The GCT Camera for the Cherenkov Telescope Array

J.S. Lapington[a], A. Abchiche[b], D. Allan[c], J.-P. Amans[d], T.P. Armstrong[c], A. Balzer[e], D.Berge[e], C. Boisson[d], J.-J. Bousquet[d], R. Bose[f], A.M. Brown[c], M. Bryan[e], G. Buchholtz[b], J. Buckley[f], P.M. Chadwick[c], H. Costantini[g], G. Cotter[h], M.K. Daniel[j], A. De Franco[h], F. De Frondat[d], J.-L. Dournaux[d], D. Dumas[d], J-P. Ernenwein[g], G. Fasola[d], S. Funk[j], J. Gironnet[b,d], J.A. Graham[c], T. Greenshaw[i], O. Hervet[d], N. Hidaka[k], J.A. Hinton[l], J.-M. Huet[d], D. Jankowsky[j], I. Jegouzo[d], T. Jogler[j], T. Kawashima[k], M. Kraus[j], P. Laporte[d], S. Leach[a], J. Lefaucheur[d], S. Markoff[e], T. Melse[d], I. A. Minaya[i], L. Mohrmann[j], P. Molyneux[a], P. Moore[f], S.J. Nolan[c], A. Okumura[k,i], J.P. Osborne[a], R.D. Parsons[l], S. Rosen[a], D. Ross[a], G. Rowell[m], C.B. Rulten[n], Y. Sato[k], F. Sayede[d], J. Schmoll[c], H. Schoorlemmer[l], M. Servillat[d], H. Sol[d], V. Stamatescu[m], M. Stephan[e], R. Stuik[o], J. Sykes[a], H. Tajima[k], J. Thornhill[a], L. Tibaldo[l], C. Trichard[g], G. Varner[p], J. Vink[e], J.J. Watson[h], R. White[l], N. Yamane[k], A. Zech[d], A. Zink[j], and J. Zorn[l], for the CTA Consortium[q]

[a]Department of Physics and Astronomy, University of Leicester, University Road, Leicester, LE1 7RH, UK

[b]CNRS PSL Research University, Division technique DT-INSU, 1 Place Aristide Briand, 92190 Meudon, France

[c]Department of Physics and Centre for Advanced Instrumentation, University of Durham, South Road, Durham, DH1 3LE, UK

[d]Observatoire de Paris, CNRS PSL Research University, LUTH and GEPI, Place J. Janssen, 92195, Meudon cedex, France

[e]GRAPPA, University of Amsterdam, Science Park 904, 1098 XH Amsterdam, The Netherlands

[f]Washington University at St Louis,1 Brookings Dr, St. Louis, MO 63130, United States

[g]Aix Marseille Universite, CNRS/IN2P3, CPPM UMR 7346, 163 Avenue de Luminy, case 902, 13288 Marseille, France

[h]Department of Physics, University of Oxford, Keble Road, Oxford OX1 3RH, UK

[i]University of Liverpool, Oliver Lodge Laboratory, P.O. Box 147, Oxford Street, Liverpool L69 3BX, UK

[j]Erlangen Centre for Astroparticle Physics (ECAP), Erwin-Rommel-Str. 1, D 91058 Erlangen, Germany

[k]Institute for Space-Earth Environmental Research, Nagoya University, Furo-cho, Chikusa-ku, Nagoya, Aichi 464-8601, Japan

[l]Max-Planck-Institut fur Kernphysik, P.O. Box 103980, D 69029 Heidelberg, Germany

[m]School of Chemistry and Physics, University of Adelaide, Adelaide 5005, Australia

[n]Department of Physics and Astronomy, University of Minnesota, Minneapolis, MN, 55455, United States

[o]Leiden Observatory, Leiden University, Postbus 9513, 2300 RA, Leiden, Netherlands

[p]Department of Physics and Astronomy, University of Hawaii, 2505 Correa Road, Honolulu, HI 96822, United States

[q]www.cta-observatory.org

Abstract

The Gamma Cherenkov Telescope (GCT) is one of the designs proposed for the Small Sized Telescope (SST) section of the Cherenkov Telescope Array (CTA). The GCT uses dual-mirror optics, resulting in a compact telescope with good image quality and a large field of view with a smaller, more economical, camera than is achievable with conventional single mirror solutions. The photon counting GCT camera is designed to record the flashes of atmospheric Cherenkov light from gamma and cosmic ray initiated cascades, which last only a few tens of nanoseconds.

