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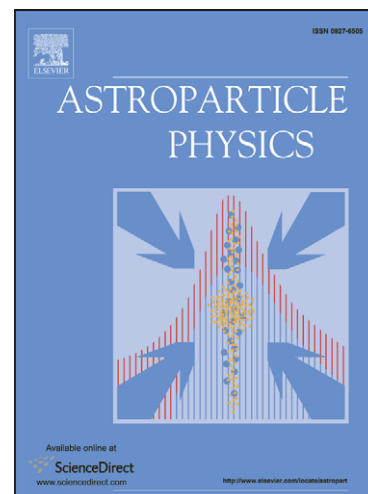
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A 15° Wide Field of View Imaging Air Cherenkov Telescope

R. Mirzoyan^{a,1}, M.I. Andersen^{b,c,1},

^a*Max-Planck-Institut für Physik, Föhringer Ring 6, D-80805 München, Germany*

^b*Dark Cosmology Centre, Niels Bohr Institute, University of Copenhagen,
Juliane Mariesvej 30, DK-2100 Kbh Ø, Denmark*

^c*Astrophysikalisches Institut Potsdam, An der Sternwarte 16, D-14482 Potsdam,
Germany*

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 a $(2-4)^\circ$ 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 prime focus designs, such as a wider FoV, a more compact size, a higher and more homogeneous resolution and a lower degree of isochronous distortion of light rays focused onto the focal plane. Also, they allow monitoring the gamma-ray activity in a sizeable portion of the sky in a single observation. This would allow one to perform a sensitive all-sky survey in a relative short time. We present an F/0.8 15° wide FoV telescope design, which provides a high and near uniform resolution and low isochronous distortion across the entire FoV.

Key words: Gamma-ray Astronomy, Imaging atmospheric air Cherenkov telescopes, Surveys

PACS: 95.55.Ka, 95.55.Vj, 95.75.Qr, 95.85.Pw, 95.85.Ry

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¹ Corresponding author

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1 Introduction

The technique of employing Imaging Air Cherenkov Telescopes (IACTs) has been successfully used for ground based gamma-ray astronomy for about two decades, revealing more than 70 sources in the course of this period. The successful race started with the discovery of the first TeV gamma-ray signal from the Crab Nebula - now regarded as the standard candle in gamma-ray astronomy - by the Whipple Collaboration in 1989 [1]. Over 20 years following that event, the sensitivity of the IACTs has improved dramatically, leading to a large increase in the rate of scientific discovery made with these instruments. In the beginning a few tens of hours were needed to detect a significant signal from the Crab Nebula, whereas today's installations operating in the same energy range require only a few minutes for the same signal strength. The

main improvements are essentially due to a) a finer pixel size of photo sensors in the imaging camera, b) an improved trigger, c) a larger size of telescopes and improved optics providing stronger signals and revealing more structures in the images (helps to further suppress the backgrounds) and d) the use of multiple telescopes operating in coincidence mode (the so-called stereo mode of observations). However, the field of view (FoV) of IACTs has not undergone a similar evolution. The largest FoV telescope had a field of about 7° [2]. Contemporaneous IACTs typically cover a $(2 - 4)^\circ$ wide FoV. A wider FoV would enable sensitive all-sky surveys to be conducted within a relatively short time frame. In optical astronomy the trend to larger FoV is evident, just to mention the LSST [3] and the Pan-starrs projects [4]. An interesting example of the use of even moderately wide FoV telescopes has been demonstrated by the H.E.S.S. collaboration. While performing observations of scheduled astronomical targets, H.E.S.S. has discovered several new sources in the $\sim 4^\circ$ effective FoV of their instrument. Subsequently, when scanning the galactic plane, multiple sources were found in the ~ 300 square degree band surveyed by H.E.S.S. - i.e. the region scanned was much larger than a single H.E.S.S. FoV. [5].

Along with the advantages of the wide FoV there are also a number of drawbacks, such as: i) compared to currently used simple prime focus constructions, they have a more complex optical and mechanical design, ii) the imaging camera will have a large transverse size and thus can vignette a significant fraction of the mirror and iii) the imaging camera will be composed of a very large number of light sensors and one will therefore need a large number of readout channels. These factors tend to make a wide FoV telescope expensive. In the following we shall present a concept for a wide FoV IACT, for which the complications due to i) and ii) are minimal. The challenge of building a camera with a large number of channels cannot be by-passed.

