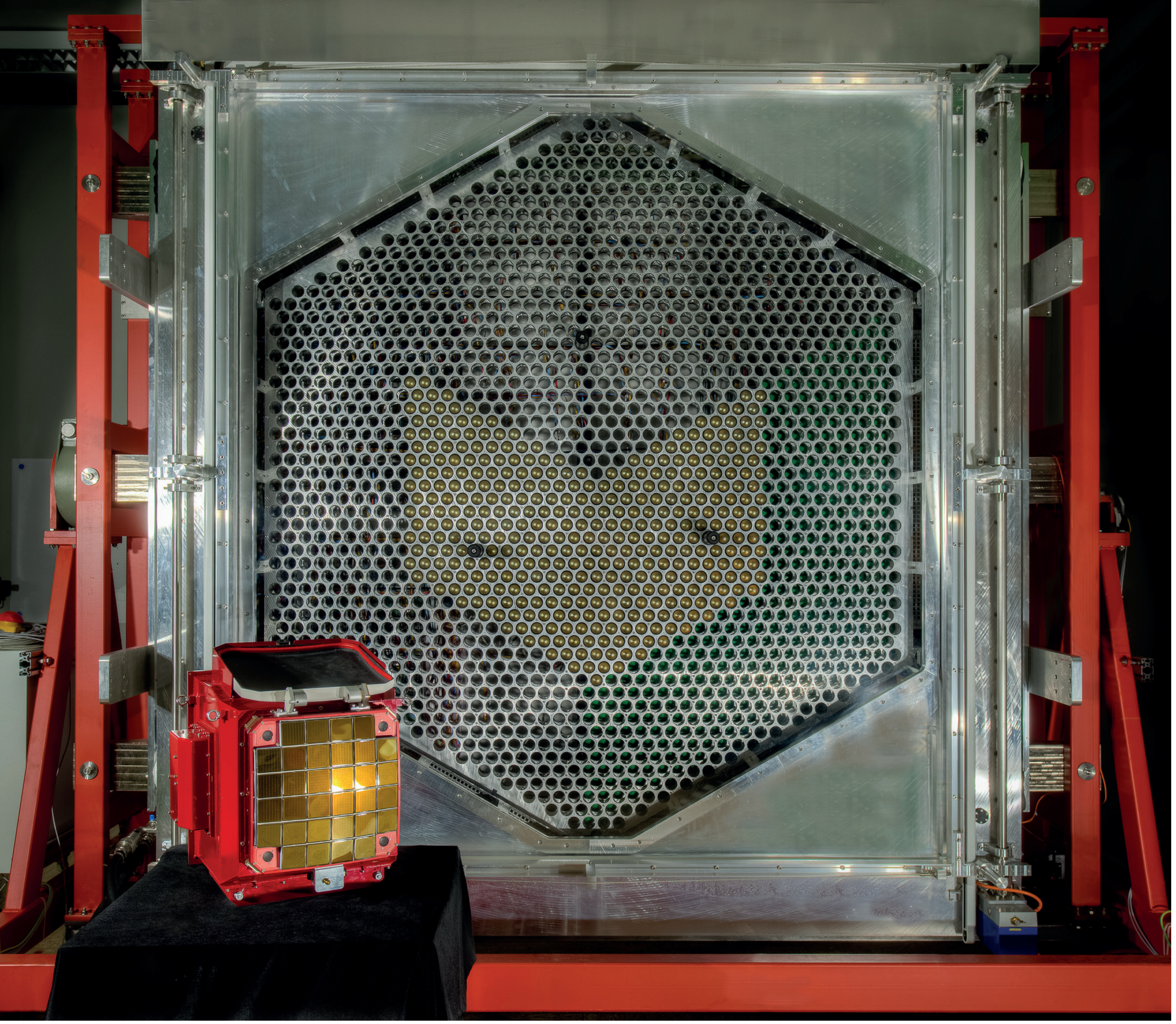

The compact CHEC Cherenkov camera developed for the Small-Size Telescope of the Cherenkov Telescope Array (CTA), in front of the 3 m wide FlashCam camera prototype, for the Medium-Size CTA Telescope.

1.1 Observational Gamma-Ray Astronomy

Introduction

Observational high-energy astrophysics at MPIK is primarily concerned with the study of non-thermal phenomena in the Universe using ground-based instruments to detect very-high-energy (VHE) gamma rays from the cosmos.

