Monte-Carlo studies of the angular resolution of a future Cherenkov gamma-ray telescope

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Abstract. The current generation of Imaging Atmospheric telescopes (IACTs) has demonstrated the power of this observational technique, providing high sensitivity and an angular resolution of $\sim 0.1^\circ$ per event above an energy threshold of $\sim 100$ GeV. Planned future arrays of IACTs such as AGIS or CTA are aiming at significantly improving the angular resolution. Preliminary results have shown that values down to $\sim 1'$ might be achievable. Here we present the results of Monte-Carlo simulations that aim to exploring the limits of angular resolution for next generation IACTs and investigate how the resolution can be optimised by changes to array and telescope parameters such as the number of pixel in the camera, the field of view of the camera, the angular pixel size, the mirror size, and also the telescope separation.

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THE APPROACH FOR STUDYING THE ANGULAR RESOLUTION

Monte-Carlo simulations of the development of gamma-ray-induced showers in the atmosphere were performed using Corsika v6.2041 [1]. Cherenkov photons produced in the shower development were recorded and in a second (post-processing) step, these photons were collected with an array of telescopes with adjustable parameters as described below. Using only those photons that hit one of the telescopes in the array, the direction was reconstructed from camera images using a Hillas-style analysis (see Fig. 1). For comparison we also applied more sophisticated reconstruction methods such as a simultaneous minimisation of all the image axes and shower cores.

Since the post-processing step is rather fast in comparison to the generation of the showers in the atmosphere, the phase space of different telescope configurations can be explored rather quickly. Adjustable parameters in the post-processing step are:

- Number of telescopes in the array
- Diameter of the telescope (mirror size)
- Distance between telescopes
- Field of view (FoV) of the camera
- Angular size of the pixels
- Light-collection efficiency of the pixels

To verify the approach taken in this study, the first proof-of-principle was to reproduce the angular resolution of H.E.S.S. as shown in Figure 2 (red points). The next step was to simulate a so-called reference array with 49 30-m telescopes with 50 m spacing, a large field of view ($10^\circ$) and a pixel size of 0.06$^\circ$ as a test of the most optimistic version of a future array that all other configurations could be measured against. This reference array can also be compared to the (optimal) case in which all Cherenkov photons emitted in the showers are collected and used for the reconstruction as reported in [2].

As can be seen from Figure 2, our approach gets within a factor of 2–3 of that optimal angular resolution with a value of $\sim 0.025^\circ$ at 1 TeV. This gives us confidence in the approach since this reference array - albeit prohibitively expensive - is by no means optimised.
Apart from the array and camera parameters that could be improved, similar to the original study [2], the analysis is not optimised and could certainly be improved (in particular the tail-cuts).

Since this paper does not allow us to address the full phase space of possible changes to the array and camera configurations, in the following we will focus on two of the most important variables that affect the angular resolution of a future Cherenkov system: telescope multiplicity (that is the number of telescopes participating in the event) and angular pixel size. We also investigated the effect of other parameters such as mirror size, distance between the telescopes and light-collection efficiency of the individual photodectors but found rather modest dependencies of the angular resolution on these parameters (they mostly affect the energy threshold and effective area).

ANGULAR RESOLUTION AS A FUNCTION OF TELESCOPE MULTIPLICITY

Given that the directional reconstruction is performed via the intersection of image axes, an important question that can be addressed in our scheme is the dependence of the angular resolution on the number of telescopes participating in the event. For this, telescopes were randomly switched off from the reference array (49 telescopes with 50m telescope spacing) and the resulting angular resolution was plotted as a function of the average multiplicity for two different energies (300 GeV and 1 TeV) as shown in Fig. 3.

