Simulation of imaging air shower Cherenkov telescopes as part of the TAIGA Project

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The Tunka Advanced International Gamma-ray and Cosmic ray Astrophysics (TAIGA) project aims at observation of cosmic rays beyond 100 TeV and gamma rays above 1 TeV via observation of the extensive air showers (EAS) caused in the atmosphere. Two common detection techniques are timing arrays and imaging air shower cherenkov telescopes (IACT). Timing arrays yield good directional and energy reconstruction, but provide only mediocre gamma-hadron-separation at their energy threshold. IACTs are good at separation, but since a stereoscopic view of a shower is needed for high reconstruction accuracy, it is difficult to achieve the large effective areas needed for ultra high energy observations.

In this work we present the simulations performed to explore and optimize our IACT design and the first steps towards hybrid reconstruction.

1 Motivation

The highest energies in the gamma ray spectrum are a very interesting domain of cosmic accelerators. Many kinds of sources have already been studied up to a range of tens of TeV, but latest results from experiments like IceCube hint at the existence of sources accelerating particles up to the PeV range, so-called Pevatrons. While the charged particles from such sources are lost in the interstellar magnetic fields, they produce pions in the ambient medium which subsequently decay into gamma-rays. These gammas carry less energy than the original partice had (O(10) less), so a gamma ray source at $>$100 TeV would be a Pevatron. For further details on Pevatrons, see [1] (these proceedings).

The flux of gammas with such a high energy is low, making it necessary to instrument large areas on the Earth's surface to reach sufficiently large effective areas needed for sensitivity. This paper presents a method to address this challenge.

2 A combination of known approaches

Two common and well-understood methods of observing the high energy gamma ray sky are timing arrays and imaging air cherenkov teleskopes (IACTs).

Timing arrays sample the Cherenkov light front of EAS. Core position and direction of incidence are calculated from the arrival time distribution of the air shower front. The comparatively low number of readout channels per km^2 is an advantage for instrumenting the very large areas needed for proper sensitivity.

IACT systems use two or more telescopes with (most often tesselated) mirrors and multichannel cameras to take images of the EAS. Using a Hillas-type image shape analysis[2], a good distinction between EAS initiated by gammas and EAS caused by the proton background is possible. The downside of this method is that a stereoscopic view of a shower is needed to reconstruct impact core position and shower angle with sufficient accuracy. This sets an upper limit to the spacing of the telescopes (about 300 m) since at least two telescopes need to be inside the Cherenkov light pool to get more than one shower image. Consequently, covering large aeras with IACTs requires a large number of detection and readout channels per instrumented km^2.

The idea behind the TAIGA project is to combine both techniques to use both their strengths while compensating for their weaknesses. A timing array will determine arrival direction and impact point of the air shower, which is then used to interpret the IACT camera image to determine the nature of the EAS primary. Since the directional information is reconstructed by the timing array, the need for stereoscopy does not apply and the spacing between the telescopes can be doubled.

The TAIGA experiment will consist of the already deployed HiSCORE timing array and custom designed IACTs.

HiSCORE stations contain 4 photomultiplier tubes (PMTs, 8"diameter) each, looking directly into the night sky through winston cones. 28 stations have been deployed at Tunka Valley, Russia (51° 48' 35" N, 103° 04' 02" E, 675 m a.s.l.) with a spacing between 100 m - 150 m covering about 0.25 km^2 and have been in operation since winter 2014. Further extension is envisaged up to 3 km^2.

The custom designed IACTs will be Davies-Cotton telescopes with a 4.3 m tesselated mirror dish, a focal length of 4.74 m and a 540 PMT pixel camera with a field of view of 10° diameter. These telescopes will be placed at a 600 m spacing, a prototype is already in construction.

3 Simulations

To evaluate the detector design, a Monte Carlo (MC) simulation was done in three steps. First, the shower itself was simulated using CORSIKA-6990 [3](IACT option for generation of Cherenkov light, hadronic interaction models QGSJET [4] and Gheisha [5]). The shower data is then evaluated independently by the simulation routines for HiSCORE and for the IACTs.

Detection by HiSCORE is calculated with the sim_score[6] code, a custom simulation software based on the IACT package performing a full detector simulation including all response functions. From the simulation of gamma-ray induced EAS, the resolution for core position, incidence angle, and reconstructed energy is determined.

The IACT simulation is done with sim_telarray[7] and performs a full raytracing of the Cherenkov photons through the telescopes' optics. This takes the telescope design properties into account, e.g. mirror dish shape, mirror reflectivity and (mis-)alignment, camera size, shadowing by masts and camera, and camera PMT efficiency. Last simulation step is the addition of noise from NSB and the electronic parts.