2 Wide FoV

For the successful operation of an IACT, one needs to provide a relatively high optical resolution to efficiently select the rare gamma shower images from the few orders of magnitude more frequent images induced by hadron (background) showers. Although the images of gamma showers tend to be small in size compared to those of hadrons, such a selection is not straightforward because the distributions of the parameters used to describe their images (see, for example, [6]) overlap significantly. The differences in shape parameters of gamma and hadron images are in the range of $(0.1 - 0.2)^\circ$ for the TeV energy range and they are a few times less for the (sub) 100 GeV energy range. Therefore, for a successful image discrimination the telescope shall provide a Point Spread Function (PSF) that is $\leq (0.1 - 0.2)^\circ$ for the TeV energy range

and a few times less for the (sub) 100 GeV range. The simplest and most straightforward way to design a large FoV telescope is using the prime-focus design, i.e. with just a single (primary) mirror surface of a required minimum f/D . Five telescopes of different prime-focus designs were simulated in [7]. In that study ten optical resolutions in the range of $(0.01 - 0.1)^\circ$ RMS, with a step size of $(0.01)^\circ$, were simulated.

It has been shown in [7], for example, that by using a F/2.7 optics, one can design a 10° wide FoV telescope of parabolic design that can provide a resolution of 0.05° everywhere in the FoV. In the same study it was 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 at a resolution of 0.05° , albeit at the expense of a higher degree of isochronous distortion. In the recent work [8] the authors described an interesting 15° wide FoV aplanatic two mirror telescope design for gamma-ray astronomy. They also showed that one can improve the angular resolution for gamma events as the optical resolution in the FoV approaches a limit of $1'$. An alternative way of constructing a wide angle optics is to follow the design of the EUSO mission [9], which has refracting optics that allows a full FoV of 60° or even larger. The GAW telescope for TeV gamma astronomy is following that design in their construction [10]. Two double-sided Fresnel lenses were planned to be used in the optical design of EUSO. The disadvantages of that design were considered to be the relatively high light losses, especially for relatively large incident angles of light. Also, distortion of images because of scattering of light by the Fresnel lenses must 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. A variation of the EUSO-type solution could be to construct a stationary wide FoV telescope or a telescope that includes some kind of secondary optics.

2.1 *Vignetting in prime focus design*

The plate scale of a telescope, giving the ratio of angular distance on the sky to length in the focal plane (in deg./m), is

$$\delta = \frac{57.3}{f} \quad (1)$$

where f is the telescope focal length. For a given detector field of view θ , the diameter of the detector assembly is

$$d = \frac{\theta}{\delta} \quad (2)$$

For a prime focus telescope of a given focal ratio, $F = f/D$, where D is the telescope diameter, vignetting factor, i.e., shadowing, of the detector assembly is given by

$$Vignetting = (d/D)^2 = \left(\frac{\theta \times f}{57.3} / D \right)^2 = (\theta/57.3)^2 \times F^2 \quad (3)$$

Thus, for example, a telescope with $F/2$ and $\theta = 15^\circ$ will have a vignetting factor of 27 %, whereas a camera with a field of view of $\theta = 10^\circ$ will have a vignetting factor of just 12 %. We have mentioned above that prime focus telescopes of $F/2$ - $F/2.7$ of a few different designs can provide a FoV of 10° with the desired optical resolution. For simplicity let us consider an $F/2$ design. In the case of $F/2$ design, when compared with the $F/1$ case, we see that:

- the imaging camera will be 2 times further away from the mirror,
- the imaging camera pixels must have a 2 times larger linear size,
- the imaging camera weight may increase by more than a factor of 4,
- the camera support mechanics must be significantly stiffer and
- the vignetting by the camera will increase by a factor of ≈ 4 .

There are therefore several reasons to consider designs which are faster. 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) a higher and more homogeneous spatial resolution across the FoV, c) faster optics/more compact size and d) lower isochronous distortion. In the following we want to concentrate on a specific wide FoV telescope solution that comprises more than one optical element.

