmospheric Cherenkov showers, rather than from primary VHE gamma-rays. The first hint arises from the composition of the diffuse background at these energies. Hadrons are some orders of magnitude more abundant than gamma-rays. Additionally, some preliminary Monte Carlo simulations have been performed by the group. I list below the assumptions that have to be made to take into account the status of the system.

- M1 with only 2 petals
- PSF = 2 times worst than nominal one (to account for missing mirror alignment)
- NSB = 500 MHz (estimated)
- trigger coincidence window = 30 ns
- super-pixel trigger threshold = 14 p.e. (estimated from lab measurement, extrapolated for gain at lower HV)

This study predicts a rate of showers initiated by protons with energy >50 TeV of ~ 0.15 Hz. This is within an order of magnitude of the triggers recorded (12 events in 300 seconds = 0.04 Hz). Given the low quality and the small amount of the data no further detailed analysis was performed. Nonetheless the system proved to be working and able to acquire Cherenkov showers. It was the first time a prototype telescope with Schwarzschild-Couder optics was successfully used to see Cherenkov light, and the first prototype for CTA to achieve this result.

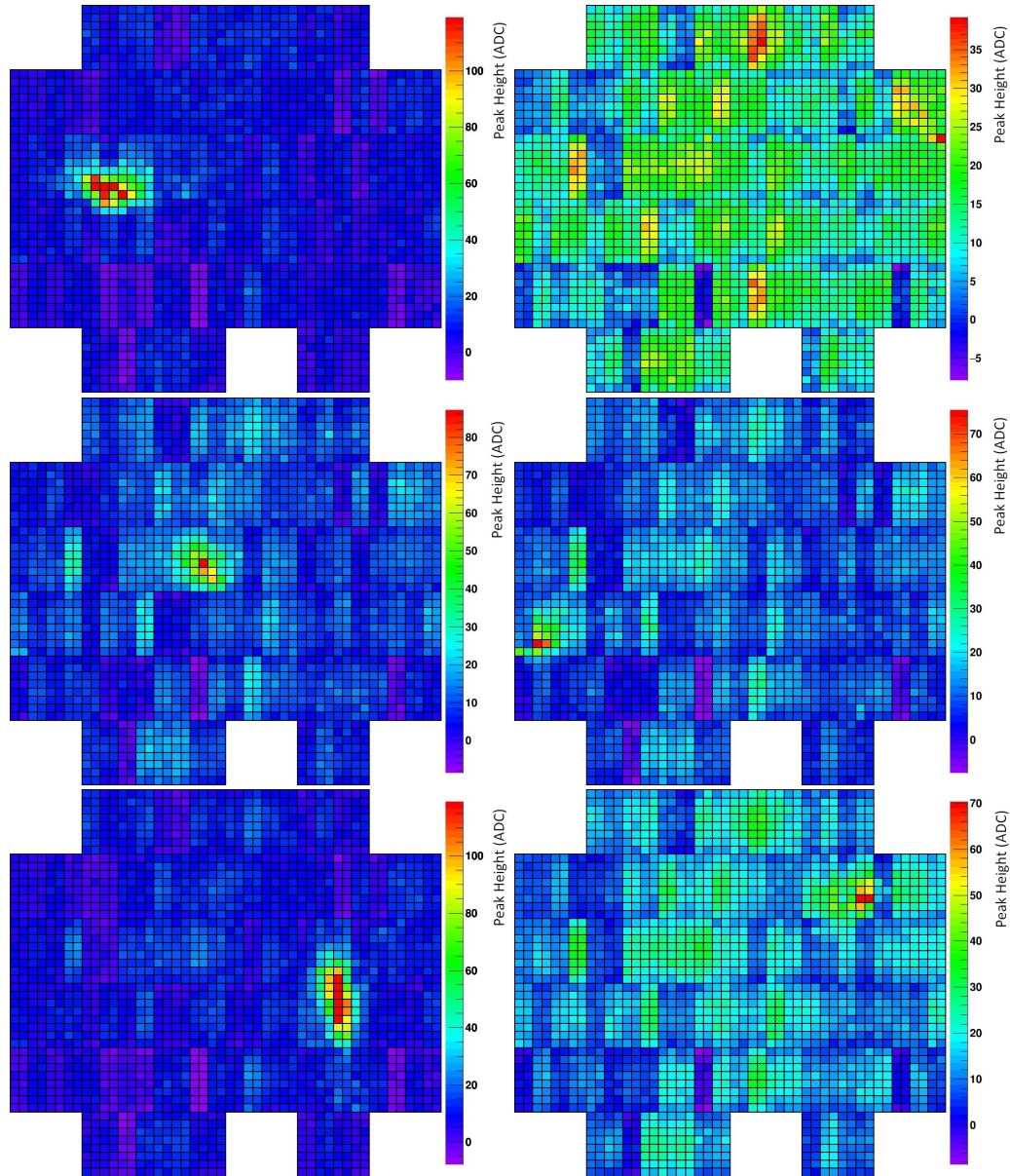


Fig. 5.8 The very first on sky light events recorded during the integration of the camera with the telescope structure at the Observatoire de Paris in Meudon. Each pixel shows the peak height in a color-coded scale. The data are not calibrated in p.e., only the sample-dependent pedestal of the digitiser has been subtracted. The first six out of the total twelve events are shown.

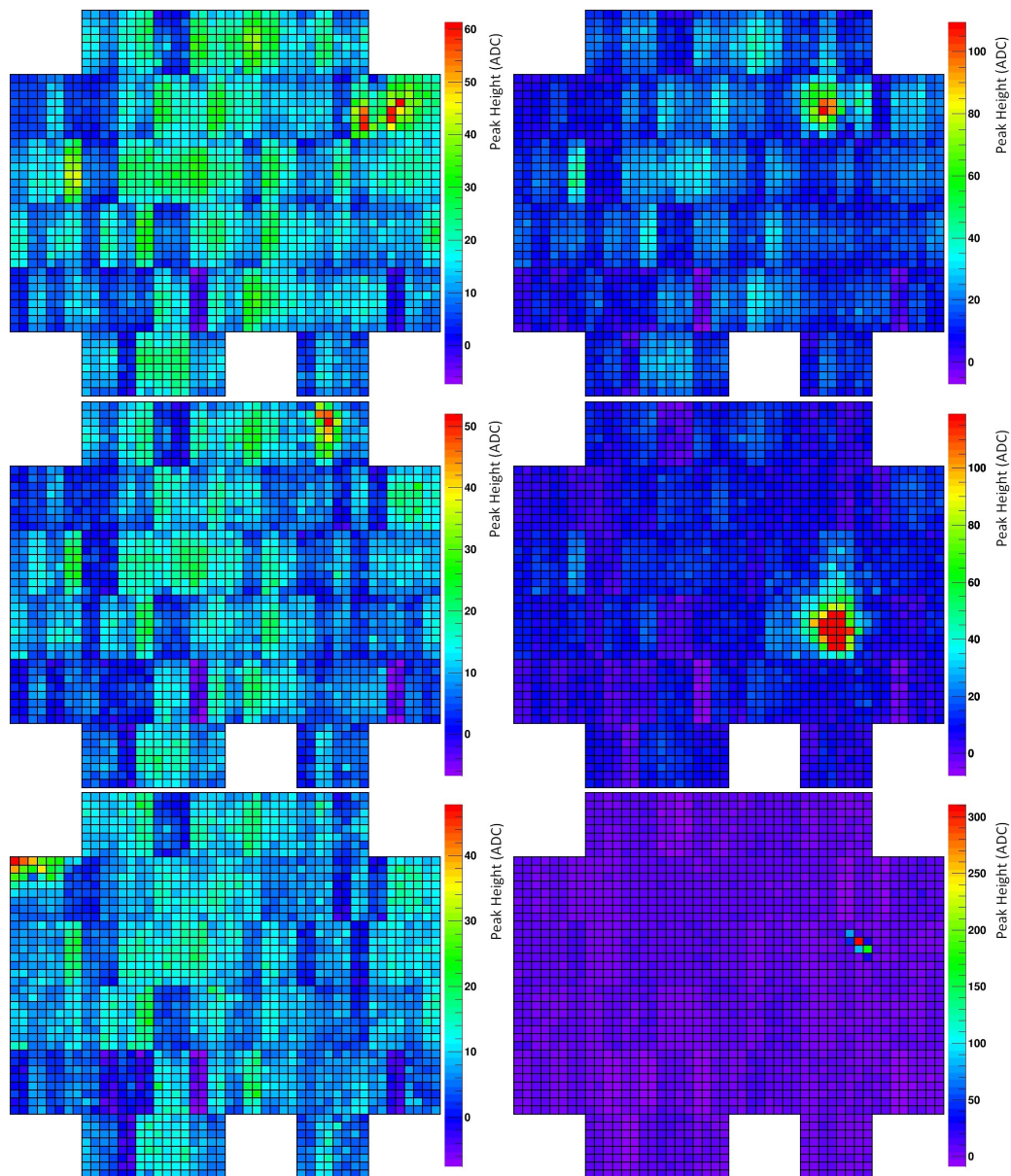


Fig. 5.9 The very first on sky light events recorded during the integration of the camera with the telescope structure at the Observatoire de Paris in Meudon. Each pixel shows the peak height in a color-coded scale. The data are not calibrated in p.e., only the sample-dependent pedestal of the digitizer has been subtracted. The last six out of the total twelve events are shown.

