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Alignment of the mirror facets of the H.E.S.S. Cherenkov Telescopes

R. Cornils[1] **and I. Jung**[2]

[1]Universität Hamburg, II. Institut für Experimentalphysik, Luruper Chaussee 149, D-22761 Hamburg, Germany
[2]Max-Planck-Institut für Kernphysik, PO Box 10 39 80, D-69029 Heidelberg, Germany

Abstract. The H.E.S.S. project is one of the next generation instruments for VHE gamma-ray astronomy. A stereoscopic system of four Imaging Atmospheric Cherenkov Telescopes (IACTs) with a mirror area of about $100\,\mathrm{m}^2$ will be built in the Khomas Highlands of Namibia. Each reflector will consist of 382 individual mirror facets. These are quartz-coated, aluminized and equipped with a support-drive unit which is controlled by a dedicated system to provide an automated alignment. Tests showed that for individual light spots in the focal plane a positioning accuracy of better than 0.05 mrad can be achieved.

1 Introduction

The accuracy of the mirror alignment as well as the stability of the mirror support are essential for the quality of the data which will be taken with the H.E.S.S. stereoscopic system (W. Hofmann, 2001). The concentrator of each Cherenkov telescope consists of 382 mirror tiles with a reflectivity better than 80% and a focus spot diameter (for 80% of the light) less than 1 mrad, corresponding to a rms spot width of 0.28 mrad. Each mirror is equipped with two DC motors to provide together with the feedback by a CCD camera an automated alignment system which uses images of stars reflected onto the telescope camera lid to monitor the position of the mirrors (see Fig. 1) (W. Hofmann, 1998a). The basic concept is as follows: A CCD image of the camera lid will be taken. Next the mirror, which has to be aligned, will be moved by a distance large compared to the spot size and another image will be taken. By subtracting these two images, the current position of the mirror is determined and the mirror can be moved to the correct position. This will be done with all the mirrors in sequence. The alignment accuracy is constrained by the electronics, the mechanics of the mirror support, and by the stability of the support under different loads, weather conditions as well as the design of the alignment algorithm. First

Correspondence to: I. Jung (ira.jung@mpi-hd.mpg.de)

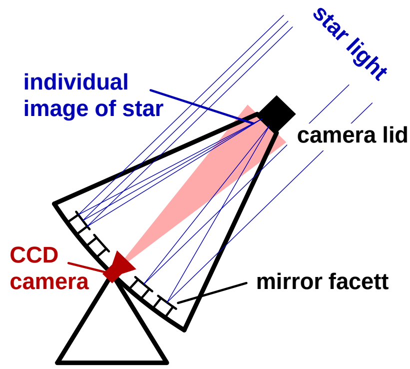

Fig. 1. Mirror alignment technique. The alignment of the mirror facets is done by using images of stars. Individual light spots in the focal plane (camera lid) are imaged with a CCD camera for optical feedback.

a short summary of the requirements on mirror supports is given, then the mechanics and electronics are described and finally tests and their results as well as Monte Carlo simulations concerning mirror alignment are presented.

2 The mirror support-drive unit

Requirements on the mirror support-drive unit include (W. Hofmann, 1998b):

– Thermal expansion and mechanical adjustment should not stress the mirror.

– The pointing accuracy of a mirror is required to be ten times smaller than the diameter of the spot size, i.e. 0.1 mrad or less.

– Individual mirrors should be adjustable over a range of ± 17.4 mrad.

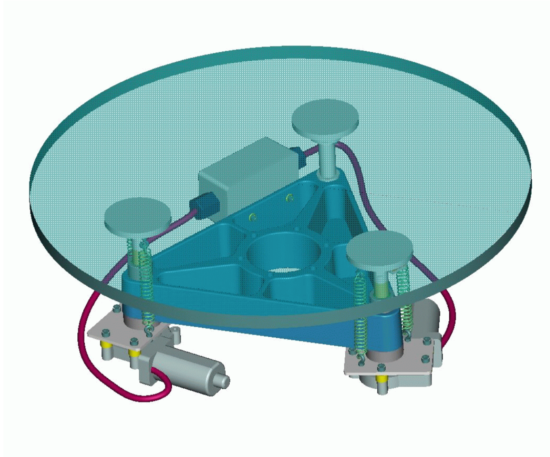

Fig. 2. Mounting system with actuators for the mirror adjustment.