Gamma rays in the VHE energy range – with energies in the domain of 10^{12} electron volts – cannot be produced as thermal radiation, like the electromagnetic radiation in most other wavelength regimes; only in the Big Bang were high enough temperatures reached for a very short time. Rather, gamma rays are believed to have their origin in interactions of high-energy cosmic particles with interstellar gas or radiation fields. The high-energy particles themselves – nuclei or electrons – are deflected in Galactic and intergalactic magnetic fields and either cannot reach the Earth at all – in the case of sources in distant galaxies – or will only arrive after a million-year diffusive motion, where they lose all directional information concerning their origin. Imaging the locations where, and identifying the mechanisms by which, particles gain their high energies is hence very difficult. The secondary gamma rays, however, trace the populations of such particles; allowing the cosmic “particle accelerators” to be revealed. Spectral gamma-ray measurements enable the flux and spectrum of the primary particles to be derived.

Owing to the low flux of Teraelectronvolt (TeV, 10^{12} eV) gamma rays – ranging from a few gamma rays per m^2 per year to one per m^2 per century for the sources of interest, detection techniques rely on the Earth’s atmosphere to absorb the gamma rays, creating a cascade of secondary particles – an air shower – which are then registered over a large area – some 10^4 to 10^5 m^2 – either directly or indirectly using ground-based detector systems. The development and operation of such detection systems is an essential element of MPIK's programme in astroparticle physics, and is summarised in this section of the report; the scientific results are the subject of the following Chapter 1.2.

Air showers can be detected via the particles penetrating to the ground, via the Cherenkov light and fluorescence light emitted by shower particles in the atmosphere, and via their radio emission. Fluorescence light and radio detection are so far only feasible at ultra-high energies, and have not found application in gamma-ray astronomy. Work at MPIK started – about three decades ago – with ground-based particle detection – the HEGRA and CRT air shower arrays – but then quickly turned to the more promising Cherenkov technique, evolving through three generations of instruments: the HEGRA telescopes, the currently operating High Energy Stereoscopic System H.E.S.S., and the Cherenkov Telescope Array CTA, under construction.

Cherenkov telescopes image the optical Cherenkov light produced by air shower particles, that illuminates a circular area of about 250 m diameter on the ground and can be detected there (Fig. 1). Cherenkov telescopes use large optical reflectors to focus – on dark nights – the Cherenkov light onto a matrix of photon detectors, the “camera”. Compared to (at most) m^2-sized satellite-based instruments, which intercept the gamma rays above the atmosphere, Cherenkov telescopes provide huge detection areas of 10^5 m^2 and beyond, governed by the diameter of the Cherenkov light pool; their energy coverage ranges from few tens of GeV to – currently – tens of TeV. At TeV energies, the faintest sources detected have a flux as low as 10^{-13} gamma rays per cm^2 and second. The H.E.S.S. telescope system has been a main contributor to the breakthrough of VHE gamma-ray astronomy in the last

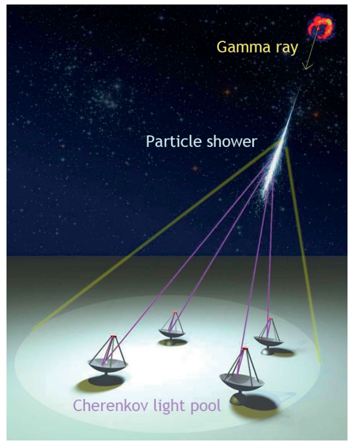

Fig. 1: Detection of primary gamma rays using the Cherenkov light from the gamma-ray induced air showers. The different views of the air shower provided by multiple telescopes allow reconstruction of the shower geometry and hence of the direction of the incident gamma ray.

Fig. 2: The H.E.S.S. telescope system in Namibia, with the four 108 m^2 telescopes CT1-CT4 operational since late 2003, and the new 614 m^2 telescope CT5, inaugurated in 2012.

decade; the Cherenkov Telescope Array (CTA) currently under preparation builds upon this success and will provide the next-generation open observatory for gamma-ray astronomy.

Only recently, with the participation in the high-altitude HAWC air shower array, has interest at MPIK in ground-level particle detection systems been revived; instruments such as HAWC cannot match the energy threshold, sensitivity, angular resolution and energy resolution of Cherenkov telescopes, but are complementary in that they provide full-sky coverage, near-100% duty cycle, and allow detection of large-scale emission features that are difficult to disentangle for the limited field of view Cherenkov telescopes.

The High Energy Stereoscopic System (H.E.S.S.)