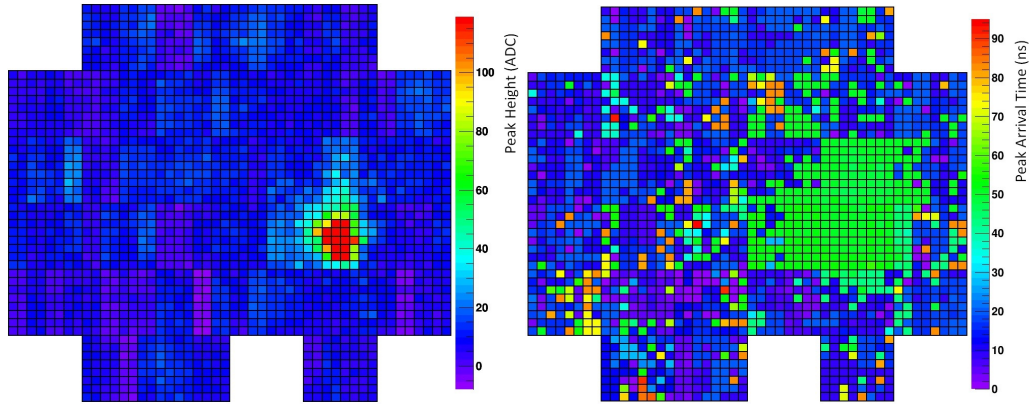


Fig. 5.10 Timing analysis for event number 10 of from the collection of events of the very first on sky light recorded during the integration of the camera with the telescope structure at the Observatoire de Paris in Meudon. *Left*: each pixel shows the peak height in a color-coded scale. The data are not calibrated in p.e., only the sample-dependent pedestal of the digitizer has been subtracted. *Right*: time of the peak arrival in a color coded-scale. The Figure shows the correlation in time of the signals.

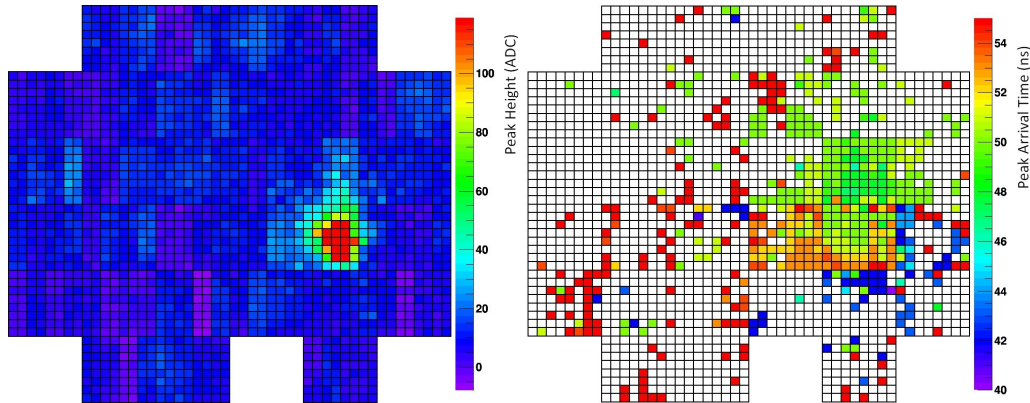


Fig. 5.11 Same as Fig. 5.10 with timing scale of the right panel constrained around the signal peak. The time signature of the shower propagating from top-right to bottom-left is evident.

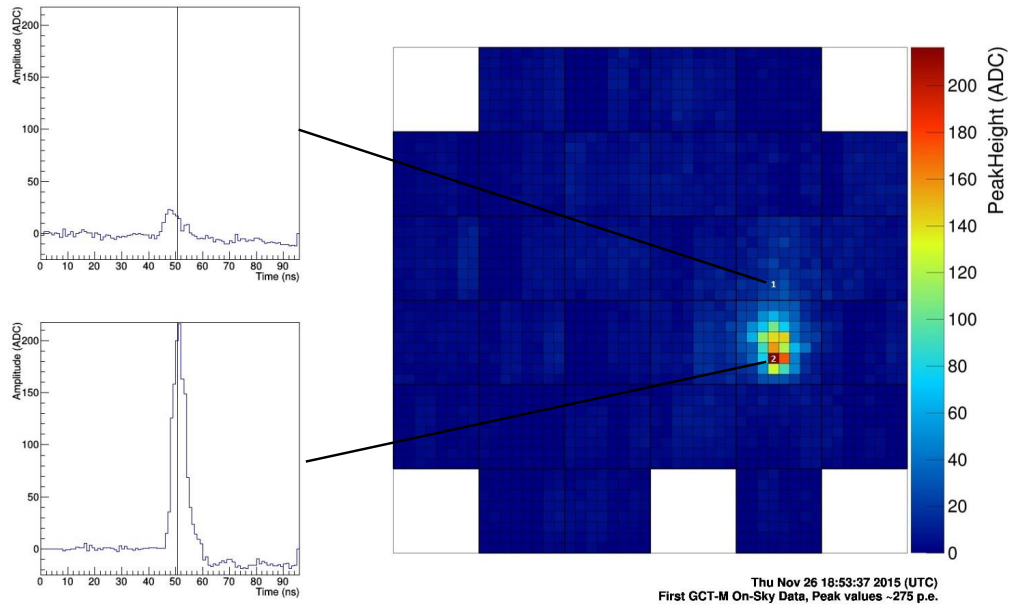


Fig. 5.12 Example event. *Left*: waveform in two different pixels, marked with 1 (top) and 2 (bottom) on the right panel. A vertical line is drawn at the same time in the two waveforms to guide the eye. *Right*: peak height distribution in the camera with a color-coded scale. The data are not calibrated in p.e., only the sample-dependent pedestal of the digitizer has been subtracted.

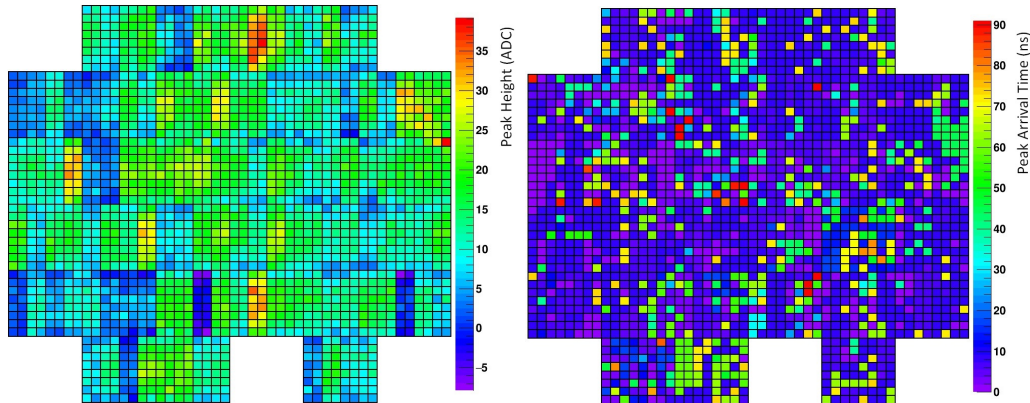


Fig. 5.13 Timing analysis for event number 2 of from the collection of events of the very first on sky light recorded during the integration of the camera with the telescope structure at the Observatoire de Paris in Meudon. *Left*: each pixel shows the peak height in a color-coded scale. The data are not calibrated in p.e., only the sample-dependent pedestal of the digitizer has been subtracted. *Right*: time of the peak arrival in a color coded-scale. Delays in the trigger chain are deterministic, so the trigger is due to the signal in the middle-right of the image. Noise level comparable with the signal. The Figure shows a poor correlation in time of the signals.

Chapter 6

An Extragalactic survey with CTA and implication from Axion-Like-Particles and secondary gamma-rays.

Current generation instruments have detected few hundred objects in the VHE gamma-ray band during the past decade, a good fraction of which also come with distance measurements from multi-wavelength campaigns [72–76]. As described in the Introduction, CTA is expected to come online within the next few years and to outperform current IACTs (see sec:1.4). Its improved flux sensitivity and larger field of view (FoV) will enable the detection of many new sources and will allow for population oriented studies at VHE [77]. An up-to-date estimate of detectable sources is needed in order to devise the best CTA survey strategies.

