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The optical system of the H.E.S.S. II telescope

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The stereoscopic system of four large imaging atmospheric Cherenkov telescopes operated by the H.E.S.S. collaboration in the Khomas Highland of Namibia is planned to be extended by a central very large telescope. The new telescope with its 30 m type reflector, called H.E.S.S. II, is designed to provide a total mirror area of 600 m^2 for the imaging of extensive air showers onto the Cherenkov camera consisting of 2048 photomultiplier tubes of about 0.07° size. In order to guarantee for a stable and reliable imaging of excellent quality for the whole field of view of 3.2°, intense technical studies as well as detailed Monte Carlo simulations of the optical system have been performed.

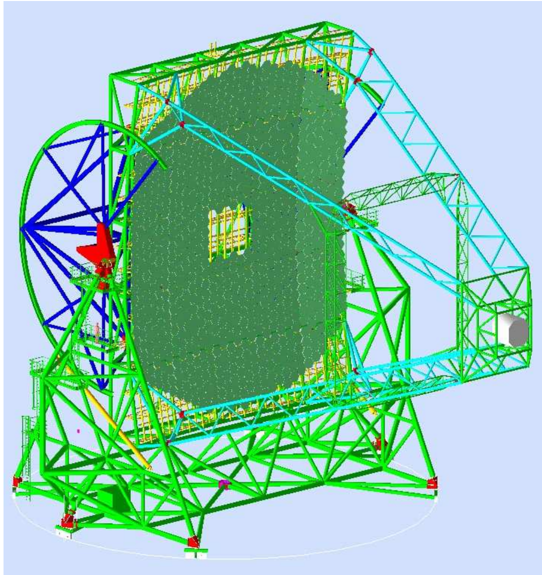
1. Introduction

The H.E.S.S. collaboration is planing to expand its stereoscopic system of currently four imaging atmospheric Cherenkov telescopes [5] in order to extend its energy range for observations of high energy phenomena in our universe. The current telescopes with their 13 m reflectors [1] and fine-grained Cherenkov cameras with a large field of view [6] are best suited for the exploration of the gamma-ray universe in the energy range from about 100 GeV to several 10 TeV. To lower the energy threshold to 20 GeV or below and to improve the sensitivity above 100 GeV the system will be complemented by a central very large telescope with a reflector diameter of about 30 m. The complete optical system of the new H.E.S.S. II telescope with a total mirror area of about 600 m^2 represents a natural evolution of the very successful system of the current H.E.S.S. telescopes [3].

2. The optical system

The H.E.S.S. II telescope (see Fig. 1 (left)) is designed to have a total mirror area of about 600 m^2, as is required for a considerable improvement of image quality and photoelectron statistics in the 100 GeV range, and for a threshold around 20 GeV, overlapping with satellite instruments but providing orders of magnitude larger effective detection areas. The dish size represents a compromise between the desire to maximize the mirror area and the objective of keeping the cost and technical risk inherent in the extrapolation from current telescopes at a reasonable level; both of which increase rapidly for larger dish sizes. A minimal $^f/_d$ ratio of 1.2 is required to achieve very good imaging over the field of view, which translates to a focal length of about 36 m. Larger $^f/_d$ ratios would improve imaging near the edge of the field of view, but scaling laws imply that the weight and cost of the camera support structure grow steeply with increasing focal length.

The reflector will be of parabolic shape which minimizes the time dispersion of photons forming the image. A Davies-Cotton mirror arrangement, such as used for the H.E.S.S. Phase I telescopes, offers slightly improved off-axis imaging, at the expense of a time dispersion of photons which is at a tolerable level of 1.4 ns r.m.s. for a 13 m dish, but which grows linearly with diameter at fixed $^f/_d$. For a 30 m dish the time dispersion of the pulse would lead to an increase of the energy threshold. However, deviations of up to ±0.1 m from the exact parabolic shape are tolerable. The dish is a rectangular spatial truss of 32 m height, 24 m width and a



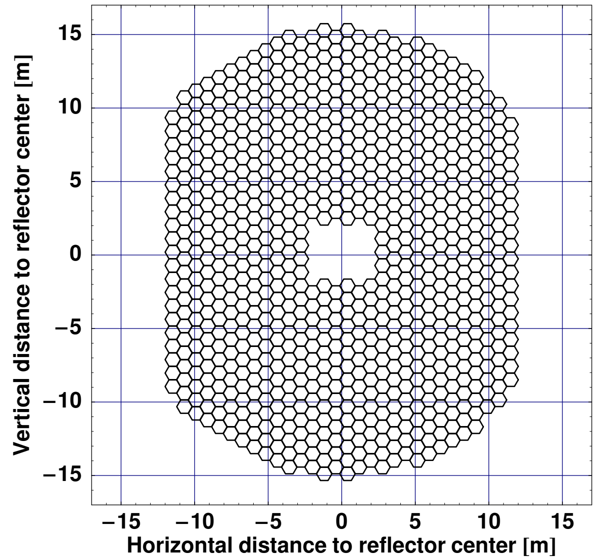


Figure 1. *Left:* Sketch of the H.E.S.S. II telescope. *Right:* Layout of the H.E.S.S. II reflector consisting of 850 hexagonal mirror facets of 90 cm diameter (flat-to-flat). The total reflector area is 596 m^2.

