The High Energy Stereoscopic System (HESS) Project

Werner Hofmann, for the HESS collaboration

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

Abstract. The paper summarizes the status of the HESS project as one of the next-generation instruments for VHE gamma-ray astronomy. In its first phase, a system of four large Cherenkov telescopes with about 100 m^2 mirror area will be installed in the Khomas Highland of Namibia. A later expansion of the system to up 16 telescopes is foreseen.

In the following, I will briefly touch upon the physics goals of HESS, review the basic configuration choices governing the layout of the HESS telescope array, cover some details of the technical implementation, summarize the key performance parameters and close with the current status of the project. I will concentrate on the first phase of the project.

I PHYSICS GOALS OF HESS

The basic physics goal of HESS is to provide a comprehensive study of non-thermal phenomena in the universe, using TeV gamma-ray emission as a diagnostic tool, with emphasis on the precise spectral and spatial mapping of sources. In this context, "TeV gamma rays" stands for the $10^{12\pm1}$ eV range. TeV gamma rays are (almost) always secondary products; one is primarily interested in the parent populations, including in particular galactic and extragalactic nonthermal electron populations, and the nucleonic component of the nonthermal universe. In addition, issues in observational cosmology and astroparticle physics can be addressed, and sky surveys will provide an unbiased view of the TeV gamma-ray sky.

Gamma rays from nonthermal electron populations are characterized by their double-humped spectra governed by synchrotron radiation at low (often keV) energies, and by the IC component at high energies. From the analysis of multiwavelength spectra, the electron spectrum and the local B fields can be determined. Interesting galactic sources include pulsar nebulae; a source of the strength of the Crab Nebula can be detected almost anywhere in the Galaxy. Among extragalactic sources, AGNs are of special interest. HESS will be able to detect a source like

Mrk 501 out to $z \approx 0.3$, limited mainly by the $1/r^2$ decrease in flux rather than by absorption of gamma rays in interactions with the IR/O background.

A central part of the HESS program will be the search for the elusive sources of the nucleonic cosmic rays. Here, gamma rays are used to probe the product of the local CR density times the local gas density. Targets include SNR as CR sources, but also Giant Molecular Clouds which allow to probe the distribution and spectrum of CR throughout the Galaxy. Probing the CR flux in external galaxies is also of great interest; here, starburst galaxies and clusters of galaxies are expected to generate a detectable gamma-ray flux.

Observational cosmology and astroparticle physics with HESS includes the measurement of the IR/O background density with its implications concerning the history of galaxy formation, the search for pair halos around AGNs, which allow to measure absolute distances, and the search for WIMP annihilation lines from the galactic center.

II CONFIGURATION CHOICES

Site. At the time of the Kruger Park meeting, the Calar Alto in Spain was considered the prefered site for HESS. Since then, the HESS collaboration has abandoned this option, both because of the climatic conditions, which would require expensive domes for the telescopes, and because of a preference for locations on the southern hemisphere, with direct view onto the Galactic center. A suitable site, with excellent and documented optical quality, mild climate, and a large and easily accessible area has been located in the Khomas Highland in Namibia, near the Gamsberg, about 1.5 driving hours from the capital, Windhoek. The Gamsberg, a table mountain at about 2300 m asl., has been discussed as a possible site for a European southern observatory, and the optical quality of the Gamsberg site has been monitored continuously from 1970 to 1975 and in 1994/1995. In terms of the number of spectroscopic and photometric nights, the Gamsberg area is equivalent to La Silla. Because of the difficult access, the top of the Gamsberg is not suitable to install large telescopes. However, apart from seeing, which is not an issue for Cherenkov telescopes, the highland around the Gamsberg, at about 1800 m asl., provides the same conditions. Therefore, the plan is to rent an area of about 10 km^2 of one of the large farms near the Gamsberg. The infrastructure required for HESS – a control building, a residential building, and power generators – is more or less identical to the infrastructure of a typical farm, and will be built by the MPG in a similar style. Fig. 1 shows a view of the candidate site, which is easily accessible from the main road.