Blazars, a class of active galactic nuclei (AGNs), are the dominant population in the VHE gamma-ray sky. Currently, ~ 200 VHE blazars have been reported [78] out to redshift $z \sim 1$ [79, 80]. The number of VHE blazars is expected to dramatically increase with an improved IACT sensitivity. Indeed, it should be possible to perform a statistical study of VHE blazars in the CTA era (see, e.g., Inoue & Tanaka 2016 using current IACT blazar samples [81]), which will provide the key to understand AGN populations in the VHE band and high-energy phenomena in the vicinity of super-massive black holes.

The expected potential of this upcoming VHE blazar CTA survey has been studied in the literature (Inoue, Totani, & Mori 2010 [82], Dubus et al. 2013 [77], Inoue, Kalashev, & Kusenko 2014 [83], and more). Very recently, Ajello et al. [19] reported an improved model of the spectral energy distributions (SEDs) and evolution (gamma-ray luminosity function, GLF) of blazars based on the latest catalog from the Large Area Telescope [84] on board the *Fermi* gamma-ray satellite. Utilizing those latest models, in this chapter I will show the expected source count distribution and redshift distribution at the energy bands covered

by the CTA sensitivity. I will also consider the cases for the high altitude water Cherenkov (HAWC) [85] and the large high altitude air shower observatory (LHAASO) [86, 87].

VHE gamma-rays propagating in intergalactic space are known to be attenuated by the extragalactic background light (EBL) [88–91]. EBL attenuation would affect the expected number of extragalactic source detections in a future survey. Recent studies have detected attenuation of gamma-rays on the EBL [92–94], using a dataset dominated mostly by optical depth of the order of the unity. However, distant VHE blazars appear to have harder intrinsic spectra than predicted by simple gamma-ray emission models [90], as well as a redshift dependence of the observed spectral index that is different from what was expected [95, 96], although a large uncertainty remains in the measured redshifts and spectral indices [97, 98]. To explain such intrinsically hard spectra, several scenarios have been proposed in the literature, such as secondary cascade components generated by very high energy cosmic-rays [99–101], emission from stochastically accelerated particles in the jet [102], axion-like particles (ALPs) [38, 40, 43, 44, 103, 104] and Lorentz invariance violation [38]. Although stochastic acceleration scenarios also suffer from EBL attenuation, the other mentioned processes would affect gamma-rays propagation in the intergalactic space, potentially hardening the observed blazar spectrum as compared to the pure gamma-ray absorption on standard EBL scenario. This would be particularly true for sources located at high redshifts. In this chapter, I will study the implications of ALPs and secondary gamma-rays on the source count distribution.

Axion-like Particles

Here I recall the concept of ALPs, that I already mentioned in the Introduction of this thesis. ALPs are pseudo-scalar bosons, similar in properties to standard QCD axions [32] but with a coupling constant independent of their mass. They are predicted by several extensions of the Standard Model and can constitute all, or part of, the dark matter density (see, e.g., [105] for a recent review). Photons couple with ALPs in the presence of external magnetic fields, therefore, should these particles exist, the VHE gamma-rays would oscillate back and forth to ALP in the source magnetic field and in the intergalactic magnetic field (IGMF). ALPs would not interact with the EBL, possibly resulting in a less opaque universe for VHE gamma-rays. See Fig. 1.4 for a diagram of ALP/photon mixing. As a result, CTA would observe spectral hardening [106] of distant sources due to this effect. Blazars are known to be variable objects, thus, finding statistically-significant spectral hardening in individual sources may be challenging. Instead I study whether CTA could be expected to see a hint of ALPs in the source count distribution, which would be modified, especially at the highest energies probed by the experiment.

Secondary gamma-rays from hadronic interactions

High and ultra-high-energy cosmic-ray (UHECR) source acceleration has not yet been uniquely identified, and AGN could contribute to it up to the multi-EeV range [107] (but see also [108]). Protons which have escaped from the AGN can interact with the intergalactic photon fields via photo-pion production ($p\gamma \rightarrow p\pi^0 / n\pi^+$) and electron/positron pair production ($p\gamma \rightarrow pe^-e^+$). Both channels lead to a cascade of sub-particles and secondary gamma-rays, which would be detected along the line of sight of the blazar [100, 101, 109–114], provided that the IGMF is not strong enough to significantly bend the trajectory of the primary cosmic-rays [109, 111]. Protons with energies around ~ 1 EeV, i.e. below the Greisen–Zatsepin–Kuzmin (GZK) cutoff, would not be absorbed by the cosmic microwave background (CMB) and could then propagate over cosmological distances before interacting with the EBL photons in the infrared to ultraviolet wavelength. Therefore, secondary gamma-rays generated by those protons would be emitted closer to the observer than the original cosmic-ray acceleration site and thus would suffer less absorption on the EBL. The flux of secondary gamma-rays would add to the primary source flux, enhancing the number of detectable sources for a certain flux sensitivity [83]. Throughout this chapter I consider the cosmology constants: $H_0 = 67 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_M = 1 - \Omega_\Lambda = 0.3$.

6.1 Method

The cumulative source count, above a certain flux limit F is given as

$$N(> F) = \int_{z_{\min}}^{z_{\max}} \int_{\Gamma_{\min}}^{\Gamma_{\max}} \int_{L_{\gamma\min}(F,z,\Gamma)}^{L_{\gamma\max}} \Phi(L_\gamma, z, \Gamma) \frac{dV}{dz d\Omega} dL_\gamma d\Gamma dz, \quad (6.1)$$

where z is the redshift of the source, Γ is a photon spectral index (see eq. 6.11), L_γ is the intrinsic source gamma-ray luminosity in the energy band $0.1 - 100$ GeV. I set $z_{\min} = 0.001$, $z_{\max} = 4$, $\Gamma_{\min} = 1$, $\Gamma_{\max} = 3.5$, $L_{\gamma\max} = 10^{52} \text{ erg s}^{-1}$ as in [19]. $L_{\gamma\min}$ is the intrinsic source luminosity in the $0.1 - 100$ GeV energy band, corresponding to the flux F detected at Earth. I constrain $L_{\gamma\min}$ to be greater than $10^{42} \text{ erg s}^{-1}$ following [19]. Φ is the blazar GLF and V is the comoving volume [115]:

$$\frac{dV}{dz} = D_H^3 \frac{(\int_0^z E(z)^{-1} dz)^2}{E(z)}, \quad (6.2)$$

$$E(z) = \sqrt{\Omega_M(1+z)^3 + \Omega_\Lambda}. \quad (6.3)$$

For the GLF, I use the luminosity dependent density evolution (LDDE) model in [19]:

$$\Phi(L_\gamma, z, \Gamma) = \frac{dN}{dL_\gamma dV d\Gamma} = \quad (6.4)$$

$$= \frac{A}{\ln(10)L_\gamma} \left[\left(\frac{L_\gamma}{L_*} \right)^{\gamma_1} + \left(\frac{L_\gamma}{L_*} \right)^{\gamma_2} \right]^{-1} \exp \left(-\frac{[\Gamma - \mu(L_\gamma)]^2}{2\sigma^2} \right), \quad (6.5)$$

$$\mu(L_\gamma) = \mu^* + \beta [\log(L_\gamma) - 46], \quad (6.6)$$

$$z_c(L_\gamma) = z_c^*(L_\gamma/10^{48})^\alpha, \quad (6.7)$$

With L_γ in unit of erg s^{-1} .