3 The Schmidt Telescope

Of all telescope designs, the Schmidt telescope, and solutions derived from it, provides the widest FoV. Specifically, Schmidt type systems provide by far the largest number of focal plane spatially resolved pixels on the focal plane per optical element [11]. 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. We have developed a design of a 7 m Schmidt telescope that is suitable as an IACT. Our design consists of simple optical components, is compact (low f/D) and is realistic to implement. The primary design characteristics of the telescope are given in table 1. The optical parameters of the telescope are listed in table 2.

The classical Schmidt telescope uses a spherical mirror and an aspheric refrac-

tive corrector plate, normally referred to as the 'Schmidt corrector', which is located at the centre of curvature of the mirror. The Schmidt telescope has a curved focal plane, which is con-focal with the mirror. The entrance pupil (the stop) is located at the Schmidt corrector. In order to accept light without vignetting from directions that are relatively far away from the optical axis, the mirror must be somewhat larger than the Schmidt corrector. Thus, for a given incidence angle, only a part of the mirror, equivalent to the size of the Schmidt corrector, is used.

The Schmidt corrector pre-deforms the impinging wavefront so that after reflection on the spherical mirror, it is free of spherical aberration. As the only 'on-axis' aberration of a spherical mirror is spherical aberration, the Schmidt telescope is therefore nominally aberration free at the wavelength for which the the Schmidt corrector is optimized. At an off-axis field position, the Schmidt corrector makes some angle with the chief ray, the chief ray being defined as the ray that passes through the centre of the entrance pupil, i.e. the centre of the Schmidt corrector. Thus, while the spherical mirror appears the same for any field position, the Schmidt corrector will be at an angle to the beam for an off-axis field position. It will therefore not correct perfectly for spherical aberration at off-axis field positions. However, because the Schmidt corrector is a thin plate, aberrations increase very slowly with the field angle. We see that the Schmidt telescope is free of 3rd order coma and astigmatism, exactly because the entrance pupil/corrector is placed at the centre of curvature of the spherical mirror.

A simplified version of the Schmidt-type telescope is used by the AUGER collaboration for their air fluorescence telescopes: the corrector plate is replaced by an aperture diaphragm, combined with an annular Schmidt corrector [12]. This aperture eliminates the 3rd order coma. The remaining spherical aberration is acceptable for the given f/D , and satisfactory for the requirements of fluorescence telescopes.

4 The layout of a IACT Schmidt telescope

In a Schmidt telescope, the corrector is a very weak aspheric transparent optical element. Because the corrector is weak, chromatic effects are moderate for a telescope with $f/D \approx 1$.

We have developed a specific Schmidt type design, optimizing it for the use as wide FoV IACT (Fig. 1), using the ZEMAX optics design software. The design has an F-ratio of 0.80, an entrance aperture of 7 m, a total length of 11.2 m and a FoV of 15° diameter, with a polychromatic image quality that is well below $1'$ RMS radius across the entire field. This is achieved with a

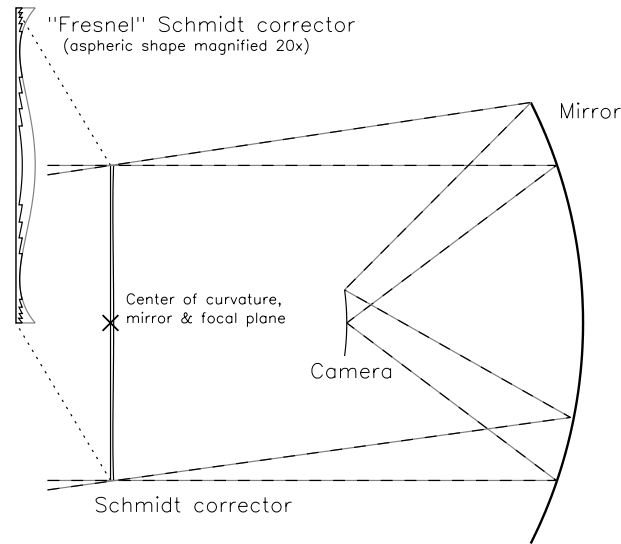


Fig. 1. *Layout of the Schmidt-type IACT. The mirror and the focal plane have their centre of curvature at the centre of the corrector plate. In the insert in the upper left corner, the Schmidt corrector is shown with the aspheric shape magnified by a factor of 20. Both the nominal corrector (shaded line) and a Fresnel version is shown.*

corrector of acrylic plastic and a weakly aspheric mirror.