Energy regime and telescope size. The layout of the telescope system, under certain funding constraints, represents a compromise between the wish to have a large number of telescopes for best reconstruction and large detection area, and the desire to reduce the energy threshold and maximize the intensity of the images, implying a large dish area. A critical parameter is the sharing of costs between

FIGURE 1. One of the candidate sites for HESS, on the Farm Goellschau in the Khomas Highland of Namibia. The Gamsberg is visible at the horizon (the flat-top mountain in the center).

the camera and the mount and dish; rather general arguments indicate that best overall performance is achieved when the camera costs are 1/2 to 1/3 of the total cost. Of course, physics arguments may enforce a different sharing of costs.

Unlike MAGIC, HESS never aimed for the lowest possible energy threshold. In particular, the identification of accelerators of nucleonic CRs will rely on the high-energy ends of spectra, where simultaneous electron acceleration is inefficient because of synchrotron losses. In order to cover extragalactic objects out to $z \approx 1$, a threshold for spectroscopy around 100 GeV seemed appropriate, which also implies detection capability down to 40 GeV, with reduced resolution. These thresholds are reached with a 100 m^2 dish, consistent with the cost sharing arguments given above.

Number of telescopes. In Phase I of the HESS project, four telescopes are foreseen, reflecting both the available funding and arguments concerning the sensitivity and the control of systematic effects.

Obviously, at least two telescopes are required for stereoscopy. Only with three telescopes, however, is the shower geometry overconstrained, allowing consistency checks of the shower reconstruction. With four telescopes, two independent measurements of the shower parameters are possible, a big help in understanding the characteristics of the instrument.

Concerning sensitivity, Monte Carlo simulations show a significant gain in background rejection for three-telescope and four-telescope events, as compared to events with only two views. The number of valuable three-telescope events is doubled for a four-telescope system, as compared to a three-telescope system. This is achieved at a cost increase of less than 30% (taking into account the fixed infrastructure cost).

The significant increase in sensitivity for three-telescope and four-telescope systems, predicted by the simulations, can be verified using the HEGRA IACT system, by turning off in software some of the telescopes. Using the Mrk 501 data set, one finds that the significance $S/\sqrt{B}$ for weak sources improves like 1 : 1.83 : 2.52 when using 2, 3, and 4 telescopes, respectively. Only in the limit of larger numbers N of telescopes is the significance expected to follow the asymptotic $\sqrt{N}$ behavior.

A four-telescope system has the additional advantage that two sources can be observed simultaneously in stereo mode. This is mainly relevant for time-variable sources; the sensitivities given above imply that for DC sources the best strategy is to observe each source for half of the time with the full system.

Arrangement of telescopes. The four telescopes will be arranged in a square with a base line of about 120 m. Simulations show that the best sensitivity is obtained for base lines between 100 m and 150 m; the exact value represents a tradeoff between energy threshold (which is slightly lower for the shorter base line) and performance at higher energies, but is quite uncritical. The 120 m spacing is large compared to intertelescope spacings of other existing or discussed systems. To verify the simulations, pairs of telescopes of the HEGRA system were used to study the significance $S/\sqrt{B}$ of the Mrk 501 signal as a function of telescope distances. The arrangement of telescopes in HEGRA provides pairs spaced at about 70 m, 90 m, 110 m and 140 m. In accordance with simulations, the measured performance depends only weakly on the spacing (Fig. 2).

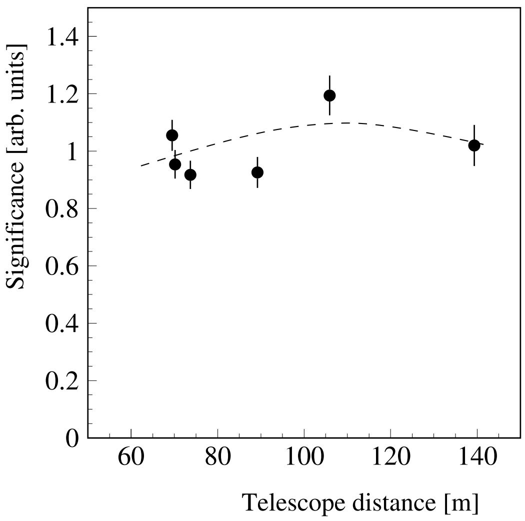

FIGURE 2. Significance $S/\sqrt{B}$ of the Mrk 501 signal, evaluated using pairs of HEGRA telescopes at different spacings.