To relate $L_{\gamma\min}$ to a certain flux limit F , I make use of the definition of luminosity distance D_L :

$$F_\nu = \frac{1+z}{4\pi D_L^2} L_{(1+z)\nu}, \quad (6.8)$$

$$D_L = D_H(1+z) \int_0^z E(z)^{-1} dz, \quad (6.9)$$

and an average blazar SED template presented in [19]:

$$\frac{dN_\gamma}{dE}(E, \Gamma, z) \propto \left[\left(\frac{E}{E_b} \right)^{1.7} + \left(\frac{E}{E_b} \right)^{2.6} \right]^{-1} e^{-\tau(E, z)}, \quad (6.10)$$

where τ is the opacity coefficient of the Universe to VHE gamma-rays due to absorption on the EBL. The dependency from Γ derives from:

$$\log E_b(\text{GeV}) = 9.25 - 4.11\Gamma. \quad (6.11)$$

From eq. 6.8

$$F_{\gamma \frac{1}{1+z}} = \frac{1+z}{4\pi D_L^2} L_\gamma, \quad (6.12)$$

$$\int_{0.1\text{GeV}}^{100\text{GeV}} E \frac{1}{1+z} \frac{dN_\gamma}{dE} \left(E \frac{1}{1+z}, \Gamma, z \right) dE = \frac{1+z}{4\pi D_L^2} L_\gamma. \quad (6.13)$$

Resolving for L_γ and replacing $\frac{dN_\gamma}{dE}(E, \Gamma, z)$ from 6.10

$$L_\gamma = K \frac{4\pi D_L^2}{1+z} \int_{0.1\text{GeV}}^{100\text{GeV}} E \frac{1}{1+z} \left[\left(\frac{E \frac{1}{1+z}}{E_b} \right)^{\gamma_a} + \left(\frac{E \frac{1}{1+z}}{E_b} \right)^{\gamma_b} \right]^{-1} e^{-\tau(E \frac{1}{1+z}, z)} dE, \quad (6.14)$$

where K is a constant. The flux F (expressed in $\text{ph}^{-2} \text{s}^{-1}$) observed at Earth will be considered in different energy band with lower limit $E_{\min}$ and its relation to $\frac{dN_\gamma}{dE}(E, \Gamma, z)$ is

used to relate $L_{\gamma\min}$ to F by replacing K from eq 6.14 with:

$$F_{>E_{\min}} = \int_{E_{\min}}^{\infty} \frac{dN\gamma}{dE}(E, \Gamma, z) dE = \quad (6.15)$$

$$= K \int_{>E_{\min}}^{\infty} \left[\left(\frac{E}{E_b} \right)^{\gamma_a} + \left(\frac{E}{E_b} \right)^{\gamma_b} \right]^{-1} e^{-\tau(E,z)} dE, \quad (6.16)$$

$$K = \frac{F_{>E_{\min}}}{\int_{>E_{\min}}^{\infty} \left[\left(\frac{E}{E_b} \right)^{\gamma_a} + \left(\frac{E}{E_b} \right)^{\gamma_b} \right]^{-1} e^{-\tau(E,z)} dE}. \quad (6.17)$$

From eq 6.14 and eq 6.17:

$$L_{\gamma\min} = F_{>E_{\min}} \frac{4\pi D_L^2}{1+z} \frac{\int_{0.1\text{GeV}}^{100\text{GeV}} E \frac{1}{1+z} \left[\left(\frac{E \frac{1}{1+z}}{E_b} \right)^{\gamma_a} + \left(\frac{E \frac{1}{1+z}}{E_b} \right)^{\gamma_b} \right]^{-1} e^{-\tau(E \frac{1}{1+z}, z)} dE}{\int_{E_{\min}}^{\infty} \left[\left(\frac{E}{E_b} \right)^{\gamma_a} + \left(\frac{E}{E_b} \right)^{\gamma_b} \right]^{-1} e^{-\tau(E,z)} dE}. \quad (6.18)$$

For the absorption of gamma-ray photons due to the EBL, I adopt the EBL model of [116] as the reference one. I obtain no significant disagreement in results computed when comparing to other EBL models [117–119]. Below, I explore the effect of two different scenarios on the cumulative source distribution.

6.1.1 Axion-like Particles

The spectral distortions induced by photon/ALP mixing on top of the EBL-absorbed source spectrum are computed following [44]. The general effect is a hardening of the spectrum for sources at $z > 0.2$, yet this result largely depends on the properties of the IGMF, to a large extent unconstrained at present [120–126]. In this chapter, for simplicity, I present the case for a IGMF strength of $B = 10^{-10}\text{G}$ and 10^{-11}G , uniform in 1 Mpc domains but whose orientation randomly varies from one domain to another. It is important to emphasize that the ALP scenario presented in [44] for the intergalactic case only represents *an average* case over a large number of realizations of the IGMF configuration (strength and orientation). It has been shown that this average typically leads to a less opaque universe to gamma-rays as due to ALPs; however the actual range of possibilities is expected to be much larger and, indeed, may lead to a more opaque universe [127]. Therefore, as the precise effect of intergalactic ALP mixing on source spectra is hard to predict due to the random nature of the IGMFs, the results shown here may be taken with caution and as a proof-of-concept only. To calculate the source count distribution in the presence of ALPs,

eq. 6.18 is replaced with

$$L_{\gamma\min} = F_{>E_0} \frac{4\pi D_L^2}{1+z} \frac{\int_{0.1\text{GeV}}^{100\text{GeV}} E \frac{1}{1+z} \left[\left(\frac{E \frac{1}{1+z}}{E_b} \right)^{\gamma_a} + \left(\frac{E \frac{1}{1+z}}{E_b} \right)^{\gamma_b} \right]^{-1} dE}{\int_{E_{\min}}^{\infty} E \left[\left(\frac{E}{E_b} \right)^{\gamma_a} + \left(\frac{E}{E_b} \right)^{\gamma_b} \right]^{-1} e^{-\tau(E,z)} \times ALP_{Boost}(E,z) dE}, \quad (6.19)$$

where $ALP_{Boost}(E, z)$ is a correction coefficient computed with [44] that takes into account the effect on the observed spectrum of the ALP/mixing photons. In Fig. 6.1 I show an example of how this modifies the observed spectra for different values of Γ and redshift of the source.

6.1.2 Secondary gamma-ray from hadronic interactions

The secondary gamma-ray flux from proton cascades in the intergalactic medium is calculated with the code described in [128, 129] for the two cases $B = 10^{-15}$ and 10^{-17} G. The secondary gamma-ray spectral shape does not strongly depend on the bolometric proton luminosity of the source, nor on the proton injection spectrum [100, 109]. However, the gamma-ray flux is proportional to the bolometric luminosity of the source, $L_{p,bol}$. In Ref. [130], the authors estimated $L_{p,bol}$ to be of the same order, or slightly higher than $L_{\gamma,bol}$ for BL Lac objects, while being one or two orders of magnitude greater than $L_{\gamma,bol}$ for FSRQs. The argument assumes a largely hadronic jet populated by one proton per electron, i.e. this implies a negligible content of positron-electron pair population in the jet. Although a scenario with positron-electron pairs exclusively in the jet is ruled out by X-rays observation of FSRQs [131], I must note that a certain leptonic component in the jet cannot be ruled out [131–134]. In this work I assume $L_{p,bol} = L_{\gamma,bol}$ and I consider for the proton injection spectrum

$$j_P(E) \propto E^{-2} \exp(-E/E_{p,max}) \exp(-E_{p,min}/E), \quad (6.20)$$

with $E_{p,max} = 1$ EeV, $E_{p,min} = 0.1$ EeV. A previous work from [83] performed a similar analysis, although using SED template and GLF supported by the EGRET data. In the case of secondary gamma-rays, the source count distribution is calculated replacing eq. 6.18 with:

$$L_{\gamma\min} = F_{>E_0} \frac{4\pi D_L^2}{1+z} \frac{\int_{0.1\text{GeV}}^{100\text{GeV}} E \frac{1}{1+z} \left[\left(\frac{E \frac{1}{1+z}}{E_b} \right)^{\gamma_a} + \left(\frac{E \frac{1}{1+z}}{E_b} \right)^{\gamma_b} \right]^{-1} dE}{\left[\int_{E_{\min}}^{\infty} E \left[\left(\frac{E}{E_b} \right)^{\gamma_a} + \left(\frac{E}{E_b} \right)^{\gamma_b} \right]^{-1} e^{-\tau(E,z)} dE \right] + \left[\frac{L_{Bol}(\Gamma,z)}{10^{48}} \int_{E_{\min}}^{\infty} E \frac{dN_{2nd}}{dE} dE \right]}, \quad (6.21)$$

where the observed secondary gamma-ray flux is added to the primary gamma-ray flux normally absorbed on the EBL. When this additional flux was computed with [128, 129], it was normalized to a bolometric primary gamma-ray flux of $10^{48} \text{ erg s}^{-1}$. I rescale it to the bolometric luminosity of the source:

$$L_{\text{Bol}}(\Gamma, z) = 4\pi D_L^2 F_{\text{Bol}}(\Gamma, z) = 4\pi D_L^2 \int_0^\infty E \left[\left(\frac{E}{E_b} \right)^{\gamma_a} + \left(\frac{E}{E_b} \right)^{\gamma_b} \right]^{-1} e^{-\tau(E, z)} dE. \quad (6.22)$$

Please refer to Fig. 6.1 for an example on how EBL absorption, gamma-ray oscillation to ALPs and secondary gamma-rays modify the observed spectrum of a source with photon indices of $\Gamma = 1.7$ and 2.7 located at redshifts $z = 0.3$ and 3 .