2.1 The mirror support-drive mechanics

The mirror adjustment mechanics is shown in Figure 2. An aluminum triangle with side length of 30.3 cm and a thickness of 5 cm serves as support structure. Two of the edges bear actuators, while the third one is equipped with a spherical joint. This joint and the actuators provide the support points which hold the mirror with the help of three steel plates of 8 cm diameter, that are glued on its rear. One plate is fixed on the spherical joint providing only rotational degrees of freedom. The other two plates are connected to the actuators by slide bearings allowing movements in the mirror plane, and are held in place by strong springs. The bearings of the actuators are not identical. While one allows movements in all directions of the plane, the other one is constrained to movements in radial direction only. This avoids stress and guarantees a defined motion of the mirror.

2.2 The actuators

The actuators are based on DC motors which are usually used to drive window lifts in cars. These motors are significantly cheaper than stepping motors. The motor is equipped with two Hall sensors shifted by $90°$. Together they provide four TTL edges (Hall counts) per revolution of the motor shaft which are used to quantify the movement. After a reduction by a $55{:}1$ worm gear the nominal speed is about 100 rpm and a torque of 1.5 Nm. The achievable torque at slow speeds is 6 Nm.

The motor is directly coupled to a 12 mm threaded bolt, driving the actuator pin by 0.75 mm per revolution. The characteristics of the actuators are:

- range of about 30 mm
- a resolution of $3.4\,\mu$m (equal to 0.012 mrad) per Hall count.

2.3 The motor control system

A special control system has been designed to control all actuator motors of a telescope. The concentrator is divided into twelve segments with up to 32 mirror facets (64 actuator motors). A branch cable runs along the mirrors of one segment to connect them to the control system. Within a branch, the selection of one motor out of 64 is done by 2×8 wires which form a selection matrix, implying that only one motor can be driven at a time. The twelve branch cables of a telescope are connected to branch driver boards which provide all necessary power and signal voltages. These boards are controlled by a central unit which implements the set of functions to control all aspects of the actuator motors. It is equipped with a front panel which gives manual access to the whole motor control functionality. To make an automated alignment possible, the functionality is additionally available via a VME-bus interface which is used by a VME CPU board to gain control over all actuator motors by software. It also serves to readout the CCD camera for the optical feedback of the alignment.

The signals of the Hall sensors are fed into a special decoding device which derives the information about the number of Hall counts and the direction of the motor movement. It implements a set of signal filters and consistency checks to avoid miscounts. As the alignment system does not use stepping motors, the positioning has to be implemented by the control system. This is achieved by simply switching off the motor after the desired number of Hall counts.

The actuators are not equipped with end switches but utilize a set of plate springs near the end positions. To avoid damages at the end positions, the control system implements a security shut off which takes place upon the absence of Hall counts for a certain time, using the effect that the motors significantly slow down when driving into the springs.

3 Tests of the mirror-support drive unit and of the motor control hardware

All components of the mirror alignment system have been tested extensively to ensure that they meet the requirements.

3.1 Test of the motor control hardware

The signals of the Hall sensors are transferred over large distances from the mirror dish to the electronics hut. Although the decoding device should avoid miscounts, it has been verified if noise and drop-in signals lead to wrong counts by driving a motor randomly for nearly $2.5 \cdot 10^7$ Hall counts. No deviation between the motor position and the position counter was found.

Due to the positioning mechanism, the motors tend to surpass the target position by a few Hall counts so the attempt to reach the target position exactly must be iterated. The reliability of the positioning has been tested by initiating $5 \cdot 10^4$ positioning attempts while recording the number of needed

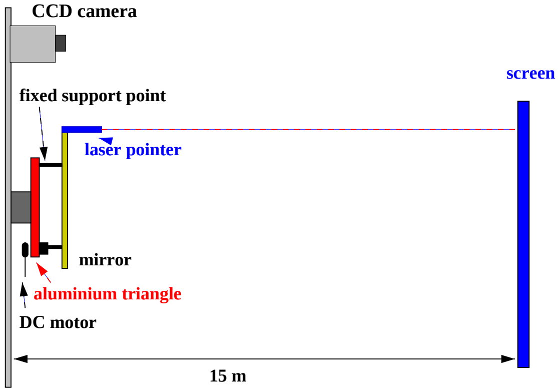

Fig. 3. Test setup for the test of the complete mirror support drive system

iterations. It was found that on average two additional iterations are needed to reach the target position exactly, while this can always be achieved after three.

