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A Wide Field of View Air Cherenkov Imaging Telescope

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Abstract: Contemporary imaging air Cherenkov telescopes (IACT) for ground-based very high energy (VHE) gamma ray astronomy have prime focus optical design. Typically these telescopes have (2-4)° wide field of view (FoV). They use F/0.7 - F/1.2 optics and provide (3-10)' resolution in the FoV. Generally a well designed telescope that includes more than one optical element, will offer some advantages not available in the case of prime focus designs. Those advantages could be a) the wider FoV, b) higher and more homogeneous optical resolution, c) faster optics/more compact size and d) low degree of isochronous distortion of focused light. Also, they can allow one in a single observation to monitor the gamma ray activity in a sizeable portion of the sky as well as to perform in a relatively short time scale a sensitive all-sky survey. We report below on a 15° wide FoV telescope design.

Introduction

The technique of Imaging Atmospheric air Cherenkov Telescopes (IACT) is successfully used for ground based gamma ray astronomy, already some ~50 gamma ray sources are discovered. The starting point of the successful race was the discovery of the first TeV gamma ray signal from the Crab Nebula by the Whipple collaboration in 1989 [1]. In the mean time the sensitivity of the IACT telescopes has substantially improved. Today's installations operating in the same energy range need just a few minutes for the detection of the same signal strength. The main improvements are essentially due to a) finer pixel size, b) improved trigger, c) larger size of reflectors and d) use of multiple telescopes operating in coincidence mode (the so-called stereo mode of observations). The field of view (FoV) of IACTs did not undergo substantial changes. Contemporary IACTs typically cover (2-4)° wide FoV in the sky. The wider FoV telescopes can offer certain advantages. These can allow one in a single observation to monitor the gamma ray activity in a non-negligible portion of the sky. Obviously in a relatively short time one can perform a sensitive all-sky survey. While performing observations of scheduled astronomical targets, the H.E.S.S. collaboration has discovered several new sources in their relatively large ~ 4° wide FoV cameras [2]. Along with the advantages of the wide FoV there are also a number of drawbacks, such as: a) compared to simple prime focus telescopes, the wide FoV have more complex optical and mechanical designs, b) the imaging camera can have a large transverse size and thus can shadow a non-negligible part of the reflector area and c) the camera shall be composed of a very large number of light sensors and correspondingly one will need large number of readout channels. All these will make the wide FoV telescope expensive.

Wide FoV

For the successful operation of an IACT, one needs to provide an optical resolution that is necessary for selecting the rare gamma shower images from the few orders of magnitude more frequent images produced by hadron (background) showers. The differences in shape parameters of gamma and hadron images are in the range of (0.1-0.2)° for the TeV energy range and they are a few times less for sub- 100 GeV energy range. In simulations [3] we studied the dependence of the r.m.s. optical resolution (in the range of (0.01-0.1)°) on the design F/number for different prime focus optical designs. One can assume that a resolution of 0.05° shall be adequate for successful imaging, at least for energies ≥ 100 GeV. In the recent work [4] it was shown that one can still gain in angular resolution of gamma sources when going down towards 1' optical resolution. The simplest and straightforward way to design a large FoV telescope would be a telescope with just primary mirror of a required minimum F/number. We have shown in [3], for example, that by using F/2.7 optics, one can design a 10° wide FoV telescope of parabolic design. In the same paper we have shown that a Davies-Cotton telescope of F/2.5 and even a F/2 optics of elliptical design can provide the same 10° wide FoV, albeit at the expense of higher degree of isochronous distortion. An alternative way of constructing a wide angle optics is to follow the design of the EUSO detector [5]. The telescope in that case has a refracting optics and can allow a full FoV of 60°. The GAW telescope for TeV gamma astronomy is following that design in their construction [6]. Two double-sided Fresnel lenses were planned to be used in the optical design of EUSO. The drawbacks of that design were considered to be the high light losses, especially for relatively large incident angles of light. Also distortion of images because of scattered by the Fresnel lenses light shall be carefully taken into account. One needs to construct the refractive optics from materials that for the given thickness do not substantially absorb the short-wave near UV light in the wavelength range of 330-400 nm.

Reflector obscuration and focal scale of the prime focus design

The focal plane scale factor of a telescope of a focal length F is F/57.3 cm/°. For a prime focus telescope of a given F/D and given focal plane detector acceptance angle θ°(half angle) the relative shadowing effect in percent can be calculated as $4 \cdot (\theta/57.3)^2 \cdot (F/D)^2 \cdot 100$. Thus, for example, a telescope of F/D=2 and θ=10° (corresponds to full angle of 20°) will shadow 48.7 % of the reflector and a camera of θ=5° will shadow just 12 % of the reflector. For simplicity let us consider an F/2 optics. It is obvious that for F/2 compared to the F/1 case a) the imaging camera will be at 2 times more distance from the reflector, b) the imaging camera single elements must have 2 times larger linear size for subtending the same angle in the sky, c) the camera weight may increase ≥ 4 times, d) camera supporting mechanical structure shall be of a stronger design, e) the shadow cast by the camera will increase ≥ 4 times. In the following we want to concentrate on a specific wide FoV telescope solution that comprises more than one optical element.

