The Advanced Gamma-ray Imaging System (AGIS): Semianalytical Studies

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***Abstract*. The Advanced Gamma-ray Imaging System (AGIS) is a next-generation array of imaging atmospheric Cherenkov telescopes for gamma-ray astronomy being planned in the U.S. The anticipated sensitivity of AGIS is about one order of magnitude better than the sensitivity of current observatories.**

We are currently in the process of optimizing the array subject to a constraint on the total cost. The high dimensionality of the optimization problem requires a fast technique to narrow down the search space.

We present a simple semianalytical model of the array of telescopes based on the properties of the Cherenkov light distributions and response of a single telescope together with more detailed simulation studies of the effect of varying key design parameters. The implications of these studies including the optimal spacing for the array, the expected collection area and angular resolution are discussed.

***Keywords*: AGIS gamma rays IACT**

I. Introduction

The AGIS project under design study, is a large array of imaging atmospheric Cherenkov telescopes for gamma-rays astronomy between 100 GeV and 100 TeV. We present the ongoing simulation effort to model the considered design approaches as a function of the main parameters such as array geometry, telescope optics and camera design.

With an order-of-magnitude improvement in sensitivity, larger field-of-view (FoV), and improved angular resolution, AGIS could efficiently map a large fraction of the Galactic plane [1]. In addition to the survey capability, AGIS would provide detailed studies of the morphology of discrete γ-ray sources in our galaxy. It would efficiently address such key questions in Galactic astrophysics as the origin of cosmic rays, the nature and origin of magnetic fields near compact sources and in the inter-stellar medium (ISM), and the efficiency of shock acceleration for nonrelativistic and relativistic shocks for different magnetic field geometries.

TABLE I: Target specifications for the AGIS array

Specification	Target
Telescope Spacing	50 - 150 m (TBD)
Mirror Aperture	100 m^2
Field of View	8 deg.
Pixelation	0.05 - 0.10 deg. (TBD)
Effective Collection Area	1 km^2
Angular Resolution	0.02 - 0.05 deg.

A. Simple models

The results described in this document are a snapshot of an ongoing effort to outline the concept of the AGIS array. At this point, some key parameters of the array are considered free. The target specifications (see Tab. I) and cost limitation are the constraints that determine the possible combination of the array parameters. It is impossible to perform detailed simulations for the full multidimensional parameter space; a preliminary study to make the ranges of possible parameters narrower is strictly necessary. This can alternatively be viewed as a rejection of the regions in the parameter space that will definitely not deliver the desired performance for the target array. In order to do this, a variety of techniques can be used, including analytical studies making use of basic principles and simulations of idealized detectors. Use of idealized models can not only speed up computations, but also give understanding of the theoretical limits for the key performance characteristics like angular resolution and effective detection area.

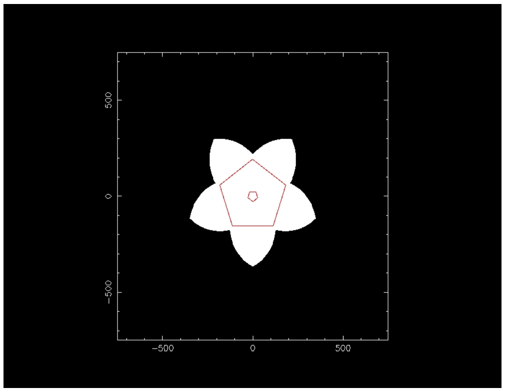
This study is focused on the following key parameters of the array: array layout, field-of-view of telescopes, camera pixel size (PS) and the optical point spread function (PSF).

B. Toy models

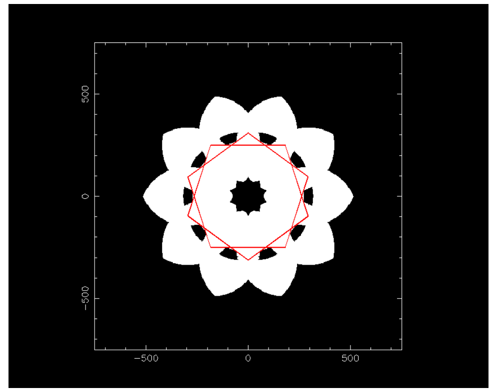
Some of the design concepts like the array layout are even difficult to describe in terms of a small number of parameters. The latter can be a rectangular or triangular mesh of telescopes with only one spacing, or it can be a hybrid array with different cell shapes with different spacings between telescopes. Such a wide variety of choices implies optimization in a multidimensional parameter space. The figure of merit for such optimization should be calculated quickly, providing a motivation for some very simple, yet reasonably precise "toy" model. One of such models will be described in subsection I-D.