Table 1

IACT Schmidt telescope primary design parameters.

Diameter	7.0 m
F-ratio	0.8
Focal length	5.6 m
Field of View	15°
Resolution (RMS)	< 1'
An-isochronicity	≤ 0.03 ns

The optical parameters corresponding to the design are given in table 2. Each row of this table fully specifies an optical surface in the telescope. The first column identifies the component. The refractive corrector naturally has two surfaces, while the mirror and focal plane are single surfaces. The second column specifies the radius of curvature of the surface, with a negative sign signifying that the center of curvature is located towards the object. The third column gives the distance between the vertexes of the current surface and the

Table 2

Optical parameters of a 7 m F/0.8 15° FoV Schmidt telescope.

Component	Radius of curvature [m]	Axial spacing [m]	Diameter [m]	4th order aspheric [m ⁻³]	6th order aspheric [m ⁻⁵]
Corrector					
surface 1	∞	0.0250	7.00		
surface 2	-103.00	10.7600	7.00	3.20×10^{-4}	6.75×10^{-6}
Mirror	-10.88	-5.2885	9.95	8.30×10^{-7}	-8.50×10^{-8}
Camera	-5.60		1.47		

next surface, i.e., the spacing of surfaces along the optical axis. The 4th column gives the diameter (clear aperture) of the surface. The 5th and 6th column gives the 4th and 6th order polynomial coefficients of the corresponding aspheric surfaces. The aspheric deformation of the mirror is very weak and can be obtained by optimally tilting segments of a segmented spherical mirror, as long as the segment size is not more than about 60 cm. The nominal isochronous distortion is less than 0.01 ns anywhere in the field. Spot diagrams are shown in Fig. 2 and the corresponding RMS spot sizes vs FoV angle are given in Fig. 3. We note that good imaging characteristics are naturally linked to low isochronous distortion through Fermat's principle.

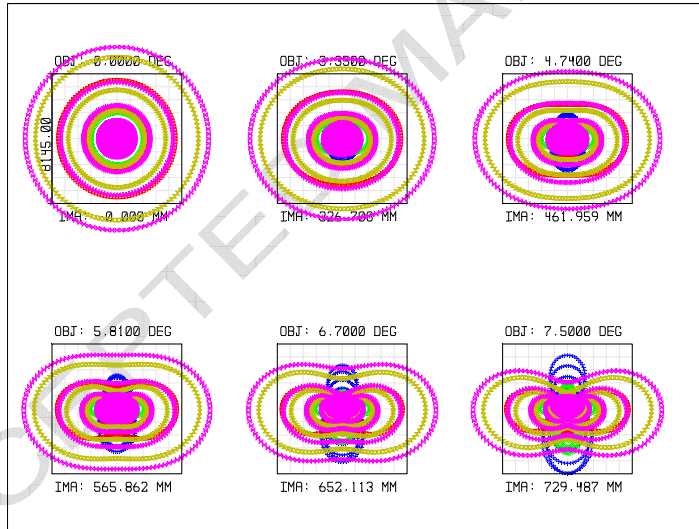


Fig. 2. Spot diagram for 6 field positions, from on-axis to 7.5°. The box size is 5 arcmin.