The H.E.S.S. system of Cherenkov telescopes (Fig. 2) is the primary workhorse of gamma-ray astronomy at MPIK. The system has been operational since late 2003, initially with four telescopes with 108 m^2 reflector area and 960-pixel cameras, and since 2013 with the additional (H.E.S.S. II) telescope with 614 m^2 reflector area and a 2048-pixel camera. In cooperation with other institutes, MPIK provided the structures and drive systems of all telescopes, the mirrors, and the photosensors of the H.E.S.S. I cameras. In late 2016, the electronics of the aging H.E.S.S. I cameras was replaced in an upgrade carried out by DESY, aimed at improving reliability and allowing higher readout rates, relevant if H.E.S.S. I telescopes are triggered in coincidence with the large H.E.S.S. II telescope with its much lower energy threshold – the original H.E.S.S. telescopes provide an energy threshold of approximately 100 GeV, whereas the H.E.S.S. II telescope registers air showers down to 20 GeV gamma-ray energy.

Over the years, the H.E.S.S. telescopes have accumulated 13 700 hours of observations, with a total of 2×10^{10} air showers recorded. MPIK serves as one of the H.E.S.S. data centres; computing capacity and disk space have been continuously upgraded to keep up with the increasing amounts of data and simulations. Figs. 3 and 4 illustrate the discoveries of VHE gamma-ray sources with H.E.S.S., and the sky coverage of H.E.S.S. observations; selected science results are presented in Chapter 1.2.

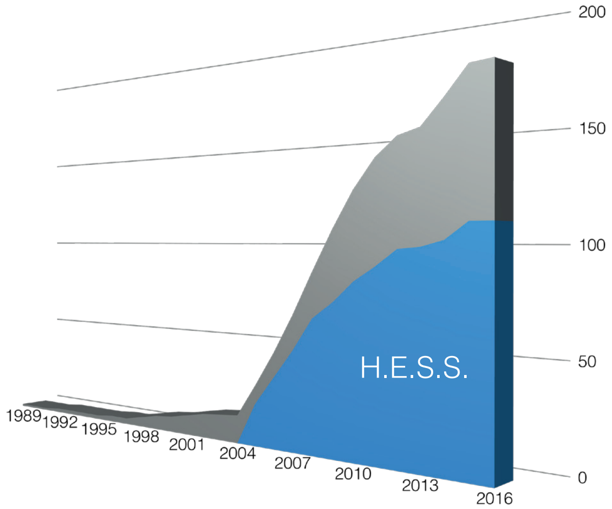

Fig. 3: Discovery of VHE gamma-ray sources over the years; the blue area shows H.E.S.S. discoveries.

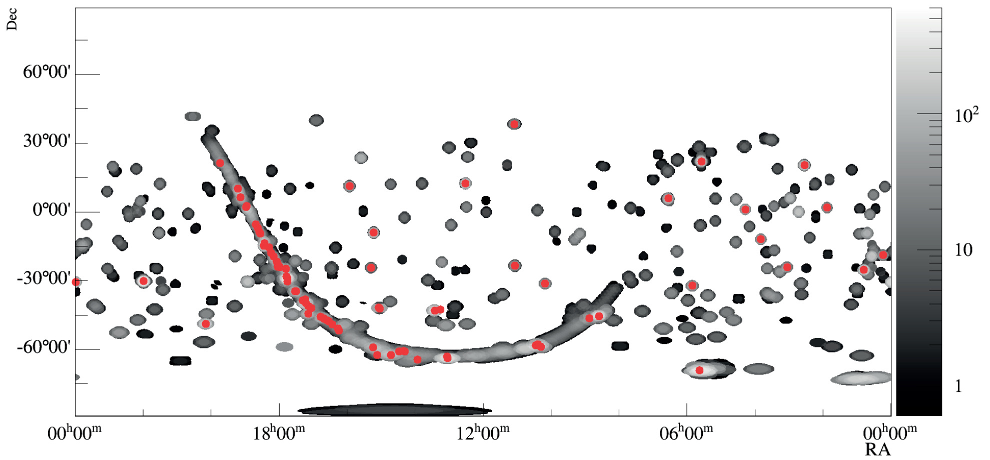

Fig. 4: Sky coverage of H.E.S.S. observations (grey circles, in hours), and H.E.S.S. detections of very-high-energy gamma-ray sources (red points).