Pixel size and field of view. Given the emphasis on the study of extended sources such as SNR, and on the survey capability, the HESS cameras need to provide a large field of view and a uniform pixel size throughout the field of view. As a compromise between cost and coverage, the cameras will initially have a 4.3°

field of view, with a later expansion to 5°. A relatively small pixel size of 0.16° will allow efficient triggering with a low threshold, and is particularly helpful for observations at larger zenith angles.

Trigger scheme. One configuration choice with significant implications on the readout electronics and its cost concerns the system trigger scheme. In stereo mode, at least two telescopes have to trigger in coincidence. Because of the propagation delays, a coincidence decision is only available after 1-2 μs. During this time, the PMT signals of the individual cameras need to be stored or delayed in some form. Cable delays are clearly excluded. One option is a deadtimeless storage, e.g. by digitizing signals in a Flash-ADC and storing the data in a ring buffer deep enough to hold a few μs. This technique is used in HEGRA; it has the advantage that also those telescopes which have not triggered, can be read out and included in the analysis.

An alternative is to use an analog sample-and-hold, or some other form of analog buffer, where following a local telescope trigger, the signals are stored for a few μs, after which the storage is reset unless a coincidence with other telescopes is detected. This approach is generally simpler and less expensive to realize, but has the disadvantage that only telescopes which trigger provide data, and that some deadtime is generated while a telescope waits for a intertelescope coincidence.

For HESS, this second option was adopted. Expected telescope trigger conditions – a coincidence of 4 pixels with at least 4 photoelectrons each – are so loose that telescopes which do not trigger will rarely contain useful images. At a predicted single-telescope trigger rate of a few kHz, the deadtime-induced losses are negligible. This choice for HESS also reflects the experience with HEGRA, where the Flash-ADC system provided little practical benefits, in particular once second-generation telescope trigger schemes allowed much lower trigger thresholds and lower noise rates than originally anticipated.

III TECHNICAL CHOICES

Mount and dish. The HESS telescopes will use a $f = 15$ m Davies-Cotton reflector composed of up to 380 individual mirror tiles (Fig. 3). The f/d ratio of 1.2 is large in order to provide good and uniform imaging over a large field of view. Mount and dish are realized as steel space frames. Both the azimuth and altitude drives are friction drives, acting on rails with a radius of about 7 m. This large lever arm reduces the forces and results in significant savings for the motors and gears.

The specifications require mirror support points to be stable to 0.14 mrad rms over the entire altitude range, such that the influence of gravity-induced or wind-induced deformations of the dish is at most comparable to the spot size of individual mirrors tiles (0.3 mrad rms), and small compared to the camera pixel size of 2.8 mrad. Bending of the camera masts is less than 2 cm, or 1/2 pixel size, and will be monitored and corrected using LEDs at the circumference of the camera, viewed

FIGURE 3. One of the HESS telescopes.

by a CCD camera on the dish.

Mirrors. The HESS Letter of Intent discussed diamond-machined aluminum mirror tiles, primarily for cost reasons. Since then, aluminum and glass mirrors from various manufacturers were acquired and tested. Two producers of glass mirrors, COMPAS and GALAKTICA, offered quartz-coated aluminized mirrors at a competitive cost. Given that the glass mirrors generally outperformed the aluminum mirrors available to us in terms of directed reflectivity and focus, and given the positive long-term experience with these mirrors in HEGRA and CAT, it was decided to use 60 cm diameter round glass mirrors. The production will be shared between COMPAS and GALAKTICA. The specifications require 80% reflectivity between 300 and 600 nm, and a focus spot of 1 mrad diameter containing 80% of the light. Mirrors for one telescope have been delivered to Heidelberg and tested, see Fig. 4. Whereas virtually all mirror surpass the specifications concerning the spot size, some of the mirrors show inferior reflectivity; they will be re-aluminized. On the dish, the alignment of each mirror can be adjusted by remote control, using two servo motors.

Photodetectors. The first four HESS telescope will use conventional 30 mm PMTs with bialkali photocathodes and 8 dynodes, operated at a gain of $2 \cdot 10^5$. PMT samples from various manufacturers were characterized with respect to gain and gain variations, cathode uniformity, afterpulsing rate, etc. On the basis of performance and cost, the Photonis PMT XP2960 was finally chosen.