After generation of camera images, sim_telarray carries out the image cleaning and the calculation of the Hillas parameters and, if more than one telescope triggered, stereoscopic reconstruction of direction, incidence angle, and energy, even though the stereoscopic evaluations are not necessary for our studies.

The simulations presented in these proceedings are the IACT's point spread function, which is a property of the telescope design, and first insights into the quality of the gamma hadron separation. Please note all results presented here are preliminary.

3.1 Point Spread Function (PSF)

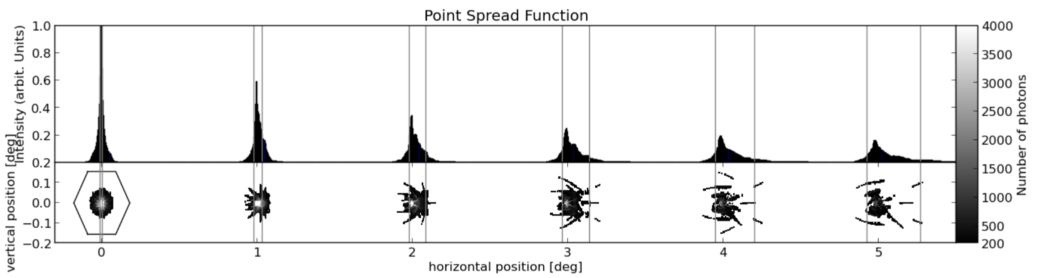

Figure 1: IACT PSF for angles of 0°-5° from the optical axis in 1D projection and in greyscale. Vertical lines indicate each spot's projected 86% range. Perfectly aligned mirrors are assumed. The finger-like structures are an effect of the outermost mirror segments.

Simulation To evaluate the intended design of the IACTs, the sim_telarray ray tracing routine was used to simulate light from an infinitly far away point source. The image of the source in the camera plane is not perfect due the abberations from the mirrors, and the resulting intensity distribution is called the PSF. To find the theoretical lower limit of the PSF, we assume perfect mirrors, no misalignments and no NSB.

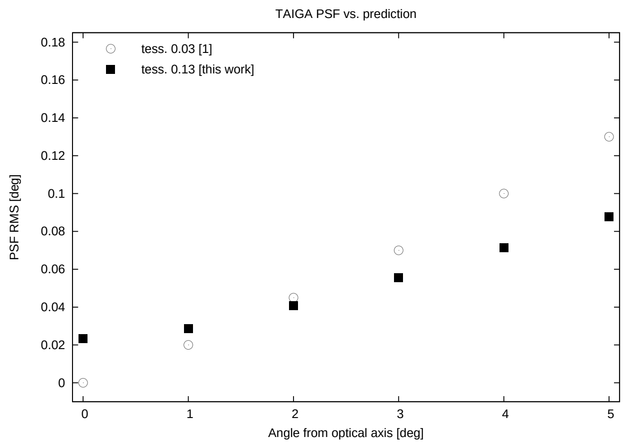

Figure 2: Comparison between analytical and simulated predictions for the PSF for F/D = 1.1. Circles: Analytical prediction [8] for a tesselation ratio of 0.03, boxes: Prediction by sim_telarray simulation ($\alpha = 0.13$). The difference in the steepness of the curve is caused by the difference in tesselation ratio.

The TAIGA IACTs are composed of 30 spherical mirror tiles (60 cm ø) on a 4.75 m ø Davies-Cotton dish. To compare our results to a semi-analytical model prediction, one must take note of the tesselation ratio, the ratio between the diameters of the individual mirror tile (d_{tile}) and the main dish (D_{dish}) :

$$\alpha = \frac{d_{tile}}{D_{dish}} \tag{1}$$

The relative size of the individual mirror tiles is important since larger tiles contribute larger abberation effects due to their spherical nature. TAIGA's IACTs are designed with a tesselation ratio of 0.13.

Figure 1 shows the image of the point source at different off-axis angles in the camera layer. The PSF is significantly smaller than a single camera pixel even at an off-axis angle of 5° at the assumption of perfect mirror alignment. The star-like shape of the spot is an effect of the outermost mirror tiles.

The impact of the tesselation ratio on the PSF can be seen in Figure 2. The analytical prediction by Schliesser and Mirzoyan[8] assumes a tesselation ratio of 0.03, meaning much smaller mirror tiles as compared to the TAIGA telescopes ($\alpha = 0.13$). The overall shape is closer to the shape of the main dish, with less abberation effects from the rims of the individual tiles.

For small angles, the minimal PSF of the TAIGA IACTs is not as good as expected from the analytical predictions. With increasing angle however the TAIGA design shows a better PSF than predicted from the 0.03 model. This is an expected and desired effect since TAIGA IACTs are telescopes with a large field of view, so faithful imaging at large off-axis angles is more important than reaching zero at the very center. Even at 5 ° off-axis, the TAIGA PSF stays considerably smaller than the radius of the camera pixels (0.19°), leaving enough room for the deviations brought by a real setup.