The H.E.S.S. II telescope has recorded 2700 hours of data, mostly together with the four H.E.S.S. I telescopes, partly also in stand-alone mode, with the other telescopes observing a different target. Development of data analysis tools proved more time-consuming than expected, due to initial hardware issues, the difficult gamma-hadron separation at low energies, and the challenge of – for the first time – combining data from different-sized telescopes; an exercise that will prove extremely fruitful towards CTA data analysis. Observations in the H.E.S.S. II era focus to a significant extent on steep-spectrum sources such as distant AGN, and on triggered observations of flaring targets such as Gamma-Ray Bursts; the powerful drive system of the H.E.S.S. II telescope and its capability to slew beyond zenith allow typical re-pointing times below one minute. H.E.S.S. II results on a number of science topics are presented in Chapter 1.2.

The Cherenkov Telescope Array (CTA)

The aim of the Cherenkov Telescope Array (CTA) project [1] is the construction of a next-generation observatory for ground-based gamma-ray astronomy (Fig. 5), with a factor 10 better sensitivity than current-generation instruments (Fig. 6). CTA will in addition provide larger energy coverage of over four decades from a few tens of GeV to several 100 TeV, better angular resolution reaching into the few-arcminute regime, and a larger field of view; it will serve as a highly sensitive instrument for surveys as well as for the search for point-like sources and the study of the morphology of extended sources. Full sky coverage will be achieved through the installation of two arrays, one in the southern hemisphere, providing full energy coverage, and a northern array with emphasis on the low-energy instrumentation. To cover the whole energy range in a cost effective way, CTA arrays will consist of over 100 Cherenkov telescopes of different classes with dish diameters of approximately

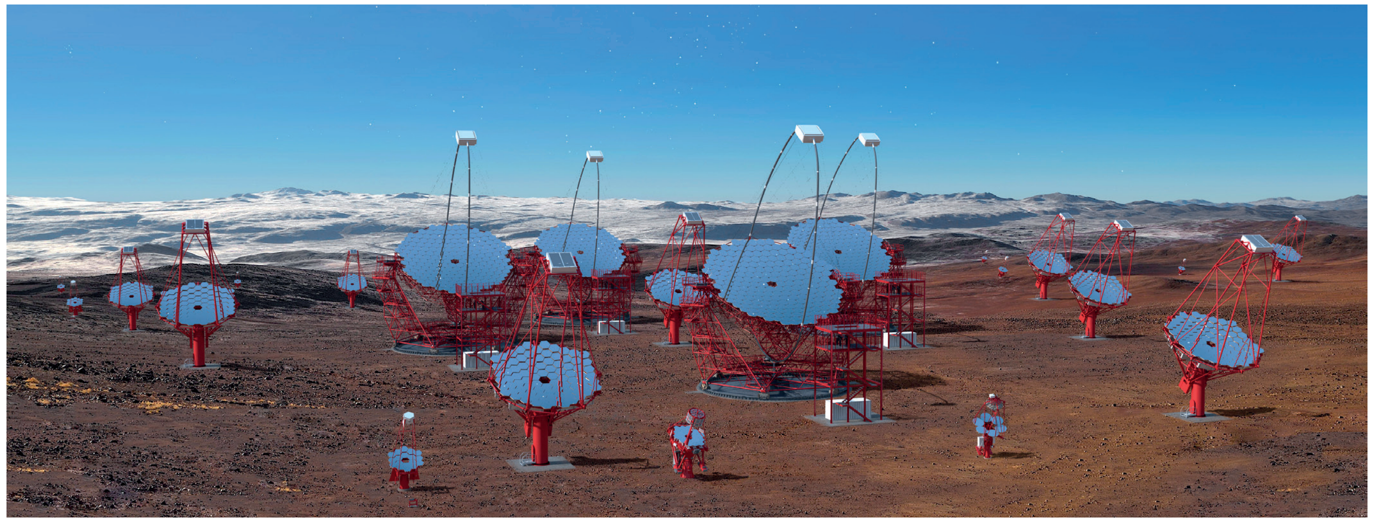

Fig. 5: Rendering of the southern CTA array, combining telescopes of 4, 12 and 23 m size. Credit: G. Pérez, IAC, SMM

