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"Convergent observations" with the stereoscopic HEGRA CT system

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Abstract. Observations of air showers with the stereoscopic HEGRA IACT system are usually carried out in a mode where all telescopes point in the same direction. Alternatively, one could take into account the finite distance to the shower maximum and orient the telescopes such that their optical axes intersect at the average height of the shower maximum. In this paper we show that this "convergent observation mode" is advantageous for the observation of extended sources and for surveys, based on a small data set taken with the HEGRA telescopes operated in this mode.

The HEGRA collaboration is operating a system of currently five imaging atmospheric Cherenkov telescopes (IACTs) for the stereoscopic observation of VHE cosmic γ-rays [1]. The telescope system is located on the Canary Island La Palma, at the Observatorio del Roque de los Muchachos (ORM), at 2.2 km asl. The system telescopes feature a mirror area of 8.5 m^2 and a focal length of 5 m and are equipped with 271-pixel photomultiplier cameras. Based on the multiple views obtained for each shower, the orientation of the shower axis in space as well as the location of the shower core can be determined. Compared to single IACTs, stereoscopic IACT systems provide superior angular resolution, energy resolution, and background rejection [1–3]. During typical observations with the HEGRA IACT system, the optical axes of all telescopes are parallel and either point directly to the source, or – in the so-called wobble mode – at a point displaced by $\pm 0.5°$ in declination relative to the source. In the latter case, the rate in a region displaced by the same distance from the optical axis, but in the opposite direction, is used to estimate off-source background rates.

With all telescopes pointing in exactly the same direction, both the operation of the system and the data analysis are simplified, but one may wonder if the detection characteristics could not be improved by canting the telescopes towards each other, such that their optical axes intersect roughly at

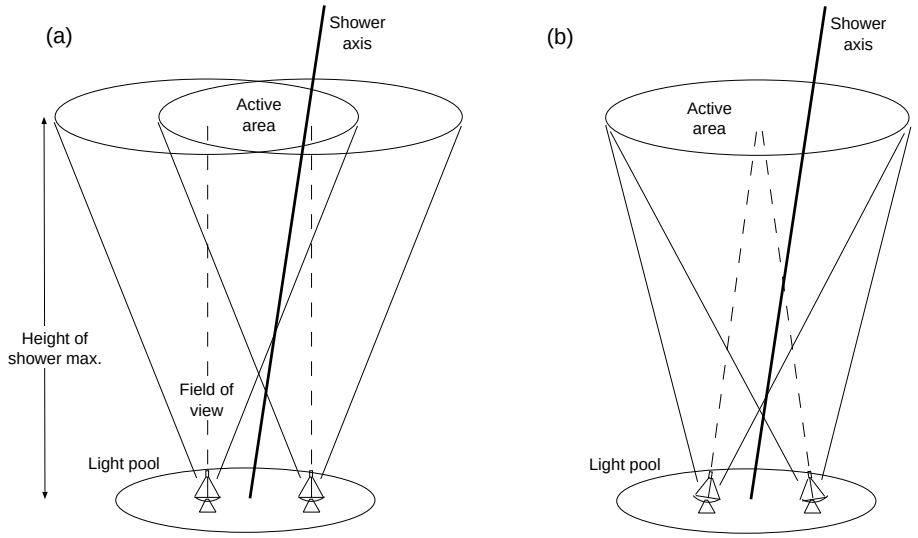

FIGURE 1. Illustration of the geometry with parallel (a) and canted (b) telescopes. The dashed lines show the optical axes of the telescopes. The "active area" indicates where the shower maximum can be observed in both telescopes.

the height of the shower maximum. Such an alignment of telescopes would guarantee that the most luminous region of an air shower is optimally viewed by all telescopes simultaneously.

The two alternatives are shown in Fig. 1, which also serves to illustrate the trigger characteristics of IACT arrays. To first approximation, an individual IACT will trigger on an air shower if two conditions are fulfilled [4]:

1. the telescope has to be located within the light pool of the shower, with its typical radius of about 120 m, and

2. the shower maximum has to be within the field of view of the camera.