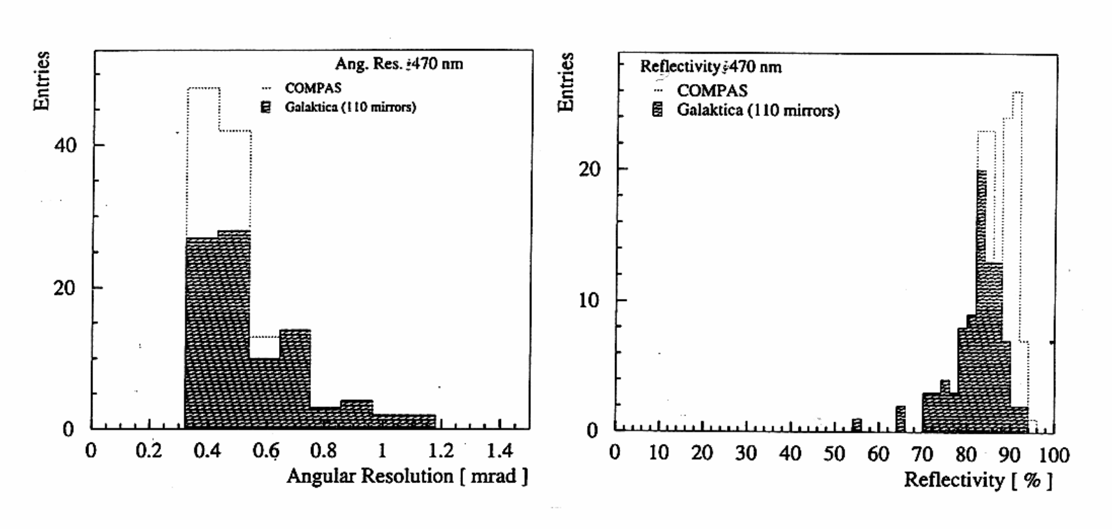

FIGURE 4. Measurements of first mirror samples. (a) Diameter of the spot containing 80% of the reflected light. (b) Directed reflectivity at 470 nm, averaged over the mirror area.

Camera electronics. Almost the entire trigger and readout electronics of the HESS telescopes will be contained in the cameras, eliminating the need for a wide-bandwidth signal transmission, and reducing the number of connectors and interfaces. Prototypes of two alternative electronics concepts have been developed: the "Smart Pixel" approach and a readout system based on the ARS analog sampling ASIC. Both concepts provide 13 to 14 bit dynamic range using dual-gain conversion, and a signal integration time of 15 to 20 ns. A modular construction allows easy maintenance and repair; pixels or pixel groups together with their electronics can be extracted from the front side of the camera. Both concepts are discussed in detail in other contributions to this conference.

The "Smart Pixel" (Fig. 5, see also the contribution by A. Kohnle) is a PMT pixel containing, behind the PMT, a DC-DC converter for the HV supply and a board with dual-gain gated charge integrators, a time-to-voltage converter, a PMT current monitor and rate meter, a discriminator, trigger and readout logic, as well as various monitoring functions. The individual pixels plug into a backplane, and are controlled and read out sequentially via an analog bus and a digital bus. To derive a trigger, each pixel receives the discriminator signals from its 6 neighbor pixels, and forms a coincidence of $N = 1...7$ pixels. These trigger decisions of all pixels are ORed, and are, via the backplane, distributed back to the pixels to provide a gate for the charge integrators. During the trigger decision time of about 50 ns, signals are delayed using a thin coax cable coiled up in each pixel.