Schmidt Telescope

From all optical solutions, the Schmidt telescope, and solutions derived from it, is known to provide the widest FoV for large aperture systems. Specifically, Schmidt type systems provide by far the largest number of focal plane spatially resolved pixels per optical element. Moreover, it is possible to work at very fast F-ratios, below F/1, thereby minimizing the obscuration and weight of the camera, and the overall size and weight of the system. There are thus several reasons to consider Schmidt-type systems for IACT optics. The classical Schmidt telescope includes a spherical reflector and an aspheric corrector plate located at the centre of curvature of the reflector (see Fig.1). It has a curved focal plane, which is confocal with the mirror. The entrance pupil (the stop) is located at the corrector. In order to accept light without vignetting from directions that are relatively far away from the optical axis, the reflector must be somewhat larger than the corrector. Only part of the reflector, which has the size of the corrector plate, reflects light for the given incidence angle. The corrector plate pre-deforms the impinging wave front so that after reflection it is free of spherical aberrations. Because the entrance pupil, which is coincident with the corrector plate, is located at the centre of curvature of the reflector, the system is automatically free of 3rd order coma. A simplified version of the Schmidt-type telescope is used by the AUGER collaboration for air fluorescence telescopes: the corrector plate is replaced just by an aperture diaphragm [7]. This aperture eliminates the 3rd order coma. The remaining spherical aberration is for the given F/number acceptable and satisfactory for the requirements of fluorescence telescopes.

The basic layout of the Schmidt system studied in this report

The corrector is a very weak aspheric transparent optical element. The mirror and the focal plane have their centre of curvature at the centre of the corrector plate.

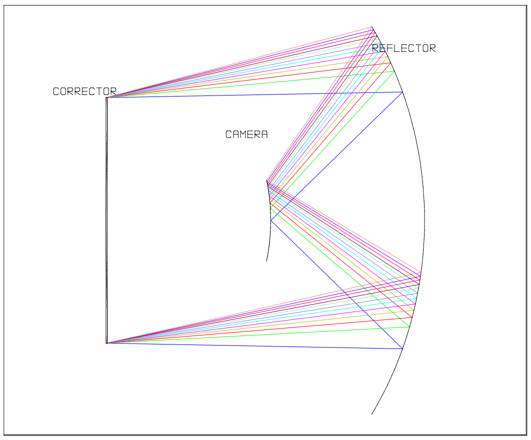

Figure 1: The basic Schmidt design.

We have developed a specific Schmidt type design, which is optimized for the use as an IACT. It has an F/0.8, an entrance aperture of 20m, a total length of 30m and a FoV of 15° diameter, with a polychromatic image quality that is well below 1′ r.m.s. radius across the entire field (see Fig.2 and Fig.3). This is achieved with a corrector of acrylic plastic and a weakly aspheric reflector. The asphericity of the reflector can be obtained by optimally tilting segments of a tessellated (segmented) spherical reflector, as long as the segment size is 60cm or smaller. The nominal isochronous distortion is less than 0.02 ns peak to valley anywhere in the FoV. The physical length of a Schmidt telescope is twice its focal length, in our design equivalent to an F/1.6 prime focus telescope, which would not, by a large margin, be able to deliver a comparable field of view with a similar image quality and isochron distortion. Because of the very fast F-ratio, the camera has a diameter of only 4.21 m, despite the large FoV.

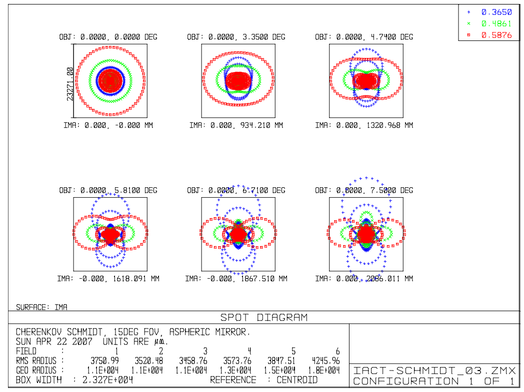

Figure 2: Spot diagrams for the 6 field positions between (0 - 7.5)° off-axis. The boxes are 5′.