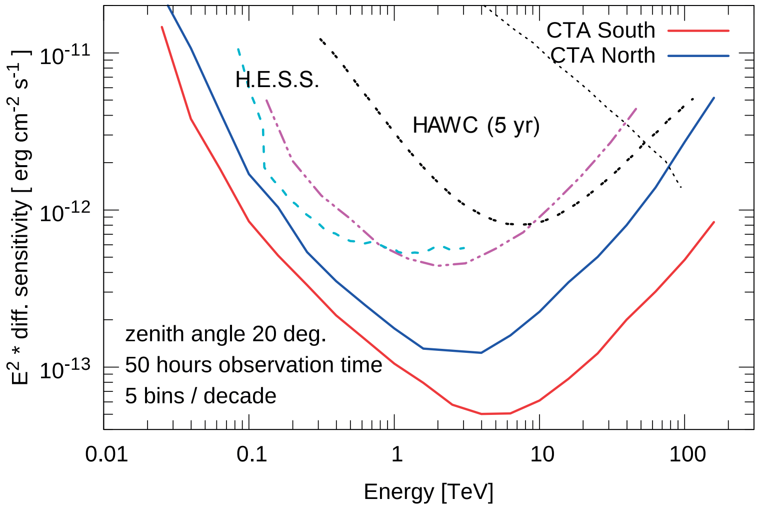

Fig. 6: Energy flux sensitivity of H.E.S.S., of the northern and southern CTA arrays and of HAWC, as a function of energy.

4, 12 and 23 m, distributed over an area of about 5 km^2 in the southern array and a smaller area in the north. CTA will be the first truly open VHE observatory, providing accessible data products and support services to a wide community.

The Cherenkov Telescope Array (CTA) Consortium formed in 2008, it now (as of late 2016) has grown to over 200 institutes in 32 countries. In 2014, the CTA Observatory (CTAO) gGmbH was founded with its seat in Heidelberg – initially at the Landessternwarte, then at MPIK – as an interim legal entity to prepare for CTA implementation. The CTA project has undergone a series of independent gateway reviews, with the Critical Design Review completed in June 2015. A comprehensive programme of site search and evaluation was conducted from 2010-2013, resulting in a shortlist of sites. In July 2015 contract negotiations began for the hosting of CTA at the European Southern Observatory (ESO) Paranal site in Chile and at the Instituto de Astrofisica de Canarias (IAC), Roque de los Muchachos Observatory in La Palma, Spain. A hosting agreement between CTAO and IAC was signed in September 2016; the agreement with ESO is expected to be signed in early 2017. In June 2016, the CTAO Council selected Bologna (Italy) and Zeuthen (Germany) to host the CTA Headquarters (HQ), and the CTA Science Data Management Centre (SDMC). Signature of an MoU between CTA parties regarding funding of CTA started in October 2016. Infrastructure construction on the sites will start in 2017, in parallel with the deployment of pre-production telescopes aiming to verify mass production, deployment and commissioning, followed by large-scale deployment starting around 2019. Initial user operation of partially-completed arrays is expected for 2021/22.

Major MPIK contributions to CTA concern (i) management: Werner Hofmann has served as Spokesperson since 2008 and was first Managing Director of the CTAO gGmbH (2014-2016), Jim Hinton has served as Project Scientist since 2012; (ii) simulations for the prediction and optimisation of CTA performance; (iii) software development and calibration algorithms; (iv) development and production of the FlashCam Cherenkov camera for the Medium-Size Telescope (MST) and (v) development and production of the CHEC focal plane instrumentation for the Small-Size Telescope (SST).

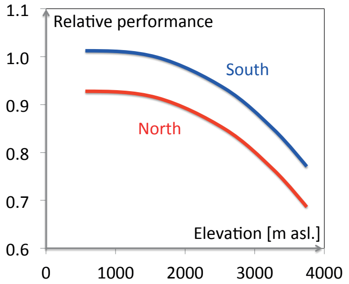

Fig. 7: Relative spectrum-averaged sensitivity of the CTA telescope arrays as a function of site altitude, for northern sites (red) and southern sites (blue), as predicted by detailed simulations. The difference between the northern and southern sites is caused by the larger geomagnetic fields at the northern sites, distorting the development of gamma-ray induced air showers.

Simulating CTA. The design of the CTA arrays is the result of a decade-long, multistep optimisation process, relying heavily on detailed simulations of the instrument, including the development of gamma-ray initiated cascades in the atmosphere, the propagation of Cherenkov light to the telescopes, ray-tracing of the imaging system and the modelling of the electronic signal processing, requiring a massive computational effort [2]. CTA simulations are based on the CORSIKA air shower simulation code interfaced to the *sim_telarray* telescope simulation package developed and continuously improved by K. Bernlöhr at MPIK.