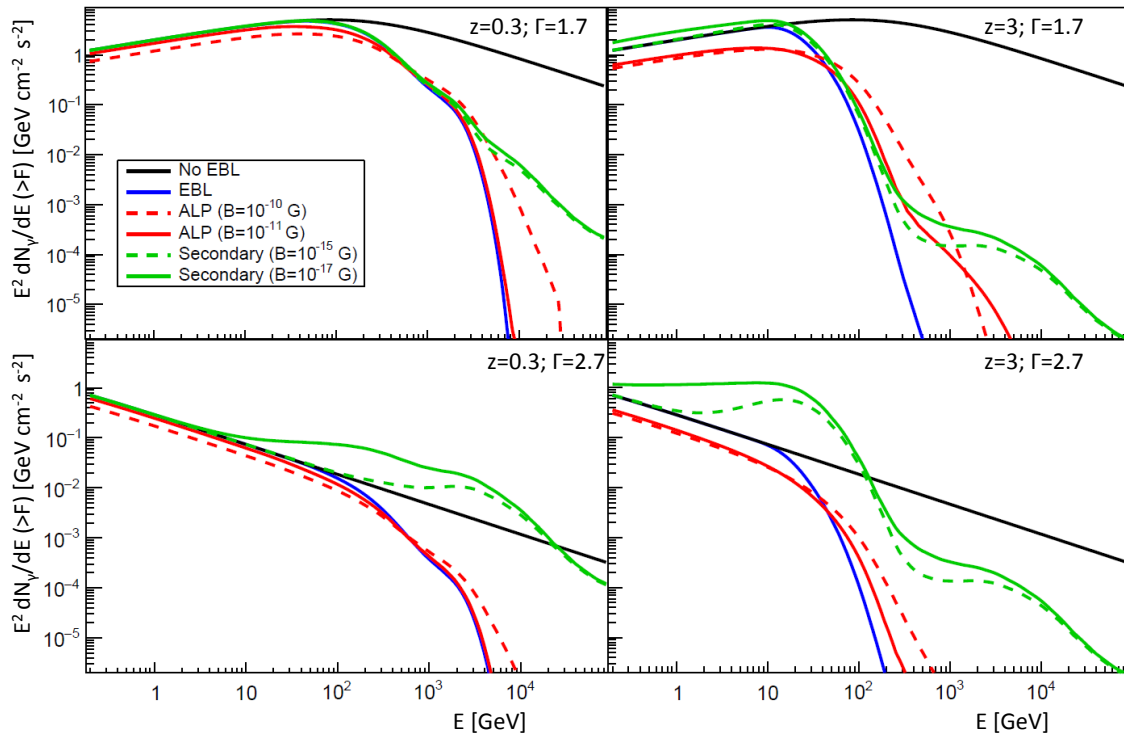


Fig. 6.1 Averaged blazar SED with different photon index Γ and redshift z as observed at Earth for four different scenarios: intrinsic spectrum (*black solid line*); EBL absorption (*blue solid*); EBL + ALPs (*red lines*); EBL + secondary gamma-rays (*green lines*). In the last two scenarios, dashed and solid curves refer to two different values of the IGMF strength, see legend. Normalization is set by the primary gamma-ray flux at 0.1 GeV to be equal to $1 \text{ GeV cm}^{-2} \text{s}^{-1}$.

6.2 Results

In Fig. 6.2 I present the blazar cumulative source count for all the above mentioned scenarios in different energy bands. I report the expected flux sensitivity limits for the reference

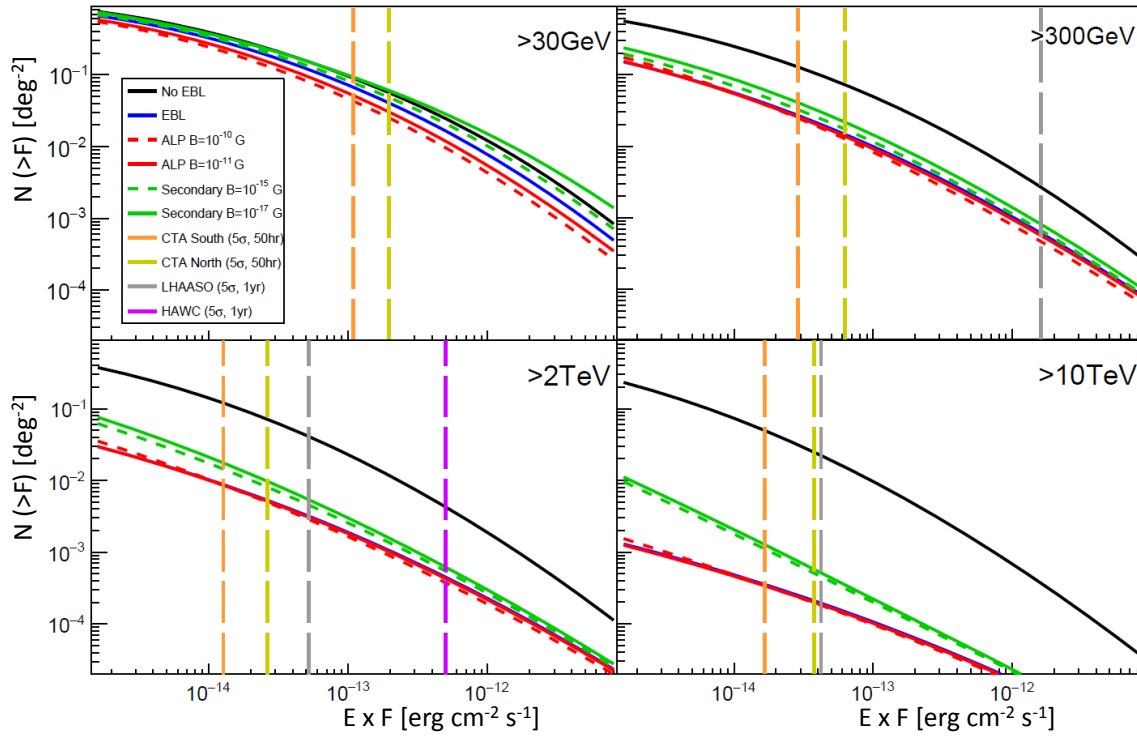


Fig. 6.2 Cumulative source count distribution in different energy bands for the different scenarios discussed in the text: intrinsic spectrum (*black solid line*); EBL absorption (*blue solid*); EBL+ALPs (*red lines*); EBL + secondary gamma-rays (*green lines*). In the last two scenarios, dashed and solid curves refer to two different values of the IGMF strength, see legend. We also show the integral flux sensitivity of CTA South (*vertical, orange dashed*) and North (5σ , 50hr observation per FoV) (*vertical, yellow dashed*); LHAASO (5σ , 1 year) (*vertical, gray dashed*); HAWC (5σ , 1 year) (*vertical, violet dashed*).

CTA-North and CTA-South (5σ , 50hr) as derived from [135] with the CTA instrument response function provided by [136]. The pronounced difference of the sensitivity between CTA-South and CTA-North is due to: at high energies to the lack of the smallest telescope in the latter, and at low energies to the presence of fewer middle sized telescope and a larger geomagnetic field intensity at the CTA-North site that degrades the precision of background rejection [137, 138]. I also present results for LHAASO (5σ , 1yr) [139] and HAWC (5σ , 1yr) [140].

In Tables 6.1, 6.2, I summarize the expected source detection count in different energy bands for a CTA unbiased survey of 250 hours from either the Southern or the Northern location, assuming the standard model with only gamma-ray absorption on the EBL. I consider the case of 50, 5 and 0.5 hours observation time. To optimize the sensitivity over a very broad dynamic range of gamma-ray energies, CTA will be constituted of three sizes of telescope with different fields of view (roughly $5^\circ, 7^\circ, 9^\circ$ from the largest to the smallest telescopes, as described in section 1.4). Observation strategies will adopt combinations of sub-arrays with different contributions to the sensitivity of the overall

array. For CTA-South, I consider FoVs of 5° , 7° , 9° respectively for observation in the energy bands > 30 GeV, > 300 GeV, > 2 TeV. CTA-North will not host any small sized telescope, thus I assume a FoV of 7° even at > 2 TeV. The portion of the sky covered in a survey of 250 hr with observation of 5 hr each is 2.4%, 4.7% and 7.7% respectively for the assumed FoV of 5° , 7° , 9° . The total portion of the sky covered scales with the inverse of the observation time per FoV.

CTA South – EBL			
Energy Band	ΔT		
	50 hr	5 hr	0.5 hr
>30 GeV	7	15	35
>300 GeV	5	13	32
>2 TeV	3	7	10*
>10 TeV	-	-	-

Table 6.1 Estimated source count for a blind survey of 250 hours for CTA-South for different energy bands and ΔT observation time per FoV. These data assume only absorption on the EBL. Note: ‘-’ mark denotes no expected detection; ‘*’ this source count corresponds to a survey of half of the sky, which is completed in ≈ 130 hours.