The GCT optics require that the camera detectors follow a convex surface with a radius of curvature of 1 m and a diameter of ~35 cm, which is approximated by tiling the focal plane with 32 modules. The first camera prototype is equipped with multi-anode photomultipliers, each comprising an 8 × 8 array of 6 × 6 mm^2 pixels

to provide the required angular scale, adding up to 2048 pixels in total. Detector signals are shaped, amplified and digitised by electronics based on custom ASICs that provide digitisation at 1 GSample/s. The camera is self-triggering, retaining images where the focal plane light distribution matches predefined spatial and temporal criteria. The electronics are housed in the liquid-cooled, sealed camera enclosure. LED flashers at the corners of the focal plane provide a calibration source via reflection from the secondary mirror.

The first GCT camera prototype underwent preliminary laboratory tests last year. In November 2015, the camera was installed on a prototype GCT telescope (SST-GATE) in Paris and was used to successfully record the first Cherenkov light of any CTA prototype, and the first Cherenkov light seen with such a dual-mirror optical system. A second full-camera prototype based on Silicon Photomultipliers is under construction. Up to 35 GCTs are envisaged for CTA.

Keywords: GCT; Cherenkov Telescope Array; Schwarzschild-Couder; Imaging Air Cherenkov Telescope; Photon-counting; Camera.

Introduction

The Cherenkov Telescope Array (CTA) [1] is a project to build the next generation ground-based γ-ray observatory. CTA will build on the strengths of current imaging atmospheric Cherenkov telescopes (IACT), employing three telescope design groupings, the Large, Medium and Small-sized Telescope arrays to enhance the sensitivity over current facilities by up to an order of magnitude [2] in the 100 GeV to 10 TeV range and extend the accessible energy range from well below 100 GeV to above 100 TeV. The SST array is optimized for sensitivity and coverage from a few TeV to 300 TeV. At these extreme energies Cherenkov light production per air shower is higher but the primary γ-ray flux is lower; the limiting science driver becoming the number of observed events as opposed to the collected Cherenkov light. Thus, the optimum SST array configuration has a large field of view comprising around seventy telescopes over a ~4 km^2 area utilising moderately sized telescopes with a ~4 m, primary mirror diameter. Three different SST prototypes [3] are being developed: the single mirror (SST-1M) instrument lead by groups in Switzerland and Poland, and 2 dual mirror Schwarzschild-Couder design (SST-2M) instruments, ASTRI, developed by an Italian consortium, and GCT by groups in Australia, France, Germany, Japan, the Netherlands, and the United Kingdom.

IACT detector requirements differ from those for conventional optical telescopes in several respects. The diffuse nature of the Cherenkov air shower requires only moderate spatial resolution, however discrimination of the very fast and faint Cherenkov air shower events from the night sky background requires photon counting detectors with nanosecond time resolution. Whereas traditional single mirror IACTs typically utilise large PMT arrays, the SST dual mirror designs demagnify the air shower image, the resulting smaller plate scale being well-suited to pixelated photon counting detectors with high time resolution, such as the multi-anode photomultiplier (MAPM) and silicon photomultiplier (SiPM) arrays. Both detector types can be tiled to cover the convex focal plane to match its 1 m radius of curvature, and are available in 8 x 8 $pixel^2$ formats of ~6 x6 mm^2 pixels, compatible with the SST-2M spatial resolution requirements.

The first GCT prototype camera (CHEC-M) [3] which utilised MAPMs was commissioned and integrated with the GATE telescope at the Observatoire de Paris, Meudon, first-light being observed in November 2015. This represented a double milestone: the first Cherenkov event detection achieved both by a Schwarzschild-Couder telescope design, and the first by a CTA prototype telescope.

The second GCT prototype camera (CHEC-S) is a refinement of the mechanics and electronics of CHEC-M with the addition of SiPM detectors to replace the MAPMs. The performance of solid-state SiPM detectors has evolved rapidly in recent year and they now offer a combination of photon detection efficiency, noise performance, lifetime and durability that give distinct advantages over the photocathode and vacuum tube technologies of MAPMs.

The CHEC-S camera is currently under manufacture and will be commissioned and tested on-telescope in 2017, followed very closely by the pre-production camera, with which it shares much in common. Three pre-production cameras, engineered for mass production, will be built in 2017 and deployed on-site at the southern CTA site, likely to be at Paranal close to the European Southern Observatory, Chile.