For the HEGRA telescopes, with their 4.3° field of view, the latter condition implies that the shower maximum – at TeV energies typically located 6 km above the telescopes – should be within 225 m from the optical axis of the telescope. For showers propagating parallel to the optical axis, the second condition is automatically fulfilled, once a telescope is within the light pool of the air shower. The camera field of view adds an additional constraint only for showers at angles of more than 1° relative to the optical axis (at least as far as triggering is concerned – to avoid truncation of images, one may want to require in addition in the subsequent image analysis that the centroid of the image is at least 0.5° away from the edge of the field of view; this will still result in a field of view of about 175 m radius at the shower maximum). Therefore, canting of telescopes is most likely not an issue for studies of point sources near the center of the field of view; it may however be important

for the observation of extended sources as well as for surveys of larger areas of the sky, where it is important to maximize sensitivity over a large solid angle. For two telescopes, the situation is relatively obvious from Fig. 1: for parallel pointing, the range of locations of the shower maximum, and hence the accessible solid angle, is much more restricted than for canted telescopes. For three or more telescopes, the conclusion depends on the locations of the telescopes and the trigger conditions; parallel pointing will reduce the solid angle for a coincidence of all N telescopes, but may increase the angle if only 2 out of N telescopes are required in the trigger and in the subsequent analysis.

Estimates of detection rates were carried out for the actual geometry of the HEGRA IACT system, with telescopes located at three of the four corners of a square of about 100 m side length, and another telescope located at the center of the square (the remaining corner telescope had at that time – summer 1998 – an older camera and was not yet included in the IACT system). The rate estimates were based on the simplified model discussed above, assuming a radius of the light pool of about 120 m and a usable field of view (without edge distortion of the images) of 3.6°. Two cases were compared: 1) parallel optical axes of all telescopes, and 2) telescopes canted such that the axes intersect in a height of 6 km, with the nominal pointing of the IACT system defined as the pointing of the central telescope. The results – event rates for a given source flux and observation time as a function of the distance of the source from the optical axis of the central telescope – are shown in Fig. 2(a)-(d). The simulations indicate almost identical total detection rates for the two pointing modes (Fig. 2(a)). However, for sources more than 0.5° from the optical axis of the system, the "convergent observation mode" provides a significantly larger fraction of four-telescope events (Fig. 2(d)). Since both the angular resolution and the cosmic-ray rejection improve with the number of triggered telescopes, the convergent mode is clearly favorable.

To verify these model predictions experimentally, three hours of observations of the Crab nebula were performed with canted telescopes. The cosmic-ray background provides a uniform flux of particles and allows to study detection rates as a function of the distance to the optical axis of the IACT system. At last qualitatively, these characteristics should be similar for hadronic showers and for the more interesting γ-ray induced showers. Limited observation time and low counting rate prevented us from scanning the field of view using the Crab nebula as a γ-ray source.

Fig. 3 illustrates the effect of the canting: the positions of the images in the different cameras coincide, whereas for the parallel pointing mode they are displaced by about $\delta \approx d/h \approx 1°$ along the direction connecting the locations of the telescopes. Here, d is the spacing of the telescopes and h the height of the shower maximum. As a consequence, in convergent mode it is unlikely that images in some of the telescopes are truncated; either all telescopes have well-contained images, or all images suffer from edge problems.

Due to slight differences in the weather conditions, the telescopes trigger

rates varied somewhat between the observations taken in convergent tracking mode, and the reference data set. Since the pointing mode may influence the trigger rates, one cannot simply normalize the data sets on the basis of the raw trigger rates. To derive the correct normalization factor, the field of view in convergent mode was artificially truncated to 2.4° diameter, and in the reference data set – with parallel pointing – the convergent pointing was mocked up by selecting in software a 2.4° field of view shifted by the canting angle. After these software trigger cuts, the detection rates can be compared, resulting in a $24 \pm 2\%$ correction.

The corrected cosmic-ray detection rates as a function of the angle relative to the system axis are shown in Fig. 2(e) for the total rate, and separately for 2-telescope (f), 3-telescope (g), and 4-telescope events (h). Here, only images within the central 3.6° of the field of view were accepted, to exclude truncated images. The observed pattern matches that predicted by the simple model: very similar total rates, but a clear enhancement of the 4-telescope rate at larger angles in case of the convergent pointing mode, at the expense of 2 and 3-telescope events. For the 4-telescope events, the diameter of the effective field of view is increased by about 0.8°.

During the data taking in convergent mode, the Crab nebula was positioned 0.5° off the system optical axis. Under these conditions, one would not expect any difference in detection rates between the two modes, and indeed the Crab signals in the two modes are well consistent within the statistical errors of about 20%.