The second readout concept, currently the favored option, uses the ARS (Analog Ring Sampling) ASIC to sample the PMT signal at a 1 GHz rate (Fig. 6, see also the contribution by M. Punch). The ARS stores 128 samples, or 128 ns, leaving

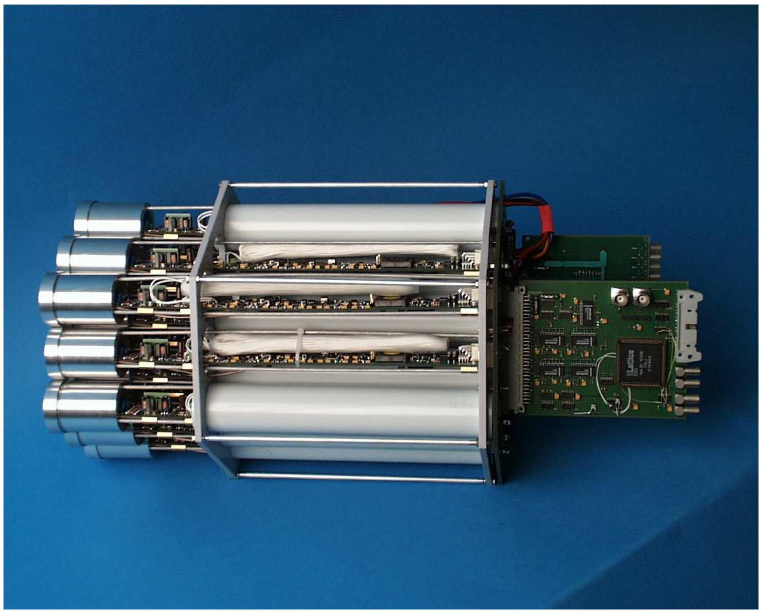

FIGURE 5. Prototype camera consisting of 19 "Smart Pixels" plugged into a backplane with boards to control the readout and triggering. The aluminum rings of each pixel serve to hold the PMTs, which are not yet mounted.

sufficient time for a trigger decision. The trigger circuitry is very similar to the approach used in the CAT telescope, and requires a coincidence of N (typically 3-5) pixels out of overlapping groups of 8x8 pixels. The length of the trigger signal provided by each PMT is determined by the time over threshold, resulting in very short effective coincidence windows around 1.5 ns, and low random-coincidence

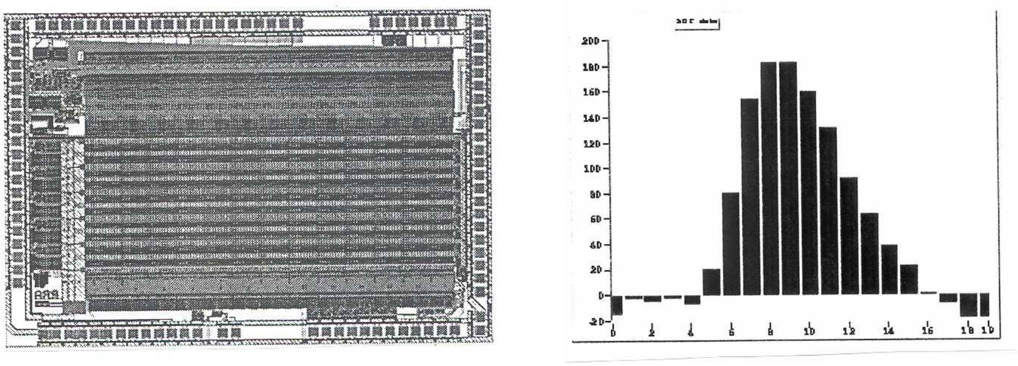

FIGURE 6. (left) The ARS analog ring sampling ASIC, providing four channels of analog storage of 128 samples each, at 1 GHz sampling frequency. (right) Typical sampled and digitized signal; each bar represents a 1 ns step.

rates. Following a camera trigger, the sampling is stopped and the samples are read out and digitized, with the option to either transmit all samples individually, or to form a digital sum over a certain signal integration window. In this concept, PMTs and electronics are packaged into modular 16-PMT units, again containing active HV supplies, current monitors, rate meters, temperature monitoring etc.