THE GCT camera

The CHEC-S design, shown in figure 1, represents the latest generation of GCT camera prototypes. The camera has an overall size of 50×52×56 cm^3, weighs 44 kg and has a total power consumption of ~600W. The curved focal plane is tiled with 32 camera modules each with a SiPM tile comprising a 16×16 array of 3×3 mm^2 pixels electrically organised as 8×8 6×6 mm^2 pixels by summing 2×2 channels: a camera total of 2048 pixels imaging a field of view of ~8°. The later pre-production camera is may use SiPMs with an 8×8 format of 6×6 mm^2 physical pixels that were not available for CHEC-S. The readout electronics are designed to provide full waveform capture of every pixel following an event trigger. The SiPM tile is mounted on a detector biasing PCB, which is coupled via a 64-channel preamplifier to the TARGET module [5], the latter providing event triggering and waveform digitisation. The modules are mounted in a rack and plug into a backplane which manages event triggering and data communications with the data acquisition board (DACQ) which communicates with the outside world.

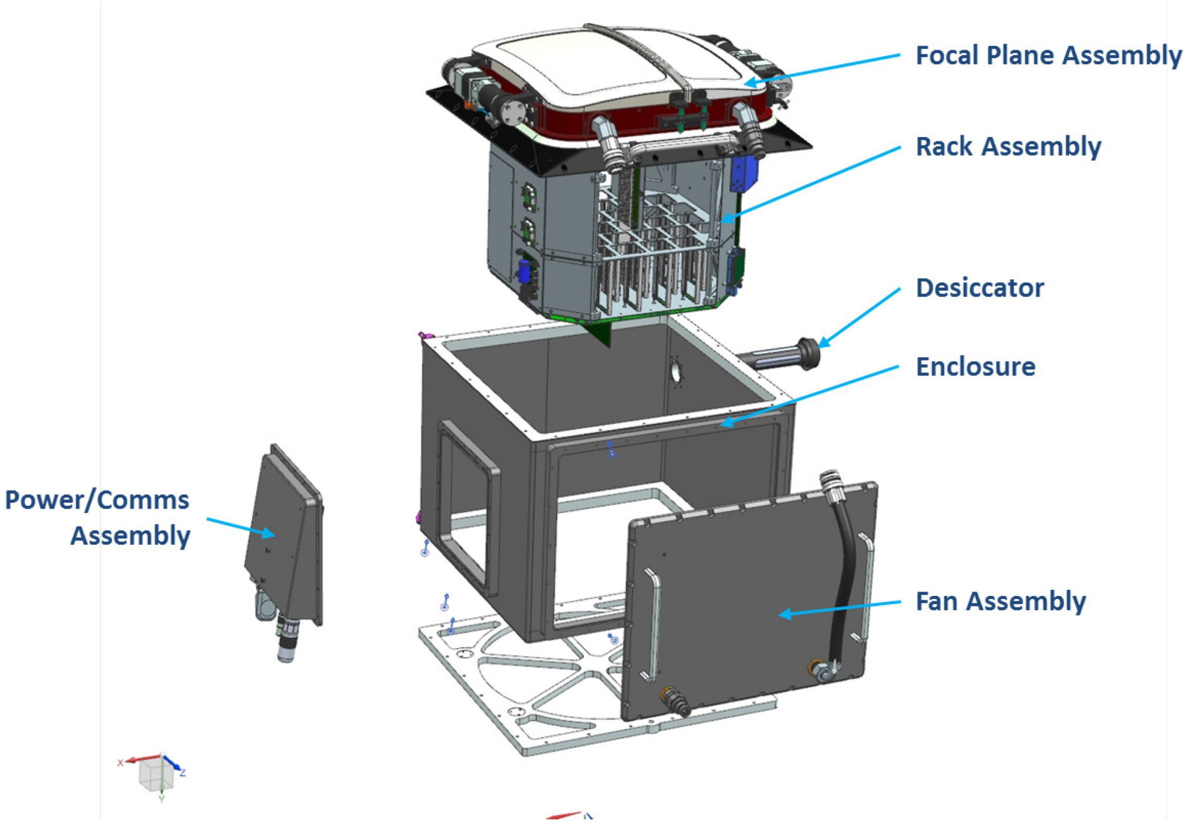

Figure 1. an exploded view of the CHEC-S camera showing the individual mechanical components. The rack assembly is shown without the FEE modules installed.

Mechanical design

CHEC-S has three major mechanical components: (i) the focal plane plate including detector window and water-tight door, operated by two motors, which protects the focal plane from weather and shields the sensors during daytime, (ii) the rack which houses the camera modules and supports the backplane, DACQ, timing, safety, power and peripheral electronics boards, and (iii) the enclosure which protects the camera internals and houses the cooling system and electrical, communications, cooling and mechanical interfaces.