The physical length of a Schmidt telescope is twice its focal length, in our design equivalent to a F/1.6 prime focus telescope, which is not, by a large margin, capable of delivering a comparable FoV with a similar image quality and isochronicity. Because of the very fast F-ratio, the camera has a diameter

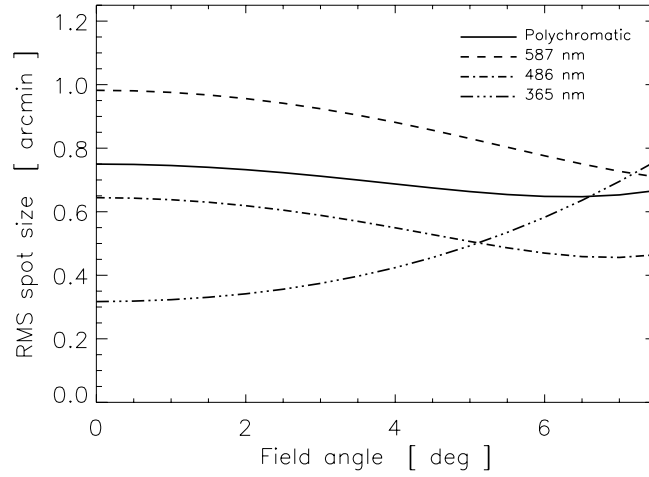


Fig. 3. *RMS spot size vs. FoV angle. The solid line is for polychromatic light.*

of less than 1.5 m, despite the large FoV. The resulting vignetting is less than 5 %. If the entire 15° FoV is to be fully illuminated by the light passing through the Schmidt corrector, the mirror must have a diameter of 9.95 m, implying that only 50% of the mirror surface is "actively used" to observe a given point in the sky. By allowing for some vignetting, the mirror diameter can be reduced down to 7 m. This is illustrated in Fig. 4. A useful compromise could be a mirror with a diameter of 8 m, which would result in 13-14% vignetting at the very edge of the field.

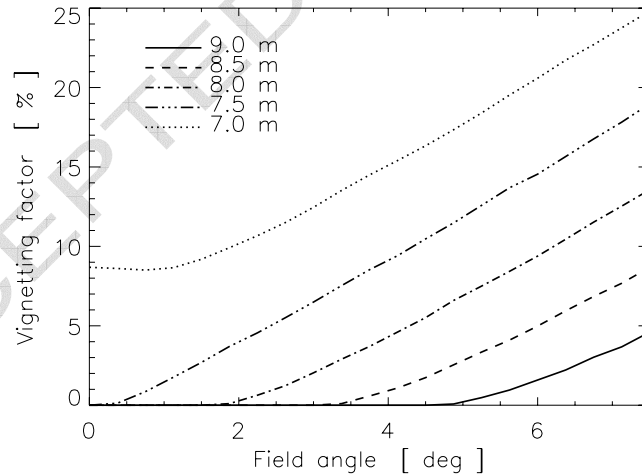


Fig. 4. *Vignetting as a function of mirror size.*

5 The practical implementation of a Schmidt IACT

The mirror of our baseline design is essentially the same as those already implemented in large Cherenkov telescopes, such as for example MAGIC, H.E.S.S. or VERITAS, except that the specification of the alignment of the mirror segments is a factor of two to three tighter, in order to match the nominal performance of the design. 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 centre 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 straightforward to construct a device with a single light source and a single camera, which will be able to monitor all mirror segments that are not obscured by the camera (about 88% 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 misalignment. 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 given design allows for a shift along the optical axis of 90 mm and a decenter of 10 mm, without increasing the spot size beyond $1'$ RMS anywhere in the field. This is illustrated in Fig. 5, where the consequence of a focus offset is also shown. Tilts of the corrector by more than one degree are required, before the spot size increases to beyond $1'$ RMS. The Schmidt corrector does therefore not pose any new stringent demands on alignment. The main challenge, with respect to alignment, remains the correct focussing of the camera across the wide FoV.

The corrector plate is an element which has as yet 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 17 mm, which would imply significant attenuation of the UV radiation. The most practical solution is to implement the corrector as a Fresnel like lens, whereby the thickness of the acrylic corrector can be minimized. Specifically, we consider to bond acrylic wedge segments onto the downwards facing surface of a substrate of 5 mm thick Borofloat sheets. This would allow for good UV transparency, even below 330 nm. Both acrylic plastic and Borofloat are inexpensive materials which are produced on an industrial scale in large dimensions. We note that the use of a Fresnel-like lens implies increased isochronous distortion, to a level of 0.03 ns, i.e., a level which is still very acceptable. Because the aspheric corrector lens is very weak, implementing it as a Fresnel lens implies vignetting and scattering of light on a level well below 0.1%, even at the edge of the field. Thus, the use of a Fresnel lens for the corrector plate does not have disadvantages that affect