C. Infinite Array Approximation

When the number of telescopes in an array is large, the contribution of the edges to the total performance is negligible and the effective detection area of the array is proportional to the number of cells. When the number of telescopes is that large, one can simulate only a single cell surrounded by a halo of telescopes. Shower cores need to be distributed only in this single cell. Any triggered telescope in the halo can be used for event reconstruction. Even if the number of telescopes is not large, we still can assume that the described simulation



(a) Initial array layout



(b) Array layout after optimization

Fig. 1: Optimization of the array consisting of two concentric cells. The white areas indicate the regions where showers would deliver signals above the threshold to at least 2 telescopes and the angle between the lines connecting these telescopes and the shower core is greater than $\sim 30°$.

technique is valid. In this situation we say that the *infinite-array approximation* is used.

D. Array Layout

A "toy" model is being used to examine the properties of different array layouts. Currently, it can be used only to estimate the effective detection area of an array. The model utilizes lateral distributions for γ-showers. A quick evaluation of the effective detection area can be made for an array using only this information. If the only change in the configuration of an array is coordinates of telescopes and/or mirror aperture and/or camera FoV, this evaluation can be made with negligible computation time. For the given energy, we evaluate the effective detection radius, determined by the required amount of Cherenkov light for the successful event reconstruction, and the corresponding lateral distribution. We assume that all showers with impact parameters smaller than the determined value of the effective detection radius trigger a telescope at all times. This assumption neglects shower fluctuations which are important at lower energies. Requesting at least $\simeq 100$ ph.e. to trigger a telescope, we reduce effects of fluctuations significantly. To trigger a system of telescopes a shower should trigger some minimal number of telescopes. At the same time, we require that the angle between lines connecting telescopes and shower core should be greater than some $\Theta_{\rm min}$ for at least one pair of telescopes. The sensitive area of such a "toy" array is shown graphically in Fig. 1a and 1b. In this figure the white areas indicate the regions where showers trigger the system of telescopes. In this figure, telescopes are located at the vertices of the polygons. Fig. 1a and Fig. 1b show the example of optimization in case of an array consisting of two concentric cells, each having 5 telescopes. Fig. 1a represents an initial guess for the spacings between telescopes of the first and the second cell. The optimization results in the same lengths for both cells. This result holds for different number of telescopes in the cell. Optimization of the "toy" model shows that the area *per telescope* for systems with different number of telescopes (3–8) and concentric cells (1–5) is approximately the same provided that the number of triggered telescopes is greater than 1. The same characteristics were also compared for the optimized arrays consisting of triangular cells. Infinite arrays with uniform spacing were compared with the arrays consisting of widely spread cells with non-overlapping detection areas. In all cases 3 triggered telescopes were required to trigger the array. According to the "toy" model, the arrays of the first type can provide $> 50\%$ more detection area *per telescope*. This is true, even though we neglect the effective area beyond the edges of a finite array. Thus, we get the power of a large uniform array over a simple sum of independent cells.

This "toy" model already shows good agreement with detailed simulations, and is currently being modified to include an estimation of angular resolution that will be calibrated by our detailed simulations (section II).

II. Detailed Simulations

CORSIKA [2], KASCADE [3] and ALTAI [4] packages were used to simulate showers. GrISUDet program [5] was used to perform detailed simulations of IACT arrays. In all cases, elevation 2500 m, vertical showers, and magnetic field $\simeq 0.5$ Gauss were assumed. Different pixel sizes between $0.05°$ and $0.20°$ and telescope distances between 50 m and 200 m were simulated in order to optimize angular resolution, effective area and background suppression. For most of this results the VERITAS data analysis chain [6] was used after an appropriate modification for different pixel sizes and camera dimensions.

III. Results and Discussion

A. Choice of Field-Of-View

The *scientific motivation* for a wide FoV is to provide a sensitive Galactic plane survey and the mapping of extended sources, aid the mapping of extended sources,

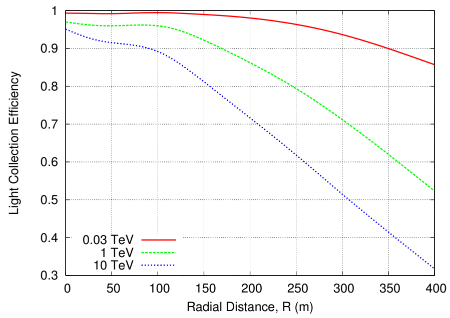


Fig. 2: Comparison of light detection for a finite FoV and an infinite FoV as a function of impact parameter. Y-axis shows the ratio of light collection efficiency of a finite FoV to the efficiency of the infinite FoV.

better match prompt GRB positions and provide a higher probability for serendipitous discoveries.