The focal plane plate supports the 32 detector modules in the required focal plane curvature. The higher heat dissipation of the SiPMs used in CHEC-S requires focal plane cooling (see figure 2) which is provided by chilled water passing through drillings in the outer frame and ribs separating the modules. The SiPM tiles and preamplifiers are cooled via copper heatsinks which mount on the focal plane assembly. This water also cools the complete enclosure removing ~600W from the electronics modules via a heat exchanger and forced air circulation. The cooling water is supplied from a separate chiller unit.

Lessons learned from CHEC-M have driven a revised design and assembly method. The electronics rack mounts onto the focal plane, allowing it to be fully populated with detectors and electronics modules prior to installation into the enclosure. The backplane is mounted on the rear of the rack and the FEE modules, including preamplifiers connected to the TARGET modules via coaxial ribbon cables, are inserted through the focal plane apertures and plugged into power and data connectors on the backplane, guided and aligned using a locating mechanism. The preassembled detector units comprising the SiPM tile, biasing board and heatsink then plug into the focal plane from the front, and the hermetically sealed window, manufactured from either acrylic or borosilicate glass, is fitted over the detectors to prevent ingress of moisture.

Following attachment of the DACQ, safety, timing, power and peripherals boards to the rack, the camera enclosure is fitted from the back, mounting onto a flange on the focal plane. The enclosure houses the heat exchanger and fan assembly, the power and communications assembly, the desiccator, and the telescope mounting flange.

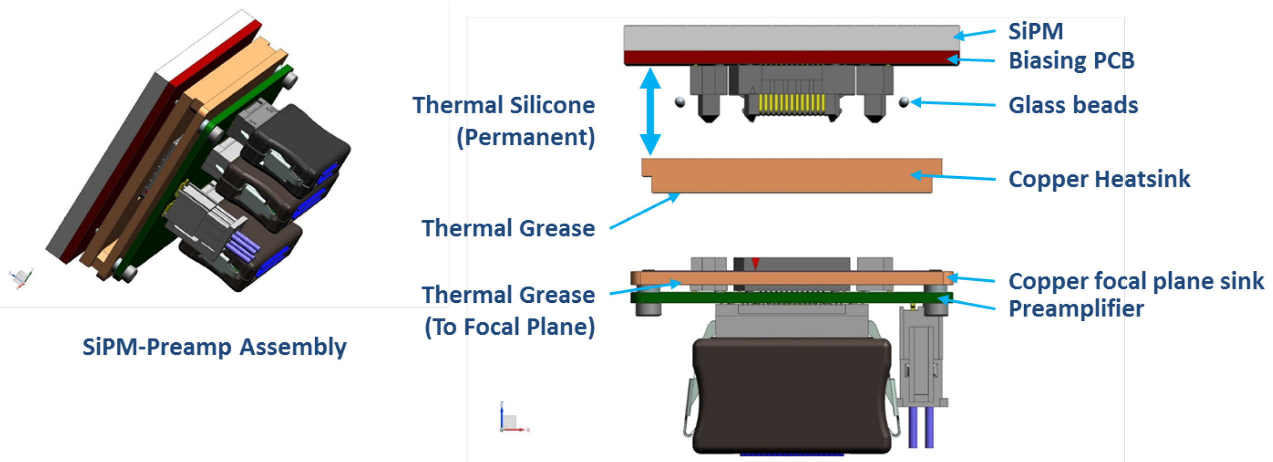

Figure 2. A drawing showing the sensor assembly, including the biasing board, preamplifier board, connectors and heatsinks which attach to the cooled focal plane plate.

Electronics

The camera electronics are divided into two logical blocks: front-end electronics (FEE) and back-end electronics (BEE). The 32 identical FEE modules each comprise a preamplifier board connected via coaxial ribbon cables to the TARGET module, which combines triggering, signal digitisation and communications functionality. The BEE comprises the backplane, DACQ board, timing board, power board, safety board and peripherals board.

The SiPM tile is bonded to the biasing PCB, which distributes the operating voltages to the pixels and output signals from the pixels to the 64-channel preamplifier board. The preamplifier is a trans-impedance design using a miniature and cost-effective quad op-amp circuit which is coupled to the TARGET modules using coaxial ribbon cables.

