# Optical design for WFCTA upgrading

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**Abstract:** Two optical designs for wide field of view Cherenkov telescope array (WFCTA), a major component of the LHAASO project, are presented. The designs aim at obtaining a good quality imaging for a cosmic ray air shower over a field of view (FOV) of $16° \times 14°$. The Fresnel lens telescope, F/0.95, has a spherical reflective primary mirror and a Fresnel lens configured just before camera to correct aberrations and spot size. It is compact and portable at the expense of refraction loss. The Davies-Cotton design with F/2 can provide $16°$ full FOV and exhibits best off-axis performance of the conventional designs. But the obscuration of camera and focal length must be increased. For both designs, the optical spot size is designed to be similar as the dimension of selected size of pixels in the focal plane camera and angular resolution is superiors than expected.

**Keywords:** optical design, WFCTA

## 1 Introduction

The astronomy of Very High Energy (VHE) gamma-rays has experienced a rapid development since past twenty years. Dozens of gamma-ray sources have been found by the present arrays of imaging atmospheric Cherenkov telescopes (IACT): HESS [1], MAGIC [2] CANGAROO [3] and VERITAS [4]. But contemporaneous IACTs typically cover a $2° \times 4°$ FOV and the largest FOV telescope has a field of about $10°$[5]. In order to find more new gamma-rays sources, wide FOV telescopes are needed to be capable of surveying the full sky.

The wide field of view Cherenkov telescope array (WFC-TA) is a major component of the Large High Altitude Air Shower Observatory (LHAASO) project. It will enhance the ability of detection in air showers depth. The two prototypes of WFCTA have been preformed and collected millions of Cherenkov events. However, for more precise and sensitive data, the prototypes must be improved and upgraded. In this paper, two possible optical layouts for the WFCTA are described. The expected optical performances of these telescopes have been studied with simulations by optical design software and ray tracing.

## 2 Constrains of WFCTA

The WFCTA is featured by its compact and portable telescopes. By adjusting the distribution of array in stages, the WFCTA will build a bridge from the ground-based to space cosmic ray observation and accomplish the continuous survey of energy spectrum. Hence, the telescope is enclosed in a one forth shipping container with inner size $2.9m \times 2.5m \times 2.38m$ which is not only compactable but also an effective shield against dust. Besides, the telescope will cover a $16° \times 14°$ full FOV while achieving a resolution of $0.5°$, and be imaging on a candidate photomultiplier camera with 1024 pixels of each $19mm$ diameter.

The optical system should provide a small and constant spot size for a distant point source of light anywhere in the FOV of the camera. The reflector of WFCTA prototype is a single spherical reflector segmented with 20 hexagonal concave mirrors. The optical spot for on-axis rays is very good, but for the rays near edge of FOV, the spots are deformed and centrifugal from chief ray. This is because there are spherical aberration, coma aberration, astigmatism and curvature of the field for spherical reflector.

It has been shown that by using a F/2.7 parabolic design [5], the telescope can cover a $10°$ wide FOV and 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 magnitude of FOV and resolution.

It is also possible to use Schmidt telescopes for the imaging technique. It is well known that a standard or modified Schmidt telescope provides a wide, aberration free FOV. The classical Schmidt telescope uses a spherical mirror and an aspheric refractive corrector plate, which is located at the centre of curvature of the mirror. This means the optical

length of Schmidt telescopes is twice its focal length. In recent work [6], a principal design of a 7m and F/0.8 wide FOV IACT has been presented.

All these schemes mentioned above, including parabolic design, Davies-Cotton telescope, elliptical design and classical Schmidt telescope, are not suitable for present WF-CAT unless decreasing the diameter of its reflector by a factor of $\sim 1/2$. One reason is that the realistic F/# which depends on the size of the container is not larger than 1. These schemes with small F/# have not good imaging performance for wide FOV. Another reason is that excellent imaging characteristics would be achieved by decreasing the active aperture of reflector for larger F/#. This will lead to degrade the efficiency of light collecting and sensitivity of telescope while keeping the same structure size.