The *technological motivation* for a wider FoV is to improve the background rejection and angular resolution even for point sources. Fig. 2 shows that $FoV = 8°$ provides as high a photon collection efficiency as 2π steradian would do for distances to shower cores equal to a few hundred meters. A wider FoV also increases the number of telescopes participating in the event reconstruction. This improves the amount of information available for recognizing the nature of the primary (γ-ray or cosmic ray) and also significantly improves the angular resolution.

B. Optical System

AGIS will use a two-mirror telescope with a Schwarzschild-Couder optical system [7]. The SC optics are expected to give a dramatic improvement in PSF. In our simulations we use a conventional DC design with a high f/D ratio to approximate the superior performance of the SC or other improved optical design. Two different optical systems were considered. The first one we tag as "Ideal". It is a DC mirror with perfect alignment of mirror facets, so that a beam of parallel light rays is very well concentrated in the focal plane. The performance of such a system is presented in Fig. 3a. The upper plots in Fig. 3 show the spot size as a function of field angle and allow a comparison of the sizes of the optical PSF with $0.05°$ pixels. Centers of the pixels are represented by mesh of dots.

To understand the degradation in the angular resolution for a non-ideal optical system, we use the same optical design with Gaussian misalignments in mirror facets so that the resulting $FWHM \simeq 0.1°$ over the FoV (Fig. 3b). In this case, the focused light is smeared over a few $0.05°$ pixels. While we anticipate that this defocusing will degrade the performance, there may also be improvements in the ability to determine centroid positions and orientation that tend to mitigate this effect.

θ^2 distribution is showing that the γ-ray angular resolution is unchanged if we assume a Gaussian blur increasing the $FWHM \simeq 0.1°$, as long as the array

TABLE II: Comparison of key characteristics of different array configurations. Crab spectrum is assumed.

$E > 1TeV$:

Configuration	R, min^{-1}	$\theta^{\circ}_{68\%}$
VERITAS	1.6	0.112
AGIS 100m, inf arr. appx., $PS = 0.05°$	3.0	0.015
AGIS 100m, inf arr. appx., $PS = 0.10°$	3.0	0.027
AGIS 80m, $PSF \simeq 0.1°$, $PS = 0.05°$	8.3	0.042

$E > 50$ GeV:

Configuration	R, min^{-1}	$\theta^{\circ}_{68\%}$
VERITAS	11.4	0.128
AGIS 80m, $PSF \simeq 0.1°$, $PS = 0.05°$	100	0.069

spacing and pixel size ($= 0.05°$) are the same. This shows that for the same telescope spacing and $0.05°$ pixels a real-life optical component allows some relaxation of technical specifications while preserving the performance of the whole system. The effect of this degradation on γ/hadron separation or trigger threshold is under study.

C. Choice of Pixel Size

By measuring the same shower with many telescopes, a 2–3 times better angular resolution compared to current small arrays of IACTs can be achieved for γ-ray events. Fig. 4 shows the improvement in angular resolution of AGIS in comparison to VERITAS [8]. Theoretical limit [9] is also shown in the same plot.

A better angular resolution using cameras with smaller pixels can be expected, as shown in [10], [11]. Simulations of AGIS in the approximation of infinite array and ideal optics, indeed, show the benefit of smaller pixels. Fig. 5 shows comparison of angular resolutions for $0.05°$ and $0.1°$ for infinite-array approximation where distance between telescopes is 100 m. For higher energies taken into account in this figure the improvement in 68% containment radius is $\gtrsim 40$ %. For lower energies the effect is less significant. For instance, at 500 GeV, the improvement in the same characteristic is $\simeq 15$ %.

D. Comparison of Key Characteristics

The following basic conclusions can be drawn from the comparison of key performance parameters in Tab. II and Fig. 6. The detection area for the simulated AGIS array is $\sim 7 - 40$ times higher than for VERITAS with a total γ-ray rate ≥ 8x higher than for VERITAS (assuming an $E^{-2.5}$ differential spectrum). The angular resolution for AGIS was found to be 2-3 times better than for VERITAS. Further improvement in angular resolution down to $\simeq 1.5$x of theoretical limit for higher energies is possible for AGIS by taking into account only those shower cores which fall into array (which results from infinite-array approximation).