depth varying between 2.7 m and 4.6 m; its front surface approximates a parabola by 5×5 flat segments. The mirror shape corresponds to a truncated circle, thereby reducing the width and cost of the mount, compared to a circular mirror. The spatial truss of the dish is optimized concerning stiffness and eigenfrequencies. Deforming under the influence of gravity, the dish retains its parabolic shape; the dominant effect being a lateral shift of the focus (*homology principle*). The mirror facets are supported by 25 identical mirror support segments welded to the dish. Due to its rectangular rather than radial and azimuthal grid of beams, the dish structure is simpler to manufacture than that of the H.E.S.S. Phase I telescopes. The reflector will consist of 850 hexagonal mirror facets of 90 cm width (flat-to-flat) as shown in Figure 1 (right). A number of different manufacturing techniques are available for mirrors up to this size. In the interest of high reliability and ease of operation, a passive support of mirror facets is used, with the dish designed rigid enough to provide stable imaging at least between 45° and 90° elevation. As with H.E.S.S. Phase I, motors for remote alignment of the facets using images of stars are foreseen, but should only be required for the initial alignment and occasional realignment of the facets.

The depth of field of a large telescope is such that for optimum shower imaging the telescope should be focused on the shower maximum [4]. Since the distance to the (average) shower maximum varies with elevation, the telescope needs to be refocused by moving the camera closer towards the dish for observations at low elevations. The camera is therefore supported by a quadrupod attached to the four corners of the dish. In order to refocus the telescope depending on zenith angle the camera is movable along the optical axis by 10 cm. The Cherenkov camera itself consists of 2048 pixels of about 0.07° size, providing a field of view of 3.2° [7].

3. Simulations

The techniques for the simulation of the H.E.S.S. II optics are based on the same principles and tools used for the study of the H.E.S.S. Phase I reflectors [2]. These algorithms proved to be very accurate to describe the actual telescope configuration.

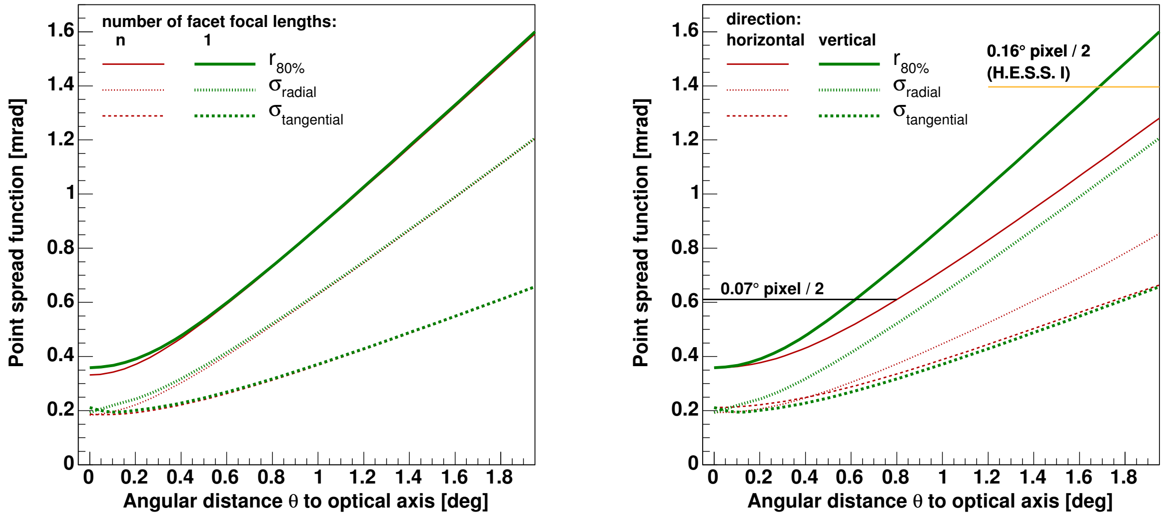


Figure 2. *Left:* Simulated point spread function as a function of the angular distance θ to the optical axis for different numbers of facet focal lengths. The lower curves (n) show the situation for the scenario in which every mirror facet is manufactured to have its nominal focal length. The top curves (1) represent the case in which all facets are manufactured to have an identical focal length of 36.74 m. Curves are shown for the vertical direction only. *Right:* Simulated point spread function for both directions with a uniform facet focal length. The top/lower curves are for the vertical/horizontal direction, respectively. The horizontal lines indicate different radii of the Cherenkov camera pixels for comparison.