Early studies included semi-analytical estimates and simulations of regular grids; from these studies emerged the need for three telescope sizes to efficiently cover the wide energy range of CTA and address all of the major science questions. The basic characteristics of these telescopes in terms of optical design, photosensor and data capture characteristics were fixed as requirements based on these early simulations, plus a first very-large-scale simulation of realistic CTA telescope arrays. Later large-scale simulations served to assess the site-dependence of performance (in particular site altitude and geomagnetic field) and to establish appropriate telescope spacing. These simulations showed that best performance is obtained by deploying the arrays at altitudes below 2000 m asl (Fig. 7); at lower altitudes, the energy threshold of the arrays increases, resulting in an optimal range around 1500 to 2000 m asl. A final very large simulations effort was used to fine-tune the layouts. In total, MPIK computing systems contributed about 10 million CPU hours to the CTA simulation effort. The final fully optimised telescope arrangement for the southern CTA site is presented in Fig. 8.

Significant effort was furthermore invested in the development of air shower reconstruction algorithms and in the simulation of calibration algorithms. The IMPACT reconstruction algorithm [3], for example, relies on the comparison of measured shower images with a library of image templates. IMPACT provides much improved performance over classical algorithms, as demonstrated with H.E.S.S. data where it is routinely used. Extensive simulations served to demonstrate the calibration of individual CTA telescopes with muon ring images, the cross-calibration of telescopes using air shower events, and the use of cosmic-ray electron spectra for overall array calibration [4].

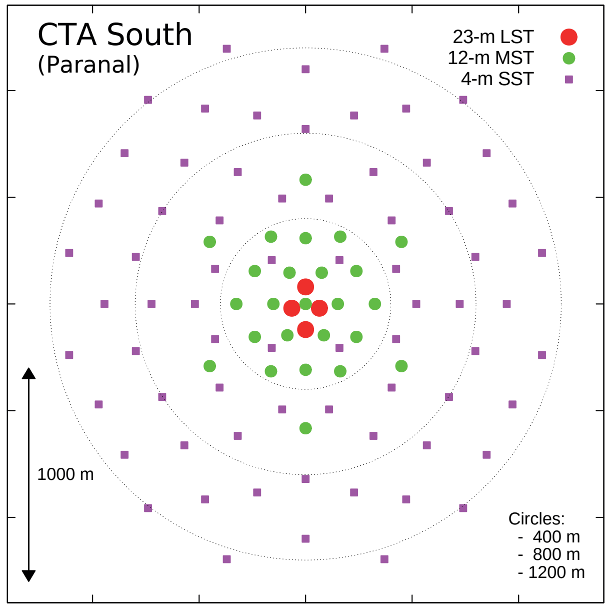

Fig. 8: Baseline layout of telescopes on the southern CTA site, combining 4 Large-Size Telescopes (LST), 25 Medium-Size Telescopes (MST) and 70 Small-Size Telescopes (SST).

FlashCam: a fully digital camera for the CTA telescopes. FlashCam [5] (see title image) is a camera development project for the 12-m medium-size CTA telescope (MST). FlashCam was initiated by the MPIK, and is carried out in cooperation with partner groups from Germany, Switzerland, Austria and Poland. In contrast to “classical” Cherenkov cameras, as installed in current-generation telescopes, the FlashCam concept follows a fully digital approach for the signal processing, using commercially available microchips produced for the growing digital communications market. Besides the mechanical structure, the key building blocks of such a camera are the photon detector plane (PDP), the readout electronics (ROS) and the data acquisition system (DAQ) with the camera server CPU (see Fig. 9).

This functional division provides a high degree of flexibility in the choice of the photosensors or in the detailed layout of the camera. The 1764-pixel photon detector plane (PDP) consists of 147 PDP-modules, each with 12 photomultiplier tubes (PMT). Each module includes high voltage supplies, preamplifiers and a microcontroller for control, monitoring and safety functions. The analogue signals from the pixels are transmitted through standard ethernet cables to the readout electronics. The custom-developed readout electronics of the camera use fast analogue to digital converters (FADC) that digitise the incoming signals continuously with a sampling frequency of 250 MSamples/s and 12-bit resolution. The digitised signals of 24 channels per electronics board are then buffered in a field programmable gate array (FPGA), where the signals are digitally processed and prepared for storage. The key point of this concept is to perform all signal processing based on digitised information. In particular, the trigger decision to store an image is computed in the camera solely from the digitised signals. Depending on the configuration, the total continuous data traffic which is processed within the camera electronics may amount to more than 2 Tb/s. Upon a trigger, the digital image information is then sent to the camera server of the data acquisition system (DAQ), using standard Ethernet components. A water-based cooling system allows the camera to be hermetically sealed, and its temperature to be kept stable.