FIGURE 3. Angular resolution as a function of the average number of telescopes in the reconstruction. Plotted on the x-axis is the average number of telescopes that participated in the reconstruction. E.g. for the 49 telescope array at 1 TeV, the average multiplicity was 16.
The 300 GeV curve does not continue to higher multiplicities, because even for the system of 49 telescopes, the average multiplicity for a 300 GeV shower is only 9 (for the reference system in which the telescopes are 50m apart). As can be seen from these curves, the angular resolution improves rather strongly when adding telescopes to an array of a few telescopes, but at a large number of telescopes, it levels off as expected since the reconstruction becomes over-constrained. This asymptotic behaviour of the angular resolution with increasing telescope multiplicity suggests that beyond 10 telescopes participating in the event, the angular resolution improves only very moderately for 1 TeV γ-rays.

**ANGULAR RESOLUTION AS A FUNCTION OF ANGULAR PIXEL SIZE**

The next property of a future TeV gamma-ray array that was studied is the dependence of the angular resolution on the (angular) size of the individual photo-sensors. A priori it is not obvious, whether a finer pixelation of the camera does improve the angular resolution, since the reconstruction is done by an intersection of image axis and individual pixels only contribute to a reconstruction of the major shower axis in case of a Hillas-type analysis. It is expected that once the pixel size gets larger than the angular width of the shower in the image, the major axis becomes rather poorly defined and the angular resolution will suffer.

**FIGURE 4.** Angular resolution as a function of angular pixel size for a fixed number of pixels (36x36=1296) for the reference array. Since the number of pixels is kept constant, the field of view increases as the pixel size increases. Only in the lowest point for the 1 TeV shower there is actually some effect visible from the reduction in the field of view (from the comparison to Fig 5). For the smallest pixel size (0.04°), the FoV is 1.44°.

**FIGURE 5.** Angular resolution as a function of angular pixel size for a fixed field of view (6°) for the reference array. As suggested already in Figure 4, the improvement with decreasing pixel size is rather modest, so the optimal pixel size is in the range of 0.05°. It should be noted, that this is true for the Hillas analysis and does not preclude a significant improvement with smaller pixels and a different reconstruction scheme.

Naturally the angular size of the individual pixels, together with the total number of pixels determines the field of view. Each pixel adds to the cost, and therefore we have taken the approach of fixing the number of pixels in the camera (and therefore the total costs) while changing the pixel size. The number of pixels was fixed at 1296 per camera. The effect of fixing the pixel size is that while the pixel size gets bigger, the FoV of the camera also increases. Fig 4 shows the angular resolution as a function of the pixel size for the reference array of 49 telescopes. As can be seen from this figure, the angular resolution gets only slightly worse as the pixel size increases and the dependence seems to be rather modest. To check whether this effect is due to the shrinking of the field of view with decreasing pixel size, we also kept the field of view at a constant value of 6° and determined again the angular resolution as a function of the pixel size. The results are shown in Fig 5. As can be seen, the behaviour is very similar to that shown in Fig 4 suggesting that the increase in the field of view has a rather small effect on the angular resolution (this has been verified independently by varying the field of view with fixed pixel size). Summarising these findings, for a Hillas-type analysis, there seems to be only a slight improvement in angular resolution when going to smaller pixels. The optimal resolution is achieved for angular pixel sizes 0.05°. It should be noted that at this stage, we do not see a clear improvement in angular resolution when using more advanced reconstruction methods than a simple Hillas-style
analysis. It should however be noted, that this is work in progress and there could be some improvement in particular with smaller pixels when using different techniques such as a Maximum Likelihood fit of all the pixels in the image simultaneously.

SUMMARY

We have devised a simple Monte-Carlo simulation scheme based on Corsika-simulated gamma-ray showers to explore the phase-space of how to build a future ground-based Cherenkov telescope with optimal angular resolution. Preliminary results point to only a modest improvement in angular resolution with smaller angular pixel size and no significant improvement (for 1 TeV showers from zenith) when having more than 10 telescopes detecting the shower. We have verified this approach by simulating a H.E.S.S.-like instrument and getting matching angular resolution as a function of energy. The next steps are an exploration of the phase space to determine parameters of the array to optimise the angular resolution.

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