In the previous work [7], a $15°$ wide FOV aplanatic telescopes with two aspheric mirrors, configured to correct spherical and coma aberrations, are considered for gamma-ray astronomy. since there is not enough space in our container, the two mirrors system with smaller separations will suffer from an excessively large obscuration by the secondary mirror. The large obscuration also leads to the reduction of the light collecting efficiency.

In the following two kinds of compromising schemes are therefore studied for our compact and portable WFCTA. For that purpose, we have analyzed the optical performances, such as optical spot size, the geometric encircled energy and correction of imaging aberration.

## 3 The telescope with Fresnel lens

### 3.1 The layout of telescope with Fresnel lens

According to expecting technical parameters, dimension of container, and available camera, any new scheme must be based on the basic design of the prototype which has a spherical reflective prime mirror. The improvement is additional configuration of a refracting optics that partly corrects imaging aberrations. A Fresnel lens is planned to be used as a refracting element. Unlike classical Schmidt telescope, this Fresnel lens is arranged between the reflector and the camera, closing to the focal plane, instead of at the location of twice focal length of reflector. The basic layout of the optical system is illustrated in Fig. 1.

This design has a F/# of 0.95, an entrance aperture about 2500 mm, a total length of 2150 mm and a FOV of $16° \times 14°$. The optical parameters of the telescope are listed in Table 1 in which each row fully specifies an optical surface in this design. The entrance pupil is located at the reflector. The first line indicates that the radius of curvature of reflector is 4400 mm and its negative sign represents a concave mirror. the refractive Fresnel lens is located at 2080 mm away from the reflector along the optical axis, which naturally formes two surfaces. The surface 1 toward the reflector has a 700 mm radius (radius of an equivalent continuous optical surface) while surface 2 is
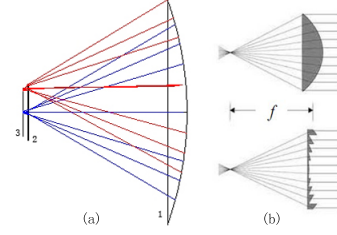


Figure 1: (a) Layout of the WFCT with Fresnel lens. The component 1 is reflector, 2 is Fresnel lens and 3 is camera, (b) A Fresnel lens and its equivalent conventional continuous surface optics with same focal length

| Component | Radius | Thickness | Semi-Diameter |
|-----------|--------|-----------|---------------|
| 1:mirror | -4400 | -2028 | 1250 |
| 2: F-lens | | | |
| Surf1 | -700 | -4 | 370 |
| Surf2 | $\infty$ | -65 | 370 |
| 3: camera | $\infty$ | | 304 |

Table 1: Optical parameters of Fresnel design for WFCT ($Unit : mm$).

plane. Its thickness is 4 mm. The camera is set behind the Fresnel lens, which is located closely to the focal plane. The camera is a flat surface with 304 mm semi-diameter corresponding to the size of the PMT array. In order to reduce the divergence of light caused by the edge of Fresnel lens out of the camera, the Fresnel lens is designed as near to the camera as possible. Due to the exceeding part with total 132 mm and the spacing with 65 mm are small enough, the incidence light can not be scattered into the active receiving area of reflector.

A Fresnel lens is an optical component which can be used as a cost-effective, lightweight alternative to conventional continuous surface optics, shown as Fig1.(b). A positive Fresnel lens in this design acts as a convergence lens which usually compensates for aberrations to some extent. It has a microstructure surface, which consists of a series of grooves with changing slope angles as the distance from the optical axis increases. Each slope acts to refract the rays in the prescribed manner. Vignetting and scattering of light caused by the Fresnel lens are on a low level, even at the edge of the field.