CTA North – EBL			
Energy Band	ΔT		
	50 hr	5 hr	0.5 hr
>30 GeV	4	9	13
>300 GeV	3	8	15
>2 TeV	1	4	4
>10 TeV	-	-	-

Table 6.2 Same as Tab. 6.1, but for CTA-North.

Interestingly, Tables 6.1, 6.2 show that a shallow and broad survey is preferred to maximize the number of sources identified. In Fig. 6.3 and 6.4 I depict the cumulative source count in redshift for all the models considered in this chapter. These Figures show results for blazars with an observed flux higher than the CTA-South integral flux sensitivity for 50 hr and 0.5 hr of exposure time. From these figures it can be seen, once again, that a survey with shorter observation time per FoV would provide the highest discovery potential.

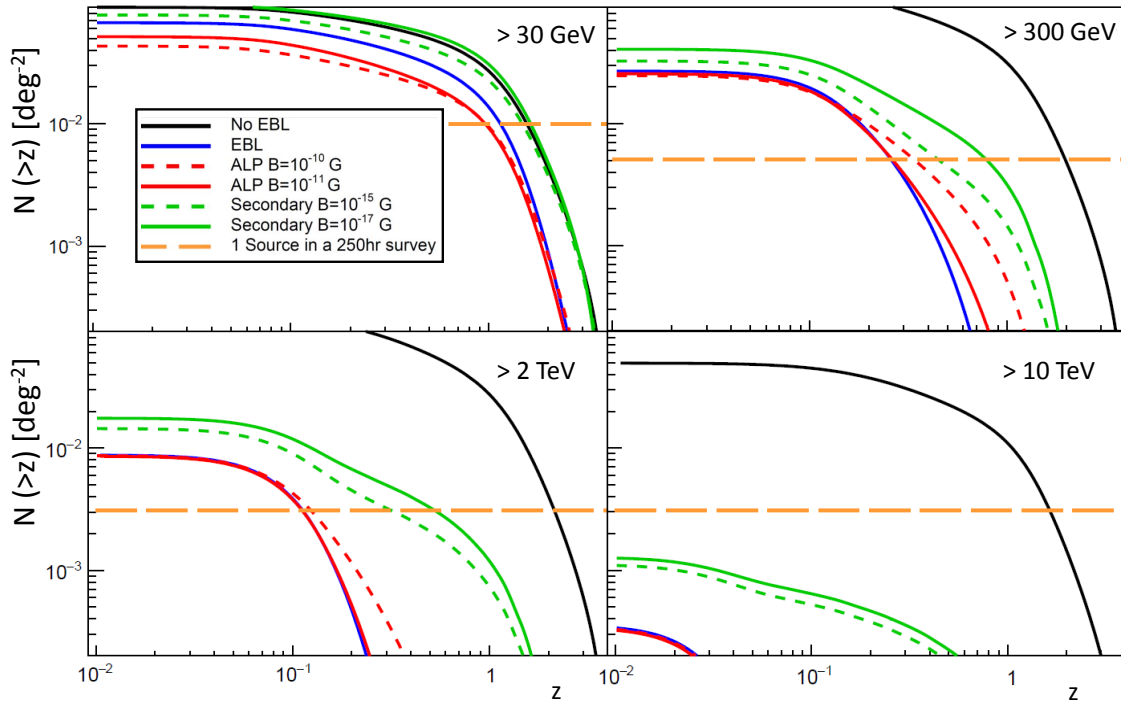


Fig. 6.3 Cumulative source count as a function of redshift for CTA-South, assuming a 5σ integral flux sensitivity and 50 hr exposure observation. Dashed horizontal line represents 1 source detected in a 250 hr survey.

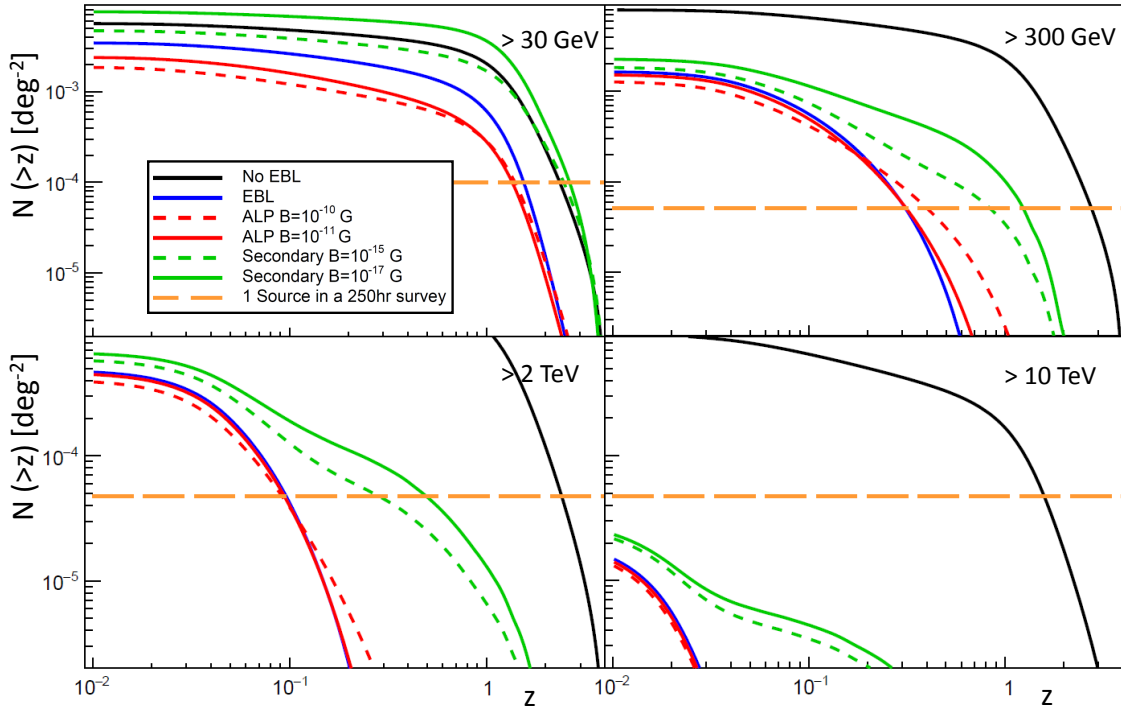


Fig. 6.4 Same as Figure 6.3, but assuming 0.5 hr exposure observations.

CTA South – 0.5 hr				
	>30 GeV	>300 GeV	>2 TeV	>10 TeV
No EBL	56	156	96*	20*
EBL	35	32	10*	-
ALP ($B=10^{-10}$ G)	19	25	8*	-
ALP ($B=10^{-11}$ G)	24	30	10*	-
Secondary ($B=10^{-15}$ G)	47	36	12*	1*
Secondary ($B=10^{-17}$ G)	76	45	14*	1*

Table 6.3 Estimated source count for a blind survey of 250 hours with observations of 0.5 hr with CTA-South in different energy bands and for the models considered in this chapter. Note: ‘-’ mark denotes no expected detection; ‘*’ this source count corresponds to a survey of half of the sky, which is completed in ≈ 130 hours.

CTA North – 0.5 hr				
	>30 GeV	>300 GeV	>2 TeV	>10 TeV
No EBL	22	68	36	8
EBL	13	15	4	-
ALP ($B=10^{-10}$ G)	7	12	4	-
ALP ($B=10^{-11}$ G)	9	14	4	-
Secondary ($B=10^{-15}$ G)	18	16	5	-
Secondary ($B=10^{-17}$ G)	32	20	6	-

Table 6.4 Same as Tab. 6.3, but for CTA-North.

6.2.1 On the impact of ALP and secondary gamma-rays

Secondary gamma-rays produce a significantly higher cumulative source count as shown in Fig. 6.2 and in Tables 6.3, 6.4, while the contribution of ALP seems more modest. Both effects are strongly dependent on the yet unconstrained IGMF strength, no firm conclusion could be drawn on ALPs or secondary photons of hadronic origin from a future CTA data analysis like the one outlined in this chapter alone. Nonetheless, Fig. 6.3 and Fig. 6.4 suggest that the different gamma-ray transport scenarios would lead to quite distinctive source distributions in redshift at the assumed CTA flux sensitivity, with possible discovery of sources at $z > 1$ at energies up to > 2 TeV for the secondary gamma-ray scenario, where a simple model including only EBL absorption would fail.