Finally, tests have assured that the security shut off prevents the actuators from damage and that it never occurs accidentally between the end positions.

3.2 Absence of stress effects on the mirror

Stress can be produced either by the gluing or by the support itself. Therefore the angular resolution and the spot shape of the mirror were measured before and after gluing and mounting the mirrors on the support. These values were also determined at different positions of the actuators, to be sure that the mirror movement does not generate stress. There was no indication of any stress effects.

3.3 Test of the stability of the mirror support drive system

Tests have been carried out to test the deviation of the support under different zenith angles, i.e. under changing influence of gravity. A complete mirror support unit was used, including the mounting, which will be used to fix it on the H.E.S.S. telescopes. Therefore the results include also the stability of the mount. The deformation of the triangles has been determined under different load and direction of strain. The weight of a mirror is approximately 11 kg. The force of gravity perpendicular and parallel to the plane depend on zenith angle. In the case of a force corresponding to 11 kg acting parallel to the plane no perpendicular deviation was measured. Loads of 5.5 kg, 11 kg and 22 kg placed on the edges of the triangle, which correspond to the support points of the mirror weight, resulted in a deviation perpendicular to the mirror plane of $(3 \pm 1)\,\mu$m, $(6 \pm 1)\,\mu$m and $(9 \pm 1)\,\mu$m. These values correspond to (0.011 ± 0.003) mrad, (0.022 ± 0.003) mrad and (0.033 ± 0.003) mrad.

The thermal expansion of the glue can add uncertainties to the accuracy of the mirror alignment. This was tested in a climate chamber. Several glued plates underwent changes from $-10°C$ to $60°C$ and humidity changes from 10% to 80%. The expansion was measured. The determined expansion coefficient was homogeneous, linear $(0.5 \pm 0.02)\,\mu$m$/°C$ and independent of humidity. Since the expansion is homogeneous, the effect on the spot position perpendicular to the focal plane is negligible.

3.4 Test of the complete mirror support drive system

During the mirror alignment all mirrors are moved to the same predefined position. Therefore it is sufficient to determine the accuracy with one mirror only.

A test setup has been constructed to simulate this procedure and to test the accuracy of the mirror positioning and the reproducibility. In Figure 3 the setup is shown. A complete mirror support unit was mounted and a laser pointer was fixed at the mirror pointing towards a screen. A CCD camera (pixel size 0.18 mrad) monitored the position of the laser spot and correspondingly the mirror position. The tests of the reproducibility consist of many repetitions of sequences with interleaving operation of both actuators. In all sequences the mirror returns to its initial position after one complete cycle. Figure 4 shows the distance between the nominal position and the position reached after one sequence of moving actuator 1 over 6 mm, then actuator 2 over 6 mm, followed by moving actuator one over -6 mm and then actuator 2 over -6 mm.

The rms deviation was 0.008 mrad. Errors in the mirror alignment using images of stars are twice the errors of this experiment since the reflection doubles the angle.

4 Alignment algorithm

4.1 Mathematical aspects

The position of an individual light spot in the focal plane $\mathbf{x} \equiv \binom{x_1}{x_2}$ is given by a function $\mathbf{x} = f(q_1, \ldots, q_n, \mathbf{a})$, which is dependent on the position and orientation q_i of the mirror facet and the position of both actuators $\mathbf{a} \equiv \binom{a_1}{a_2}$. As f ist rather complex and the exact values of the q_i are hard to determine, a linear approximation

$$\mathbf{\Delta x} = \mathbf{T}\,\mathbf{\Delta a}\,, \quad \mathbf{\Delta a} = \mathbf{T^{-1}}\mathbf{\Delta x} \tag{1}$$

is used to determine the change in $\mathbf{a}$ needed for a desired change in $\mathbf{x}$. The tranformation matrix $\mathbf{T}$ can be determined by driving both actuators individually for a certain number of Hall counts while imaging the change in $\mathbf{x}$ with the CCD camera.

The function f is not strictly linear in $\mathbf{a}$ so the transformation matrix itself is a function of $\mathbf{a}$ and the components of it vary to some ± 10 % for the whole range of the actuators. This has to be taken into account for the development of an alignment algorithm.