Together with the project partners, the MPIK has produced a prototype camera (title image and Fig. 10), equipped with the full readout electronics and (so far) about 50% of the photosensors. Based on the experience in assembling and operating the prototype, various details of the design were improved towards mass production. All performance characteristics have been verified in the lab: the prototype meets or exceeds all specifications, including amplitude and time resolution and noise. Deadtime-less readout at up to 30 kHz event rate has been demonstrated. Particular emphasis was placed on verifying the reliability of the design and the long-term stability; the prototype was so far operated in a test environment for well over 1000 hours, including temperature cycling and continuous variation of the orientation of the camera. The next step will be the construction of two pre-production cameras of the final design; for deployment and operation on the CTA southern site. In total, it is planned to build 15 cameras, with MPIK serving as the site for assembly, integration and test.

Fig. 10: Rear view into the FlashCam body, showing in the centre the photon detector plane modules, and in racks left and right the Flash-ADC modules and trigger processors.

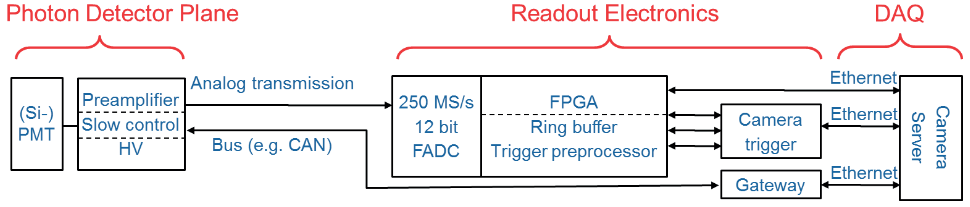

Fig. 9: Basic building blocks of a FlashCam camera.

Fig. 11: The prototype of the GCT telescopes in Paris-Meudon, during the inauguration on Dec. 1, 2015. Insert: The CHEC Cherenkov camera, see also title image.

The CHEC camera for the small-size telescopes. The Compact High Energy Camera (CHEC, see title image and Fig. 11) [6] is a development project for the dual-mirror small-size telescopes (SST-2M) of the Cherenkov Telescope Array (CTA), involving MPIK and UK, US, Japanese, Australian and Dutch institutes. The short focal length of the dual-mirror optics of these telescopes results in a very compact camera, with curved focal plane of diameter ~35 cm providing an 8° field of view. The CHEC camera in its first prototype uses multi-anode photomultipliers (MAPMs); a second prototype and the production units will use silicon photomultipliers, with a total of 2048 pixels. For signal capture, the CHEC camera employs the TARGET ASIC, a 16-channel analogue pipeline with a depth of 16 000 samples, operated at 1 GHz sampling frequency. The CHEC camera is built up of 64-channel modules, each module containing the sensors, preamplifier circuits, four sets of TARGET sampling and trigger ASICs, voltage generators for the sensors, digitisers and an FPGA for control and readout. MPIK contributions include software for testing, calibration and operation, extensive testing and characterisation of the prototypes, and optimisation of the mechanical design and of the water-based cooling system of the camera. Together with the other partners, the current plan is to provide 50 CHEC cameras, with MPIK serving as the primary site for assembly, integration and test.

On 26 November 2015, the prototype of the CHEC camera, mounted on a prototype (4-m diameter) SST-2M telescope (Fig. 11) recorded CTA's first ever Cherenkov light while undergoing testing at the Observatoire de Paris in Meudon, France (Fig. 12).

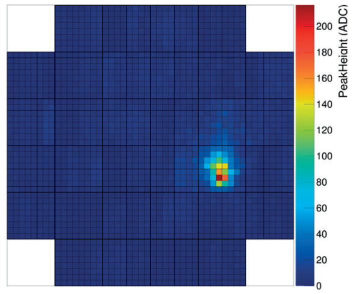

Fig. 12: One of the first Cherenkov images recorded by the CHEC camera on the GCT telescope, during testing in November 2015.

Improving the High Altitude Water Cherenkov (HAWC) Observatory

Compared to past ground-based shower particle detectors, the High Altitude Water Cherenkov (HAWC) gamma-ray detector has achieved a dramatic increase in sensitivity by combining (a) a high-altitude location at 4100 m asl. in Mexico, (b) tightly packed detectors covering about 60% of the 20 000 m^2 array area, and (c) the calorimetric detection of ground particles using deep water Cherenkov detectors, allowing to – at least partially – identify muons among the shower particles, using those to veto hadron-induced showers. HAWC consists of 300 water Cherenkov detectors of 7.3 m diameter and 4.5 m height (Fig. 13); the tanks are filled with high-purity water and each contain four photomultipliers anchored at the bottom, detecting the Cherenkov light emitted by shower particles in the water. The shower direction is reconstructed using the arrival time of the signals in the different tanks, with a precision ranging from 1° to 0.2° depending on the number of tanks hit; the sensitivity of HAWC is illustrated in Fig. 6 in comparison to H.E.S.S. and CTA.