IV. ACKNOWLEDGMENTS

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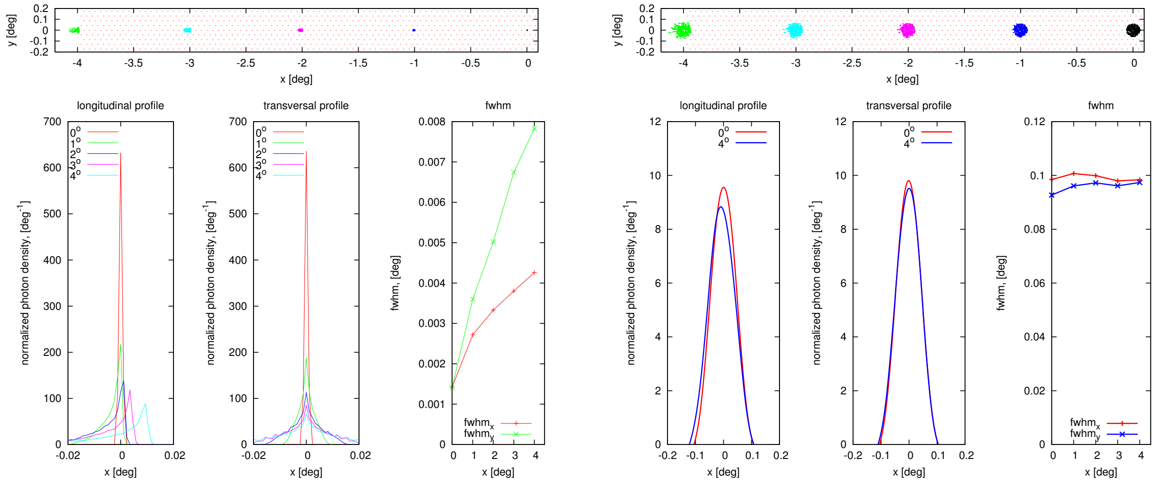

(a) "Ideal" Optics (b) "Non-ideal" Optics

Fig. 3: Scatter plots for Cherenkov light in the detector plane (upper panels) and FWHM plots (bottom panels) are shown for different angular offsets of the light source.

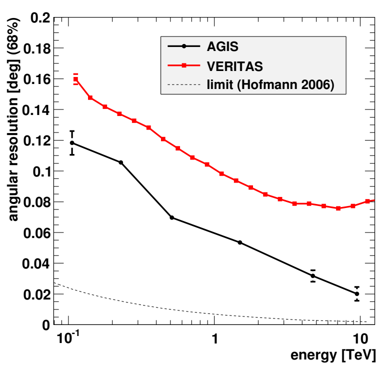

Fig. 4: Angular resolution (with $0.1°$ camera pixels) vs. energy for a 36 telescope array with telescope distances of 125m compared with VERITAS [8] and the theoretical limit as derived in [9].

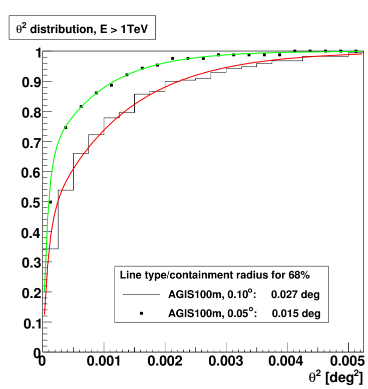

Fig. 5: Angular resolutions for $0.1°$ and $0.05°$ pixel sizes in the approximation of infinite array with spacing 100 m.

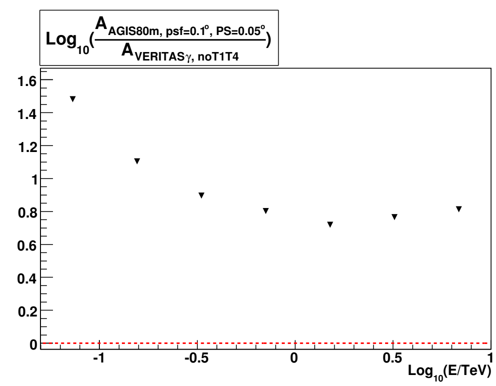

Fig. 6: Ratio of the detection area of AGIS 80m array with optical $PSF = 0.1°$ and the detection area of the VERITAS array.

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