The TARGET module provides analogue signal shaping, generates event triggers, digitises event waveforms, provide the SiPM operating voltages and handles data and control communications. The 64 channel shaping amplifiers have both a fast readout for triggering and digitisation of the Cherenkov signal and slow readout for star tracking. The fast signal is processed using four of the latest 16 channel TARGET ASIC chipsets; the chipset comprises the T5TEA chip which generates a trigger based on the above-threshold analogue sum of 2×2 adjacent detector pixels (known as a super-pixel), and the TC chip, which digitises a selectable time-slice (typically 96ns) with a resolution of 12 bits at tuneable rate, typically 1GSample/s. First level triggers from every TARGET module are routed to the trigger FPGA on the backplane which implements the camera-wide trigger based on a 2 nearest super-pixel neighbour algorithm. In the event of such a trigger the backplane initiates a full camera digitisation, and generates a unique event number which is stamped onto the raw data transferred via the backplane to the DACQ board.

The DACQ board is a 10Gbps Ethernet switch which provides the fast data link via an SFP+ fibre optic cable. Other boards for camera operation include the safety board which controls overall camera operation and provides failsafe functionality, the timing board which handles absolute event timestamping and synchronisation using a White Rabbit interface. the power distribution board and the peripherals board which controls the LED flasher calibration sources [6] positioned at each corners of the focal plane, and door closure. All camera control functionality is controlled via a separate Ethernet connection distributed via a network switch. The camera is powered from a single power supply with independent modules for primary power (12V), safety board power (12V) and SiPM bias (70V).

First results

The first prototype GCT camera, CHEC-M, was assembled and underwent commissioning from March to October 2015. The camera was integrated in stages over a period of months, checking the functionality of subsystems, and developing control and data acquisition software, as assembly progressed. Once fully operational the camera underwent thermal and functional testing. The latter was undertaken in a dark box using pulsed lasers and diffuse LED sources to simulate Cherenkov radiation and the night sky background respectively. The 32 MAPM detectors were tested at their nominal operating voltage of 1100V and measurements included single photon response and noise levels for all pixels followed by calibration which included gain matching of all camera modules and characterisation of the transfer function of every channel.