4.2 Monte Carlo simulations

To study the influences of the finite step size of the actuators and of the uncertainty of the transformation matrix on the alignment accuracy, several different alignment algorithms

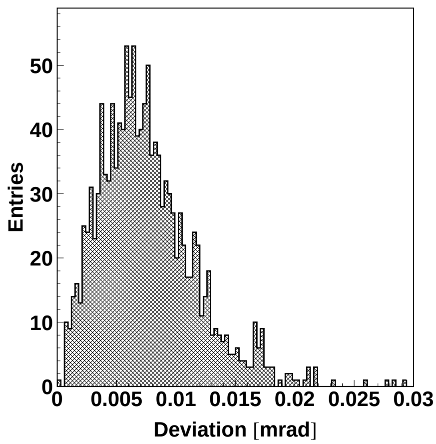

Fig. 4. Distances between the nominal position and the one reached after completion of a measurement cycle. The rms deviation is 0.008 mrad. Errors in the mirror alignment are twice the errors of this experiment since the reflection doubles the angle.

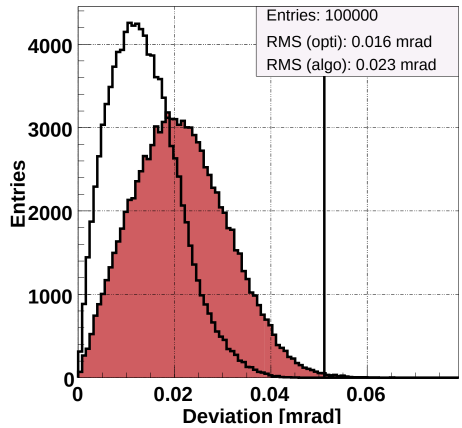

Fig. 5. Simulated alignment accuracy for a mirror with a distance of 6 m to the center of the dish. Open histogram and solid vertical line: distribution and worst case for the theoretical optimum. Filled histogram: distribution of the best algorithm found.

have been simulated without taking into account the influences of the play of the mechanics and the CCD imaging. The goal was to find an alignment algorithm which is technically easy to implement and which leads to a good alignment accuracy. For each investigated algorithm 10^5 mirror alignments have been simulated repeatedly for various distances of the mirror facet to the center of the dish. Results are presented for a distance of 6 m which is close to the maximum; smaller distances have better accuracy.

For purpose of reference, the alignment accuracy was first simulated with the exact transformation matrix to determine the maximum achievable accuracy. The deviation is then only due to the uncertainty of one Hall count in each actuator and represents the limits of the hardware. The simulation resulted in a distribution for individual light spots in the focal plane with a deviation of 0.016 mrad (rms) and a worst case of 0.051 mrad (see open histogram and solid vertical line in Fig. 5).

The corresponding distribution of the best algorithm found (see filled histogram in Fig. 5) is only slightly broader than the best possible case. It has a deviation of 0.023 mrad (rms). The algorithm is technically easy to implement since it does not require to identify a single spot which lies inside the main spot consisting of nearly 400 individual ones:

First, a rough transformation matrix is determined right at the position where the light spot has been found. Using this transformation, the mirror is then moved to four positions surrounding the nominal position at small distances to determine a more accurate transformation matrix which is finally used to move the mirror to its target position.

5 Test of the mirror alignment

Tests were carried out with the setup shown in Figure 3 for a central mirror with the linear transformation matrix determined near the nominal position. The actuators were moved to a random position with distances between 5 mrad and 11.5 mrad off the nominal position. Then the mirror was moved back to its original position by running the actuators the calculated number of steps. The rms deviation of the nominal position from the position reached by the mirror was 0.023 mrad which includes the doubling of the angle by the reflection and the inaccuracies stemming from the CCD imaging.

6 Conclusion

The accuracy of the mirror alignment of a central mirror using a simple algorithm was determined to be 0.023 mrad. For a mirror at larger distances from the center of the mirror dish, simulations show that an accuracy of 0.023 mrad (rms) can be achieved. This does not include the inaccuracies resulting from the CCD imaging, which are in the order of a few percent of the CCD pixel diameter. The pixel size in the H.E.S.S. experiment will be 0.05 mrad. Adding the influence of the deviation of the mirror support under different zenith angles of 0.044 mrad, and taking into account, that the angle is doubled by reflection, one concludes, that all requirements are fulfilled.

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References

W. Hofmann, Alignment of the HESS mirrors using images of stars, H.E.S.S. internal note (1998)

W. Hofmann, Design considerations for the HESS mirror supports and drive mechanisms, H.E.S.S. internal note (1998)

W. Hofmann, Status of the High Energy Stereoscopic System (H.E.S.S.) Project, these proceedings (2001)