6.2.2 High altitude Cherenkov observatories

Although both HAWC and LHAASO have a worse sensitivity in the sub-TeV energy range compared to current or planned IACTs like CTA, they possess much larger FoV and duty

cycles, which make them very competitive for blazar discovery at multi-TeV energies. For this reason, I also derived expected source count for a 5-year survey with these experiments, with the assumption that the integral flux sensitivity simply scales with the square root of the observation time. The results can be seen in Tables 6.5 and 6.6. Installation of the 300 water Cherenkov tanks of HAWC was completed in 2015. Since then the facility has been operating at full capacity, providing already exciting first results [141–144]. HAWC has a very wide coverage of the sky (15% instantaneous, 2/3 over 24 hr) and it has a great potential for survey discovery. Here I estimated the number of extragalactic sources HAWC is expected to detect in 5 years of operation. The instrument integral sensitivity is provided in [140] only for gamma-rays of above 2 TeV, so I report my results only for this energy range. LHAASO is proposed to be composed of different kinds of detectors based on different detection techniques. Its flux sensitivity above 10 TeV is dominated by a particle detector array covering an area of $\sim 1 \text{ km}^2$. From 300 GeV to 10 TeV, the flux sensitivity is dominated by a combination of water Cherenkov detector array, similar to HAWC, and an array of wide field IACTs. The integral sensitivity used in this work is based on the one reported in [139] for 1 year observation with the water Cherenkov detector (sky coverage $\sim 7 \text{ str}$) and 50 hr with the IACTs. The duty cycle of any IACT is around 1000 hr per year. The FoV of the IACT array of LHAASO is $14^\circ \times 16^\circ$, which means it will take ~ 5 years for the ~ 7 steradians portion of sky covered by the companion detector to drift across the IACTs for a total of 50 hr observation per FoV. As it is difficult to disentangle the sensitivity of the two main components of the observatory, here I decided to simply scale the integral sensitivity in [139] with the square root of the total observational time. As in the case of CTA, adopting a shallow survey strategy with LHAASO would be more efficient in terms of source discovery potential. However, I note, as shown in Table 6.5 and 6.6, the effect of ALPs and the secondary gamma-rays is expected to be modest.

HAWC – 5 years	
	>2 TeV
No EBL	77
EBL	8
ALP ($B=10^{-10}\text{G}$)	7
ALP ($B=10^{-11}\text{G}$)	8
Secondary ($B=10^{-15}\text{G}$)	10
Secondary ($B=10^{-17}\text{G}$)	12

Table 6.5 Estimated source count for 5 years of HAWC data, for the models considered in this paper. See text for further details.

LHAASO – 5 years				
	>300 GeV	>2 TeV	>10 TeV	
No EBL	353	685	67	40
EBL	71	55	1	< 1
ALP ($B=10^{-10}$ G)	56	48	1	
ALP ($B=10^{-11}$ G)	66	53	1	
Secondary ($B=10^{-15}$ G)	81	76	2	
Secondary ($B=10^{-17}$ G)	100	90	2	

Table 6.6 Estimated source count with 5 years of LHAASO data, in different energy bands and for the models considered in this paper. See text for further details.

6.3 Conclusion

In this chapter, I presented predictions for blazar source count distribution for different VHE gamma-ray bands from > 30 GeV to > 10 TeV. Tables 6.1, 6.2 summarize the expected number of sources discovered by means of an unbiased extragalactic survey for both CTA-North and CTA-South as a function of the exposure time. My study confirms that a shallower, more extended survey with observation time of around 0.5 hr per FoV is optimal for CTA in order to maximize the discovery potential of new sources. I also calculated the number of blazars detectable by LHAASO (see Tab. 6.6) and HAWC (see Tab. 6.5). Here I considered a steady state, averaged SED. The impact of flares in this study would be particularly relevant for high-duty-cycle experiments like LHAASO and HAWC.

I also investigated how the source count distribution would be modified in the presence of ALPs or secondary gamma-rays of hadronic origin. Tables. 6.3, 6.4 show examples of the effect that either ALPs or secondary gamma-rays may have for the detectable source count for a survey of 0.5 hr per FoV for the two CTA locations. I conclude that a simple cumulative source count analysis would not be definitive to claim ALPs detection or hadronic acceleration in AGN, yet a multi-wavelength campaign with precise measurement of sources at different redshifts could provide a hint of any of these two scenarios being at work. Most notably, for the case of secondary gamma-rays, that produces a very distinctive source count redshift distribution, with expected detections of sources at $z > 1$ at energies up to > 2 TeV (Fig. 6.3 and Fig. 6.4).

Chapter 7

Conclusions

The IACT technique has been very successful for detecting VHE gamma-rays. Indeed, previous experiments obtained outstanding innovative science results. CTA aims to push the technique to unprecedented levels, putting much focus on the technology required to achieve its ambitious goals. The state-of-the-art technology has to be improved not only in terms of performance, but also in cost per unit telescope. CTA is expected to host more than 100 telescopes, with ~ 70 SSTs. Innovative solutions to enhance performance while reducing costs are then especially relevant for telescopes tuned for the multi-TeV range of the gamma-ray spectrum. In this thesis, I described my contributions to the development of one of these proposals: the GCT camera prototype based on MAPM photosensors. I focused on the core components necessary to develop a camera able to detect VHE gamma-rays. In particular on the testing, commissioning and integration of the custom made front end electronic modules and the Backplane. Another key component was the development of the software to operate and control the camera. From very low level drivers of most of the components, to high level, user friendly scripts. I was a protagonist of the integration of the camera with the telescope structure and the data acquisition of cosmic-ray initiated Cherenkov showers. The full proof-of-concept of a dual mirror Cherenkov telescope saw light for the first time. In addition to my effort to the development of instrumentation for multi TeV gamma-ray astrophysics, I explored the potential for CTA to detect extragalactic sources. In this context I also considered the impact that a different gamma-rays propagation scenario would have. In particular I refer to the possible existence of axion-like particles and secondary gamma-rays from hadronic acceleration in AGN.

7.1 Future Work

In this section I conclude with the future work that is expected to follow my thesis. I report briefly on the effort started towards the development of a silicon photomultiplier

(SiPM) based camera, CHEC-S, and the integration of libCHEC with the rest of the CTA array software. My contribution to the development and commissioning of CHEC-M are of critical importance towards the design of CHEC-S and further pre-production camera prototypes. In the last part I comment on possible future improvement on the predictions for an extragalactic survey with CTA.

7.1.1 CHEC-S

In CHEC-M, the communications to the Backplane are interrupted every time the DACQ implementing the SPI protocol freezes due to buffer overflow. In the CHEC-S architecture, the Backplane will communicate to an external PC directly via ethernet. This connection will be fast enough to record the trigger hit pattern for every event.

One new DACQ board will replace the functionalities of the two old ones. A single 10 Gbps link over optical fiber will connect it to the PC. The buffer depth will also be increased to contain more than one entire event. The precise timing synchronization with the rest of the array, absolute trigger time-stamping and clock distribution will be provided by the same external timing board that every camera in CTA will host.

A so-called Safety Board will replace the functionalities of the Peripheral Board. It will have an independent ethernet connection to a PC and will be the first component to receive power from an power distribution board. The Safety board will in turn control the latter to supply DC voltage to the rest of the components in the camera. At the same time, it will also take care of the very safety critical parameters of the camera, like the current drawn by some components. Some simple logic will allow it to react to a dangerous value reading by switching off the relevant components. It will not be able to access all the information from all the parts in the camera; for example, the temperature read on a target module, so a higher level of control will be kept in software, as discussed in sec. 7.1.3.

During testing in the environmental chamber it was found that the CHEC-M lid was not completely water-tight. Its redesign is shown in Fig. 7.1. The dual door design will also improve performance against wind gusts. The doors are asymmetric so that the centre of the lid can be imagined by a CCD in the centre hole of the secondary. The reflection of stars on the lid surface can be used for pointing accuracy measurement.