For a parabolic reflector the nominal focal length of the mirror facets vary with the distance to the center of the reflector; i.e. every mirror facet has its own nominal focal length. But for the purpose of Cherenkov telescopes with their moderate imaging requirements it is sufficient to divide all facets into a certain number of groups with identical focal lengths, respectively. Because it is rather inconvenient to manufacture, test, and manage mirror facets for a large number of different focal lengths, the actual number is subject to minimization. The first simulation study was therefore performed to investigate the effect of the number of different focal lengths on the imaging quality. The results are shown in Figure 2 (left). Three different quantities for the spot width are used. The first two are the r.m.s. widths of the intensity distribution projected onto the radial (σ_{radial}) and the corresponding orthogonal ($\sigma_{\mathrm{tangential}}$) axis in the focal plane, respectively. They illustrate possible asymmetries in spot shape. In addition, the radius of a circle around the center of gravity containing 80% of the total intensity ($r_{80\%}$) is given to indicate the overall size. Curves are shown for two different cases. In the first scenario, which represents the optimum, all mirror facets were set up to have their nominal focal length according to a perfect parabola. Variations in the actual focal length are then only due to manufacturing imperfections. The second scenario represents the worst case in which all mirror facets are manufactured to have an identical focal length of 36.74 m, which is the mean value of the nominal focal lengths of all facets. A difference between the two cases is hardly seen. At first, this result is rather surprising. But given the fact that the $^{f}/_{d} = 40$ ratio for a single mirror facet is rather large, variations in focal length of a few percent have a negligible effect on the overall imaging quality. In addition, with increasing angular distance to the optical axis spherical aberrations start to dominate the size of the point spread function as is expected for single reflector optics. A uniform focal length for all mirror facets has therefore been adopted.

Due to the asymmetry of the reflector geometry the point spread function is expected to depend not only on the angular distance to the optical axis but also on the polar angle inside the focal plane. Simulations were therefore carried out for the horizontal and vertical directions separately. Some of the resulting intensity distributions are

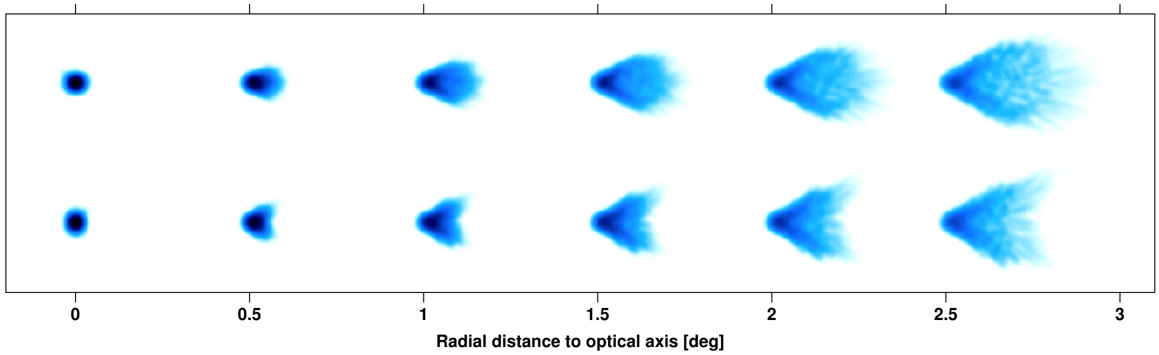


Figure 3. Simulated point spread function of the H.E.S.S. II reflector for various angular distances to the optical axis. The top series of shapes represent the (rotated) evolution in the vertical direction; the bottom series are for the horizontal direction. The intensity scale is logarithmic. Note that the actual active field of view is limited to a radius of 1.6 degrees.

shown in Figure 3. Qualitatively, it can already be seen that the series of spot shapes along the vertical direction (top) tend to develop longer tails as compared to those in horizontal direction (bottom). A more quantitative description is given in Figure 2 (right). There, the three different measures of the point spread function as a function of the angular distance to the optical axis are shown separately for the two directions. The difference between the horizontal and vertical development of the spot size with increasing angular distance is significant. In addition, the difference between $\sigma_{\mathtt{radial}}$ and $\sigma_{\mathtt{tangential}}$ – i.e. the shape asymmetry – for the vertical direction is growing relatively fast. But although the asymmetry of the reflector layout implies the need for an additional parameter to describe the point spread function in the focal plane, the actual dependencies are well understood. This will serve to improve the analysis of shower images in case there is need.

4. Conclusions

The design of the H.E.S.S. II telescope represents a cost-effective solution for a 600 m^2 type Cherenkov telescope. Rigid steel structures guarantee for reliable imaging for the whole range of operation without the need to realign mirrors in-between observations. Intense simulation studies of the reflector design have been performed which led to a comprehensive understanding of the imaging. The results show that a uniform manufacturing focal length for all mirror facets will be sufficient to form the parabolic reflector; the impact on imaging quality is negligible.

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