Single mirror PSF measurement The MC results shown in Figure 1 represent the minimal PSF possible under the assumption of perfect mirrors. Real mirrors have inaccuracies which will add up and increase the overall PSF of the telescopes. To get an estimate on these inaccuracies, the PSFs of several mirror tiles have been measured individually by placing a point-like light

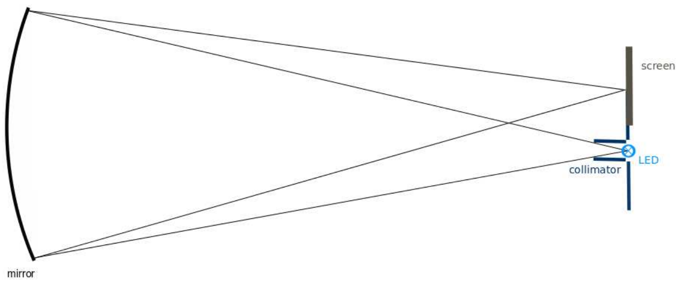

Figure 3: Scematic view of the single-mirror PSF measurement setup. To the left is the mirror, to the right the light source and screen close to the focal point.

source in the focal distance of the mirror and determining the angular size of the reflected spot (see Figure 3). For a perfect mirror, this spot should have the exact same dimensions as the source, with any spread being the contribution of deviations from a perfect spherical shape.

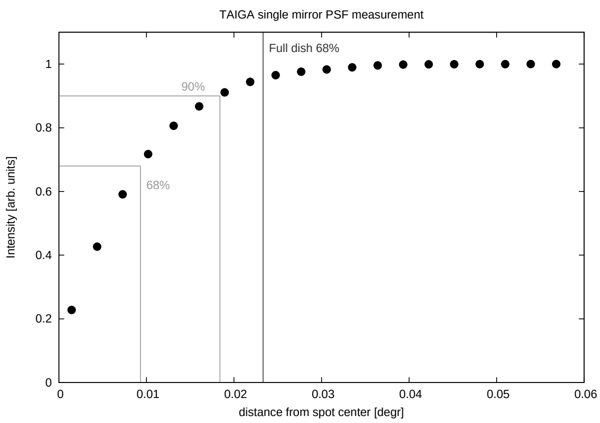

Figure 4: Example for the cumulative intensity distribution of a point source reflected by a single TAIGA mirror. Marked are the 68% (1 σ) and 90 % containment radius as well as the MC-determined radius of the minimal PSF of the whole dish. It can be seen that the single-mirror PSF is smaller than the full dish PSF by about a factor of 2.

Since a spherical mirror reflects a light source back onto itself when the source is put at the exact focal point, the measurements are done in a slight off-axis angle ($<2°$). 28 TAIGA mirrors have been measured in this procedure with all mirrors showing a PSF significantly smaller than that of the full dish (for an example, see figure 4) while not varying much between each other. Therefore, the chosen mirrors are suitable for use in the TAIGA IACTs.

3.2 Gamma Hadron Separation

The TAIGA IACTs are meant to improve the gamma hadron separation of the TAIGA array, especially at its energy threshold at about 10-50 TeV[9]. To understand the range of improvement, we first evaluate how powerful the IACTs are on their own. Since shower energy, impact parameter and direction are derived from the timing array's measurements, we can focus our analysis of the IACT images on the primary.

The parameter with the greatest dependence on the nature of the shower primary is the image width, calculated via the second moment of the amplitude distribution after image clean-

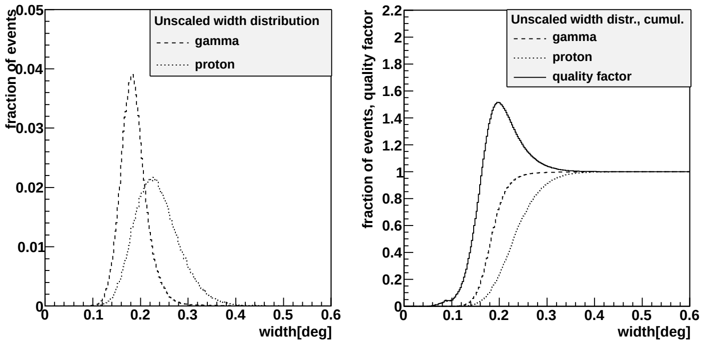

Figure 5: Raw image width distribution for zenith showers with E_{EAS} = 10-50 TeV . Dashed: Gammas, dotted: Protons, Solid: Quality factor. Left: Differential distribution. The proton distribution has a bigger mean and spread than the gamma distribution, but the two peaks still overlap much. Right: Cumulative distribution and Q for the width cut. If a cut is made on the raw data, the maximum Q does not reach 1.6.