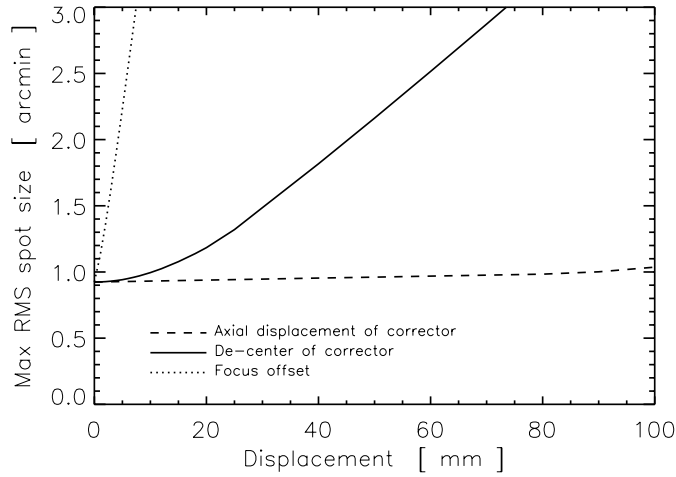


Fig. 5. *The maximum RMS spot size over the field of view, as a function of corrector radial displacement, longitudinal displacement and focus offset.*

the performance of the telescope on a measurable scale. The large Fresnel Schmidt corrector should be implemented as a segmented lens, where the segments of a size of ~ 50 cm can be held in a spider's web like mesh made from a light-weight material. This mesh will further introduce some vignetting, at the level of a few percent. Because the position of the Schmidt corrector is very forgiving, there is no need for an active control of the segmented corrector. The dominant aberration in the telescope is chromatic aberration in the corrector. For the field size and F-ratio used here, this has no practical importance. It is possible to increase the field of view, and/or use a faster design, by introducing an achromatic corrector plate. This could be done by using a combination of Polystyrene and Acrylic plastic materials. The main challenge would lie in maintaining a high UV transmittance. With an achromatic corrector plate, a FoV of up to 25 degrees would become feasible.

6 A short discussion on the cost of a Wide FoV telescope

The telescope suggested above has $1'$ resolution anywhere in the 15° wide FoV. The physical size of $1'$ corresponds to ~ 1.6 mm in the focal plane. This hints at the possible size of the light sensors that can be used in such a high resolution system. The currently operating or planned IACTs use $\sim 10^3$ pixels in their imaging cameras of a few degree aperture. The 28 m diam. H.E.S.S.II telescope will have 2048 pixels in its 3.2° FoV camera [13]. The wide FoV telescope may need, depending on the pixel size and selected FoV, about two orders of magnitude more pixels for the camera. If the light sensor element (that may include a light collector) size is about 5 mm one will need 7×10^4 pixels, and if the light sensor element size is 10 mm one will need $\sim 1.8 \times 10^4$

pixels for covering a 15° wide FoV. Usually the readout and the camera of a telescope are the most expensive items in the total cost. Therefore it will be mandatory to look for a cost-efficient light sensors and readout system. Multi-channel alkali PMTs or UV enhanced SiPMs can be used as light sensors. The relatively high cost of a wide FoV telescope can be seen as compensated by the fact that one will need only one mechanical mount for covering a huge area in the sky.

7 Summary and Conclusions

We have presented the principal design of a 7 m wide FoV IACT, which has excellent imaging characteristics over a 15° field diameter. The basic design is that of a Schmidt type telescope, F/0.8, i.e., comparatively fast. This design allows one to obtain an optical spot size of $1'$ RMS everywhere in the field, with an isochronous distortion below 0.03 ns in case a Fresnel lens is used as a corrector. It is straightforward to scale this design to larger apertures. The only aspect which changes by scaling is the isochronous distortion. For a 20 m diameter telescope, the isochronous distortion amounts to 0.06 ns. The limiting factor in the baseline design proposed here is chromatic aberration in the corrector plate. This can be overcome by implementing an achromatic corrector plate. The main challenge will however lie in filling the focal plane with detectors which would fully utilize the resolution provided by the telescope.

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