The performance of HAWC is partly limited by the relatively small size of the detector array, which implies that most showers are detected at the periphery of the array where it is difficult to distinguish between a low-energy shower with its core just inside the array, and a high-energy shower with core position far outside the array, but with a tail of its energy deposition within the array. This has resulted in the plan to add a sparse outrigger array, allowing higher-energy showers outside the array to be identified. MPIK joined HAWC in early 2016, contributing to the outrigger array as well as working towards improved algorithms for data analysis. With six members, the MPIK group is already among the larger HAWC groups. The outrigger array [7] (Fig. 14) consists of 300 smaller water tanks of 1.7 m diameter and 1.6 m height. The outrigger tanks are read out by the MPIK-developed FALCON flash-ADC system, that is based on the modules developed for the FlashCam Cherenkov camera. The ability to record waveforms – rather than time over threshold as for the current HAWC readout – provides a further opportunity to identify penetrating muons and to reject cosmic rays. Significant simulation effort was invested at MPIK towards optimising the geometry and instrumentation of the outrigger tanks.

A key motivation for joining HAWC was to gain experience towards the longer-term goal of implementing a wide field of view, large duty cycle detection system in the southern hemisphere, that would complement CTA in several ways, for example providing triggers for CTA observations of variable sources. A water Cherenkov array similar to HAWC, but at even higher altitude (~5000 m asl.), of larger footprint (~50 000-100 000 m^2) and with depth-segmented detectors for optimised identification of shower muons would further boost performance, at – in comparison to CTA – relatively modest cost.

*Konrad Bernlöhr, German Hermann, Jim Hinton,
Werner Hofmann, Michael Panter, Richard White*

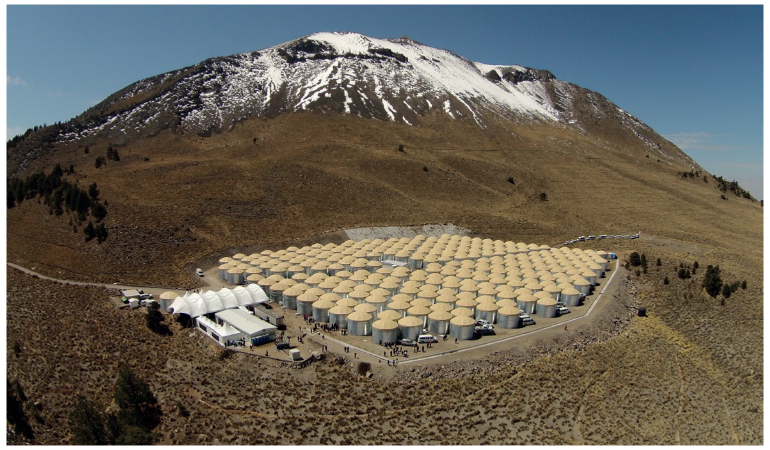

Fig. 13: Overview of the HAWC array of water Cherenkov detectors, located on the Sierra Negra in central Mexico, at 4100 m asl. Credit: HAWC Collaboration

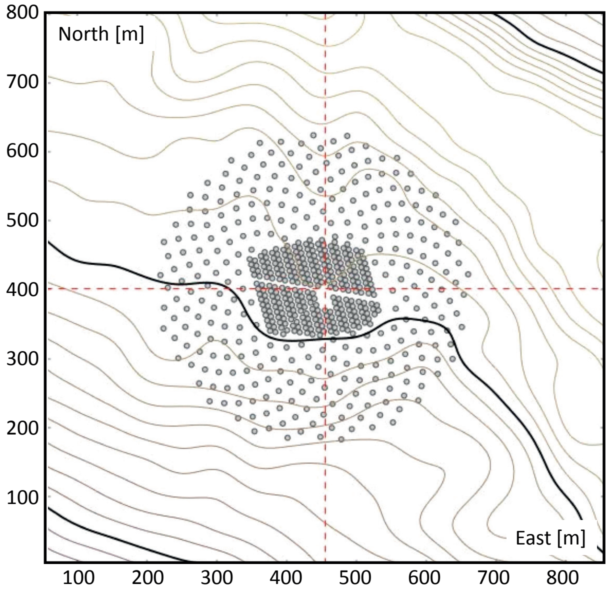

Fig. 14: HAWC "outrigger" array with 300 additional water Cherenkov detectors, currently under construction.

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