A new shaping pre-amplifier is under design, it will be based on a variation of the zero-pole-cancellation amplifier to shorten the long signal tail (hundreds of ns) typical of SiPM. For CHEC-S the photosensor of choice is SiPM Hamamatsu S12646-1616PA-50, but for future camera prototypes the photosensor is still under investigation because the technology is improving very rapidly. For example, the Hamamatsu device was improved even in the short time between order and delivery. The 100 μm resin thick coating was replaced by a thinner 20 μm film one, like shown in Fig. 7.2, to enhance PDE and reduce

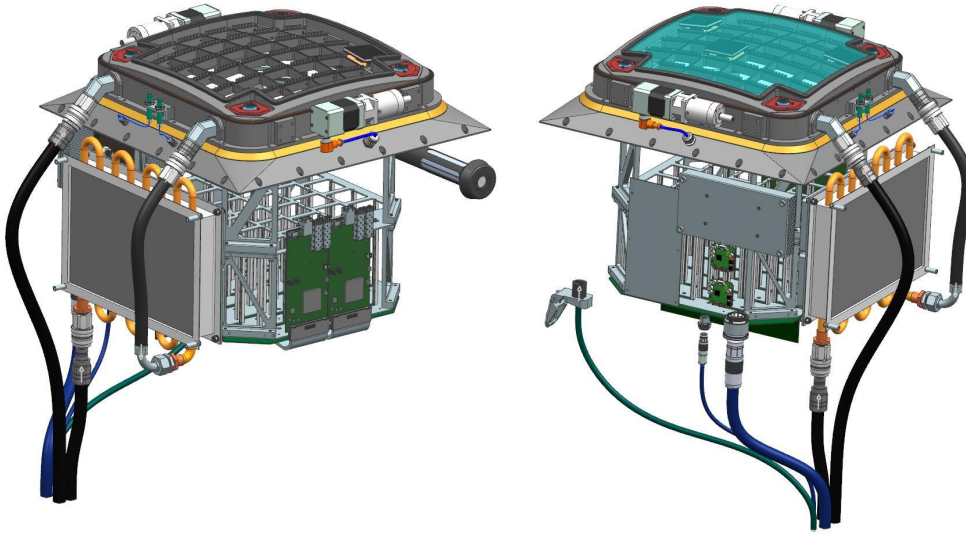


Fig. 7.1 3D CAD of the focal plane of CHEC-S. A dual door Lid is operated by two motors. Cooling pipes circulate coolant in drilled holes in the focal plane plate. Credit to the GCT collaboration.

optical cross talk between pixels. This change was reflected in the introduction of a window in front of the focal plane plate, because dirt and dust could enter the small gaps between the photosensors. The choice of the material of the window is not yet finalized.

The SiPM performances are notoriously sensitive to temperature changes. They can be corrected with a feed-back loop regulating the supplied voltage [145, 146], but stabilizing temperature is still very important. The focal plane plate of CHEC-S will be drilled to allow circulation of coolant as shown in Fig. 7.1.

The TARGET5 ASIC showed a significantly lower level of noise on the trigger line when sampling functionalities were disabled. The TARGET7 ASIC has a better dynamic range and linearity, but shows a similar behavior. The next generation of TARGET modules will have the two features in separate dedicated ASICs, T5TEA for trigger and TC for sampling. The former is based on the TARGET5 ASIC, but stripped of any sampling capacity. The very first batch of ASICs has been produced and testing has started. Design of the module PCB hosting the ASIC is under investigation.

7.1.2 Software

At the time of writing of this thesis¹, a process of simplification and slimming of external library dependencies is undergoing to reduce risk for future maintenance. At the same time the software structure has to address the change in the hardware components and their hierarchy. The major change regards the Safety Board which will have a limited set of

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very basic reactions to dangerous situations to ensure the survival of the system based on a few parameters to which it has access. It will act independently, reporting to the Camera Controller process, that will in turn handle more complex logic involving all aspects of the camera.

Recently a new study started on a redesign of the highest level software due for the integration of the camera related software with the CTA central array control software architecture. This is envisaged to happen via the standard OPC-UA protocol as a middle-ware transport layer, and a level higher via the Alma Common Software infrastructure [147].

7.1.3 Predictions for a CTA extragalactic survey

In the work I reported in Chapter 6, I considered the latest public available sensitivity studies for CTA. Those are based on the second Monte Carlo production for CTA. Some of the assumptions are based on outdated descriptions of the telescope performance and analysis tools. The prototyping phase for CTA is entering its last stage and a new, more detailed, Monte Carlo production is to be expected. The new studies will also be able to be finely tuned to the specific characteristics of the site where CTA will be built, because these locations were recently selected. Another important assumption on the estimated integral sensitivity of CTA is on the sample source spectra. The latest reported data are for a Crab-like spectrum. The predictions on the number of blazars detectable by CTA will benefit from a study tuned towards an averaged blazar SED, as I presented in Chapter 6. A new effort is due on the expectation of the instrument performance. Nonetheless the results presented in this thesis on the source count distribution still stand. Fig. 6.2 can still be used for a newly computed integral sensitivity to estimate the number of sources an instrument is expected to detect.

In my work, I focused only on blazars because they are the dominant source class in the extragalactic VHE sky. Nonetheless current IACT observatories reported discovery of a handful of starburst and radio galaxies. It is still very difficult to quantitatively estimate detectability of these populations by a survey. Although gamma-ray luminosity functions for starburst galaxies and radio galaxies are available (e.g. [148, 149]), they are still highly uncertain because the sample size is small and they make use of luminosity functions at different wavelengths considering luminosity correlations. Moreover, the SEDs of these source categories at the VHE band are not well established yet. However, CTA is expected to increase the number of these sources with its improved sensitivity [150, 151]. CTA will potentially also lead to the even more exciting discovery of new source populations in the VHE sky.

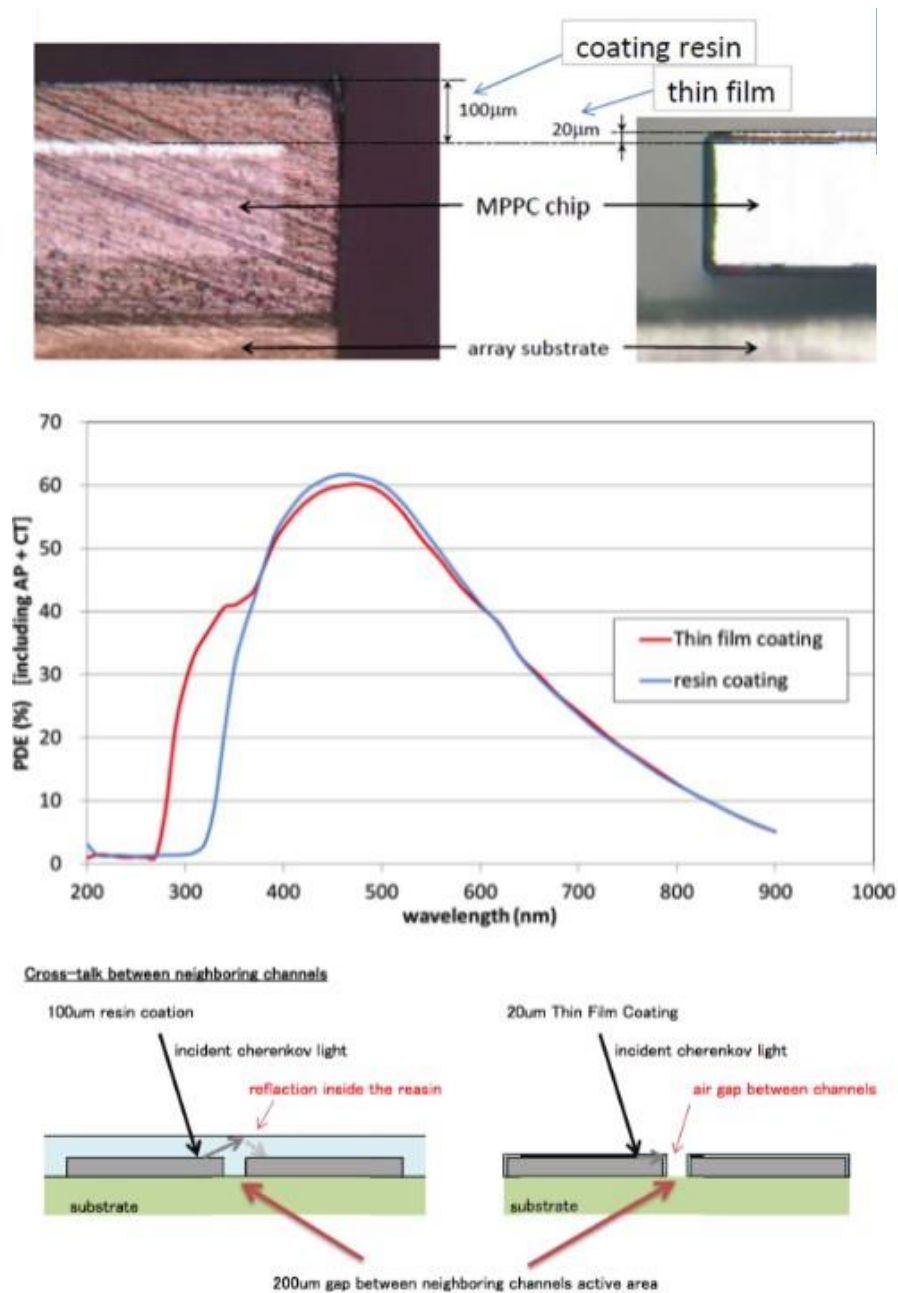


Fig. 7.2 Different coating for SiPM. Delivered sensors showed an increased PDE and reduce cross talk between pixels due to air gap allowed by a reduction of the coating resin. Credit to Hamamatsu and the GCT collaboration.

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