In summary, for stereoscopic IACT systems, the convergent tracking mode – canting the telescopes towards each other such that their optical axes intersect at the height of the shower maximum – improves the detection capabilities in particular for sources near the edge of the field of view, and is advised for observations of extended sources and for surveys.

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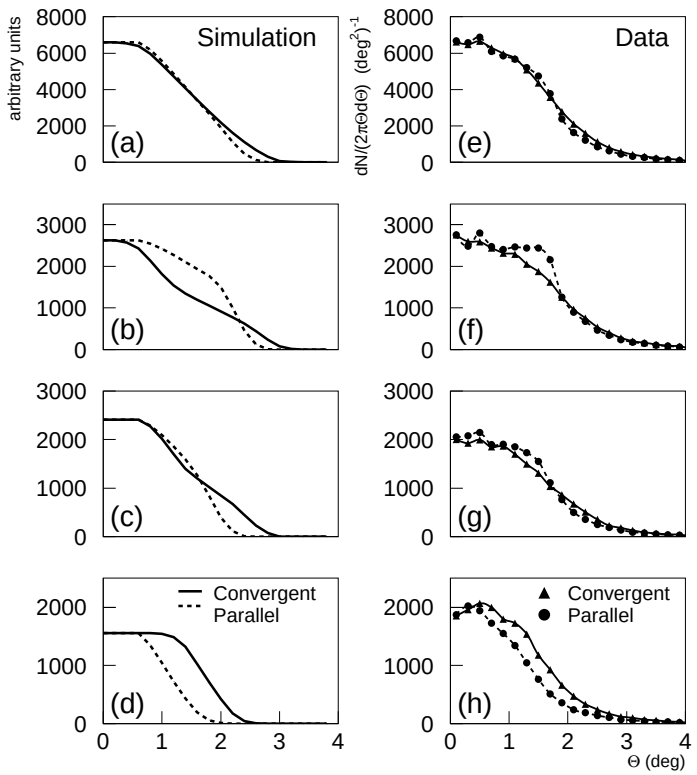

FIGURE 2. Left: simple geometrical model for the number of detected showers as a function of the angle between the shower axis and the axis of the telescope system, for parallel axes of the telescopes (dashed line) and for canted telescopes (full line). (a) Total rate, (b) 2-telescope events, (c) 3-telescope events, (d) 4-telescope events. Right: experimental detection rates for cosmic-ray showers, for all events (e), 2-telescope events (f), 3-telescope events (g) and 4-telescope events (h), for parallel (points) and canted alignment of axes (triangles).

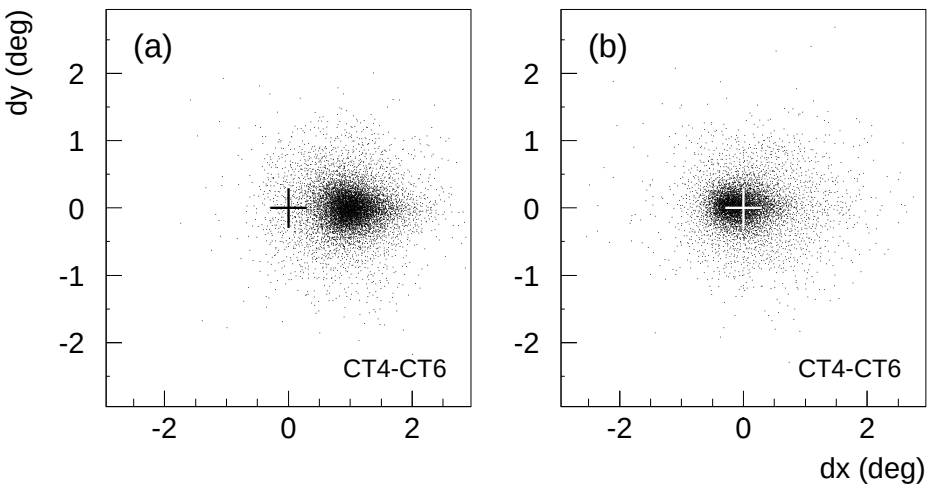

FIGURE 3. Difference in the centroid positions of images in two cameras for parallel (a) and convergent observations (b). The camera coordinate systems are rotated in a way that the x-axis points along the line connecting the telescopes.