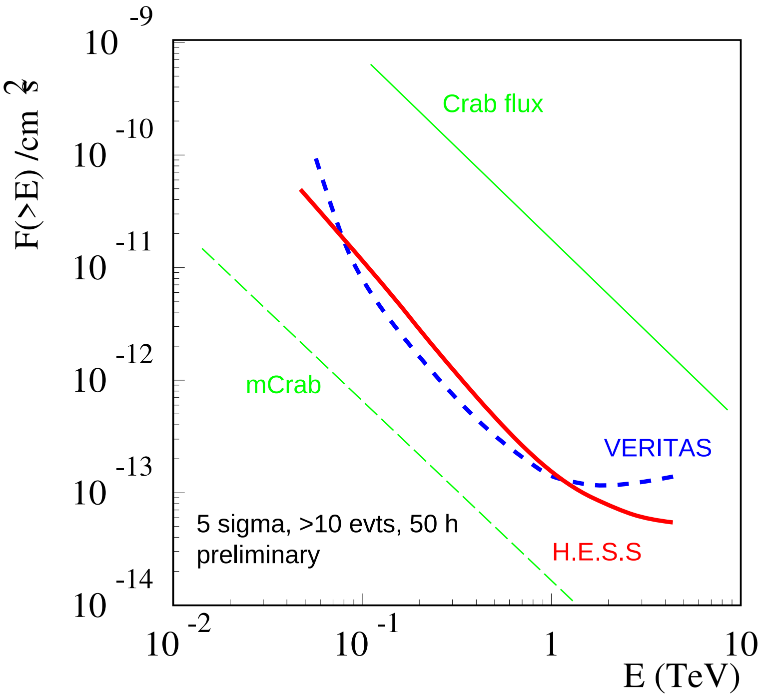

FIGURE 7. Minimal detectable flux as a function of energy threshold, for 50 h of observation time. Also shown is the sensitivity quoted in the VERITAS proposal, and for comparison the Crab flux levels. (Preliminary; telescope parameters assumed in the simulation differ slightly from the latest hardware parameters.)

IV PERFORMANCE

The initial four-telescope system will provide an energy threshold of about 40 GeV (defined by the maximal differential rate for typical sources), and full spectroscopic capability above 100 GeV, with an energy resolution of 20% or better, and an angular resolution of 0.1° or better. Fig. 7 shows (preliminary) estimates of the minimal detectable flux as a function of a (software) energy threshold, compared to the Crab flux. For 50 h of observations, a sensitivity around 10 mCrab is achieved. Also included is the VERITAS sensitivity, which is slightly better at medium energies, reflecting the larger number of telescopes. At high energies, the larger field of view of the HESS cameras results in an improved effective area. With the full 16-telescope HESS system and 100 h of observation time, limits of a 2-3 mCrab will be within reach. Illustrated in Fig. 8 is the angular resolution; HESS at 100 GeV has the identical characteristics as the HEGRA system at 1 TeV.

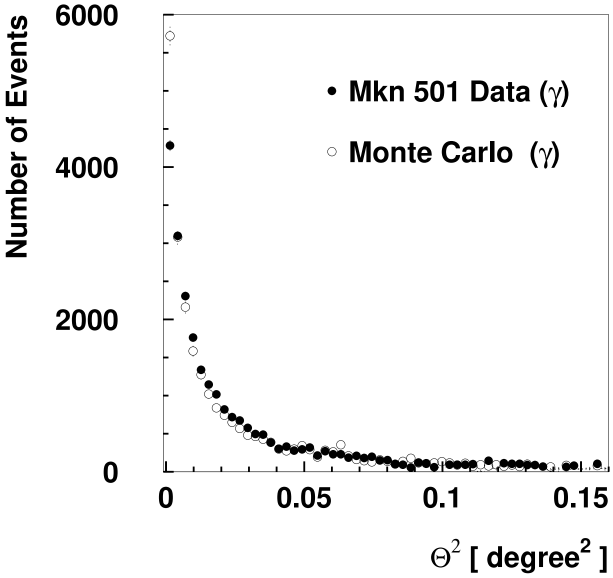

FIGURE 8. Angular distribution of reconstructed photon directions; HESS simulations at 100 GeV (open circles) compared to HEGRA data at 1 TeV (full points).

V STATUS

While decisions from some funding agencies are still pending at this time, a significant fraction of the funding required for the first four HESS telescopes is available, and the construction has started. The procurement of mounts and dishes is underway, the same holds for the PMTs. Mirrors are in production, with about 25% delivered. The electronics is in the stage of advanced prototyping. Concerning the installation in Namibia, an Exchange of Notes between the German and Namibian Governments is in preparation. Work on the infrastructure in Namibia should start early in the year 2000, with first light for the first telescope in 2001, and completion of the initial four-telescope system in 2002.