ing. This second moment depends mainly on the overall camera PMT amplitude ('size'), impact parameter and the primary. The higher number of hadronic interactions in a hadron-induced shower lead to a broader transversal momentum distribution of the particles in the shower, which in turn increases the image width compared to gamma- or electron-induced showers as seen in figure 5. A cut on the image width can separate gamma from hadron events. The cut quality factor is defined by:

$$Q = \frac{\epsilon_\gamma}{\sqrt{\epsilon_p}} \tag{2}$$

with

$$\epsilon_i = \frac{n_i(w < w_{cut})}{n_i}, \quad \epsilon_i \in (\gamma, p) \tag{3}$$

Even though the two distributions have different shapes, they still overlap strongly due to variation in the impact parameter and image size. With a width cut on the raw data, only a quality factor of Q=1.4 is reached. In order to improve the quality factor, each image width is scaled to the expectancy value for the respective image size, impact parameter and zenith angle. An exclusive gamma-only MC event data set was used to generate a lookup-table which contains the width expectancy values.

In the final experiment, the selection of the correct lookup-table entry will be done with core distance and zenith angle determined by the HiSCORE timing array. To give a first estimate of the final separation quality, a Toy core simulation was performed (see Figure 6). To emulate reconstruction by HiSCORE, the core position which is known from the MC is randomised with the HiSCORE core position resolution, and the resulting value is used as the 'reconstructed' core position when selecting the lookup table entry. This cuts on computing time since actually simulating the showers in sim_score is not necessary.

The value after scaling is called the Hybrid Scaled Width (HSCW):

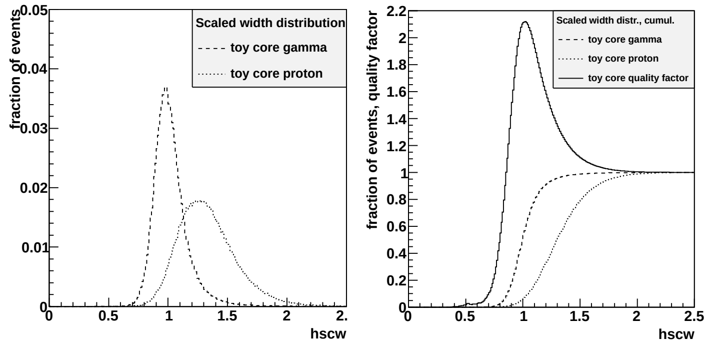

Figure 6: HSCW distribution for zenith showers with E_{EAS}= 10-50 TeV. Dashed: Gammas, dotted: Protons, Solid: Quality factor. Left: Differential distribution. Compared to the unscaled plot, the gamma and the proton distribution have moved apart significantly. Right: Cumulative distribution and Q for the width cut. If a cut is made on the HSCW, the maximum Q is about 2.1.

$$HSCW = \frac{w_{tel}}{w^{\gamma}_{MC}(d_{array}, size_{tel})} \tag{4}$$

Scaling the width makes the two distributions move apart, and now a cut on the HSCW yields us Q$\sim$1.9, which is not only better than an unscaled cut, but also better than the HiSCORE-only separation at those. The timing array can achieve Q $\sim$ 1 at the threshold and only starts to approach 2 at a hundred TeV.[10][9]

The blurring of the core position lowers the separation quality only little compared to the direct use of the MC core position ($\sim$ 1.9) even though HiSCORE's core resolution is strongly energy-dependent near the energy threshold.

4 Conclusion and Outlook

TAIGA's combination of IACTs with timing arrays is a valid method of obtaining the large areas needed to observe ultra high energy gamma rays. The design of the TAIGA telescopes will provide suitable shower images as tested both by MC simulation and measurement of prototype parts. Also, adding IACTs to a timing array will provide a possibility of rejecting the hadronic background with a quality factor of 2.1 near the energy threshold, where the timing array alone could not make a distinction.

The studies so far are not yet a full hybrid reconstruction. In the full reconstruction, the directional information stored in the IACT images will also be taken into account to improve the resolution of shower core position and incidence angle. Also the timing array signals do contain information on the nature of the primary in the signal rise time, so for higher energies the gamma hadron separation quality will be much better than 2.

Furthermore, the IACTs can be used to reduce the energy threshold.The timing array needs 4 stations with signal for a proper reconstruction, but a shower can also be reconstructed with the IACT image and one station only. The combination also makes it possible to indirectly increase the field of view of the telescopes. So far, shower images that are cut off by the edge of the camera are rejected because they are incomplete, but the shower information from the timing array might allow to interpolate the shape of the full shower.

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