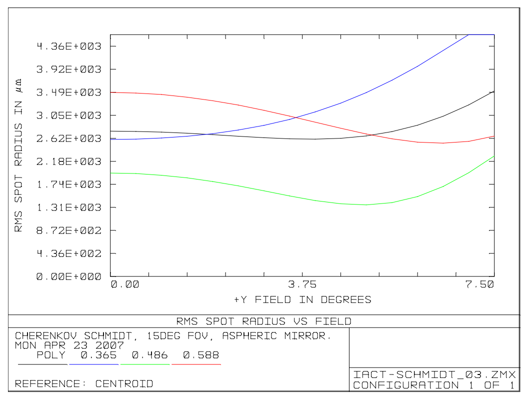

Figure 3: The monochromatic and polychromatic r.m.s. spot size as function of field angle. The vertical scale goes from (0 – 1)′.

The resulting vignetting (shadowing) is less than 4.5%. If the entire 15° FoV should be fully illuminated by the light passing through the Schmidt corrector, then the mirror should have a diameter of 28.14m, implying that only 50% of the mirror surface is used to observe a given point in the sky. By allowing for some vignetting at the edge of the field, the mirror diameter can be reduced to closer to 20m. This is illustrated in the Fig. 4. A good compromise could be a mirror with a diameter of 23-24m, which would have about 15% vignetting at the edge of the field.

The practical implementation of a Schmidt IACT

The mirror of our base line design is not different from the mirrors already used in large Cherenkov telescopes, except for the specification of the alignment of the mirror segments, which may be a factor of (2-3) tighter.

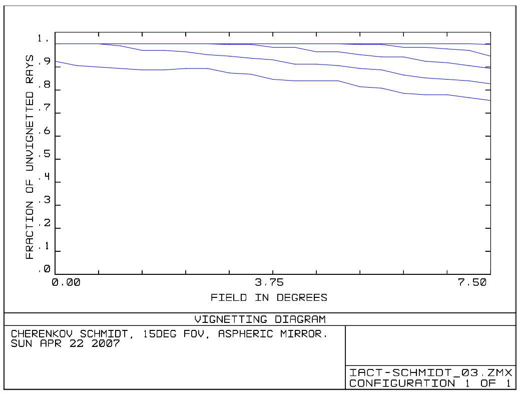

Figure 4: Vignetting as function of field angle for configurations with a 20m, 22m, 24m, 26m and 28m diameter mirror.

Our Schmidt design is ideally suited for implementing an auto collimation system for closed loop control of the mirror alignment. If a light source is located at the center of curvature of the mirror, which is by design also the vertex of the corrector plate, light reflected from the mirror should return to this point. Any deviation from this signifies a deviation from the nominal shape of the mirror. It is straight-forward to construct a device with a single laser and a single camera, which will be able monitor all mirror segments, that are not obscured by the camera (about 12% of the segments), in real time, ensuring that the high resolution of the telescope can be maintained under all conditions. The Schmidt corrector is very forgiving with respect to alignment. The centre of the corrector plate should nominally be located at the centre of curvature of the mirror, and it should be perpendicular to the optical axis. The design allows for a shift along the optical axis of 150mm, a de-center of 50mm and a tilt of 1°, without increasing the spot size beyond 1´ r.m.s. anywhere in the field. The corrector plate is an element which so far has not been implemented on a scale comparable to what is required for the optical system discussed here. The corrector plate has a maximum thickness of 50mm, which would imply severe attenuation of the UV radiation. The most practical solution is to implement the corrector as a tessellated Fresnel like lens whereby the thickness of the acrylic can be minimized. Specifically, one can consider to bond acrylic wedge segments onto a substrate of 5mm thick Borofloat sheets. This would allow one to obtain good UV transparency, even down to 320nm. Both acrylic plastic and Borofloat are inexpensive materials that are produced on an industrial scale. Borofloat is furthermore available with anti-reflective coating from factory, though not exactly with the specifications required for our application. We note that the use of a Fresnel-like lens implies increased isochronous distortion, to a level of 0.06 ns.

Conclusions

A practical design of a 15° wide FoV IACT is shown in this report. The ray-tracing simulations show that the chosen F/0.8 Schmidt design can provide an angular resolution of 1´ everywhere in the FoV and an ultra-fast timing of ≤ 0.06 ns. A tessellated Fresnel lens can be used as a corrector plate. Within tolerances of a few cm this design is not sensitive to the adjustement of the corrector plate.

References

[1] T.C. Weekes, et al., (Whipple Coll.) Astrophys. J. 342 (1989) 379-395.
[2] F. Aharonian, et al., (H.E.S.S. Coll.) Science 307 (2005) 1938-1942.
[3] A. Schliesser, R. Mirzoyan, Astropart. Phys., 24, 4-5, (2005) 382-390.
[4] V. Vassiliev, S. Fegan, P. Brousseau, arXiv:astro-ph/0612718.
[5]http://www.eusomission.org/cgibin/pub.cgi?href=welcome.html
[6] M.C. Maccarone, et al., (GAW Coll.) arXiv:astro-ph/0509706
[7] V. Verzi, Nucl. Phys. B – Proc. Supp., 165, (2007) 37-44.