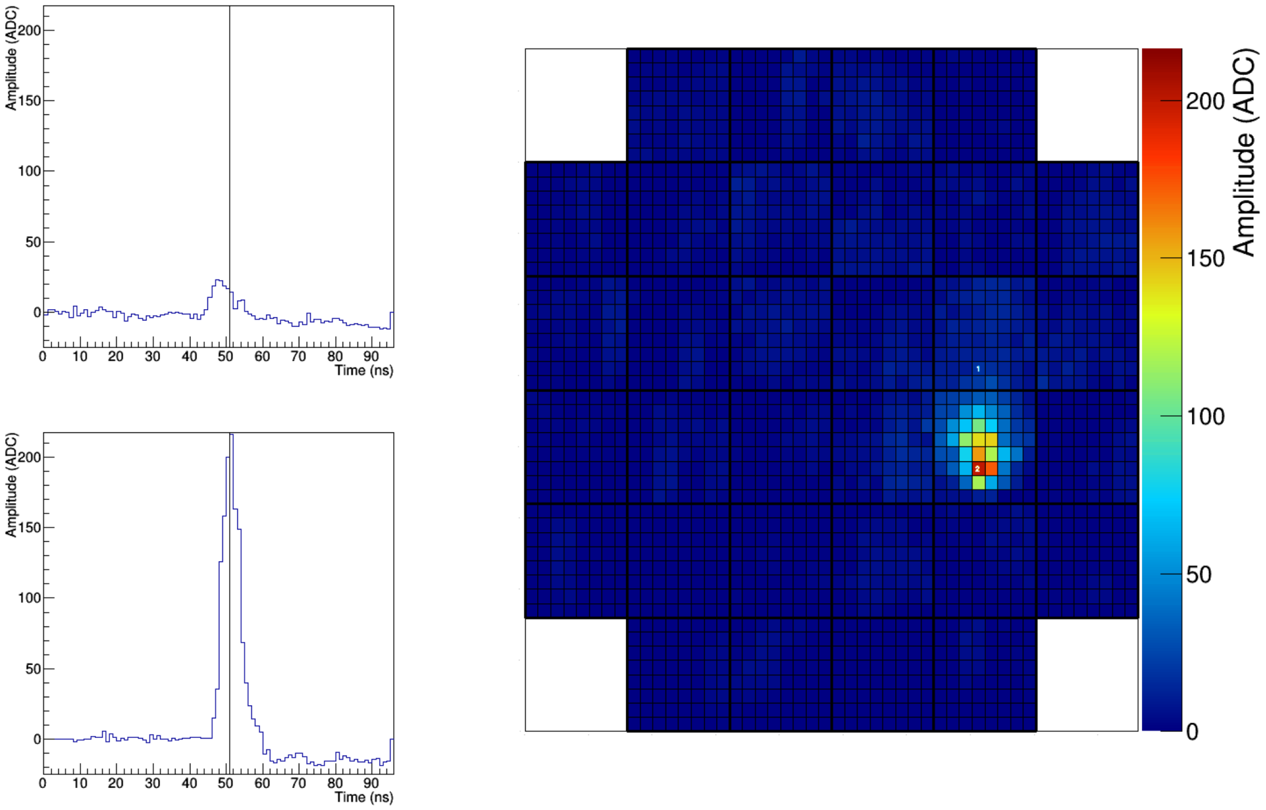

Figure 3. First light – a Cherenkov air shower event detected by CHEC-M over Paris. The left-hand plots show the temporal waveforms recorded in the pixels marked 1, and 2 in the right-hand image. The right-hand image shows the pixel intensities in the selected time bin; the peak value was ~275 p.e.

The CHEC-M camera was delivered to the Observatoire de Paris mid-November 2015 and integrated onto the GATE telescope structure over the following two weeks. Despite adverse weather conditions and the very background light levels in the Paris night sky (25-30 times higher than expected at the CTA site in Chile) first light was achieved prior to the GCT inauguration at the beginning of December. The high background light levels required reduced operating voltage and observation time was limited by weather conditions to a few minutes, however 12 Cherenkov events were observed in this time at a rate of ~0.04 event/s. Figure 3 shows one of these events with the waveform seen in two of the illuminated pixels. The data clearly shows an event of a few nanoseconds duration which moves spatially and temporally across the detector; the clear signature of a Cherenkov air shower. The intensity of the brightest pixel in this event is estimated to be ~275 p.e. based on extrapolation from lab calibration at higher operating voltage. The smaller number of data precluded any detailed study but a first level Monte-Carlo analysis showed that the data was consistent with proton showers of energy > 50TeV.

Summary

The GCT camera offers a high performance and cost-effective solution for SST-2M telescopes, capable of full waveform readout of its 2048 pixels at event rates of up to 600 count/s. The CHEC-M camera achieved 2 milestones at its inauguration in December 2015; the first observation of Cherenkov light using Schwarzschild-Couder two mirror optic and the first by a CTA prototype. CHEC-M is returning to the Observatoire de Paris in early 2017 for further operational tests on the GATE telescope, which has now undergone mirror alignment and has a fully operational pointing system. The latest CHEC-S prototype camera design has been refined using lessoned learned with CHEC-M and is close to the pre-production design. CHEC-S will utilise higher performance, robust SiPM detectors and will be compatible with both SST-2M telescope designs. CHEC-S is currently under manufacture and will be tested on-telescope in 2017.

Acknowledgements

We would like acknowledge the agencies and organizations listed at http://www.cta-observatory.org for the support and funding for the GCT telescope development.

References

[1] CTA Consortium, 2013, ‘Introducing the CTA concept ’, Astroparticle Physics, 43, 3

[2] Actis, M., et al., Design concepts for the Cherenkov Telescope Array CTA: an advanced facility for ground-based high-energy gamma-ray astronomy, Experimental Astronomy 32 (3) (2011) 193–316.

[3] Montaruli, T., Pareschi, G & Greenshaw, T., for the CTA Consortium and the SST-1M, ASTRI and GCT sub-consortia, 2015, Proceedings of the 34th ICRC, The Hague, ‘The small size telescope projects for the Cherenkov Telescope Array ’, arXiv 1508.06472

[4] De Franco, A., et al., 2015, Proceedings of the 34th ICRC, The Hague, ‘The first GCT camera for the Cherenkov Telescope Array.’, arxiv 1509.01480

[5] Tibaldo, L., et al., 2015, Proceedings of the 34th ICRC, The Hague, ‘TARGET: toward a solution for the readout electronics of the Cherenkov Telescope Array ’, arxiv 1508.06296

[6] Brown, A.M, Armstrong, T.P, Chadwick, P.M, Daniel, M.K and White, R, for the CTA collaboration, 2015, Proceedings of the 34st ICRC, The Hague, ‘Flasher and muon-based calibration of the GCT telescopes proposed for the Cherenkov Telescope Array ’, 934, arxiv 1509.00185