### 3.2 Performance characteristics of telescope with Fresnel lens

The structures in the light distribution are shown in more detail by the spot diagrams for 2 filed positions, on-axis and $8°$ of half FOV shown in Fig.2. We note that there exist some spherical and coma aberrations, however, for the fringe rays of field, the energy are mainly enclosed in the

circle that is active size of a pixel. This optical system has a rms point spread of $0.24°$ for on-axis rays and $0.28°$ for edging rays. Angular resolution is better than the expected value of $0.5°$. From the energy diagram plotted in Fig.3, enclosed energy is about $80\%$ for $0°$ incidence while nearly $50\%$ even for fringe rays corresponding to 15 mm active diameter.
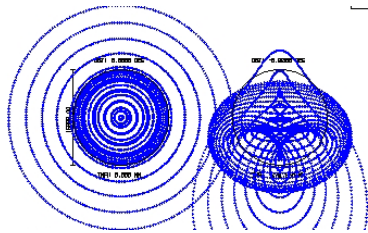


Figure 2: Spot diagram for 2 filed positions of Fresnel design, left for $0°$ and right for $8°$. The circle in black with diameter 15 mm is active size of a pixel

More detail imaging characteristics can be analyzed from the Seidel coefficients calculated by means of third-order optical theory .The Seidel coefficients are listed surface by surface, as well as a sum for the entire system, shown in Table 2. The coefficients listed are for spherical aberration (SPHA), coma (COMA), astigmatism (ASTI), field curvature (FCUR), and distortion (DIST). Comparing all these coefficients of every surface, it is concluded that (i) spherical aberration, coma and field curvature are the dominant factors impacting on the image forming and (ii) aberrations of coma, astigmatism and field curvature can be compensated by the Fresnel lens while spherical aberration and distortion have became little worse for whole system. Fortunately, the intensity of an optical spot is more significant for Cherenkov light observation, so the little distortion resulting from large FOV can be ignored. Hence, the spherical aberration is an only influence, but it is acceptable.
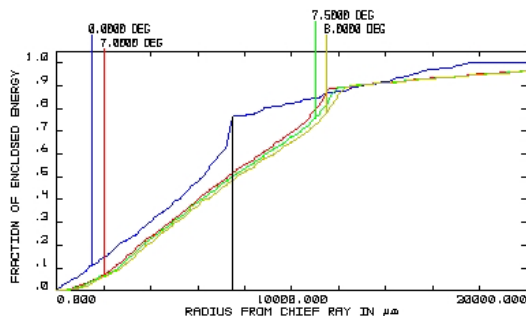


Figure 3: Geometric encircled energy of Fresnel design. The position of straight line is corresponding to the active radius of a pixel

An evident disadvantage to using a Fresnel lens is the possibility of lost light. The losses come from, on one hand, incidence on the draft facet of Fresnel lens with grooves.

| Component | SPHA | COMA | ASTI | FCUR | DIST |
|---|---|---|---|---|---|
| 1:mirror | 41.1 | -9.0 | 2.0 | -11.9 | 2.2 |
| 2: F-lens | | | | | |
| Surf1 | -3.5 | 3.2 | -3.1 | 13.1 | -9.7 |
| Surf2 | 6.6 | 3.1 | 1.4 | 0.0 | 0.7 |
| 3:camera | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Total | 44.2 | -2.7 | 0.3 | 1.2 | -6.8 |

Table 2: Seidel aberration coefficients of Fresnel design($Unit : mm$).

On the other hand, the loss depends on the UV transmittance of Fresnel lens. Usually, Fresnel lens is made up of optical plastic, such as PMMA, PC, and PS. Among these materials, PMMA has the highest transmissivity for UV, only has $73\%$. Additionally, the reflectivity of prime mirror is $83\%$( UV) and imaging efficiency is about $80\%$ for $0°$ as well as $50\%$ for $8°$. That means the total efficiency of system is not more than $48\%$ even for on-axis rays in addition to other losses of energy. If suitable material with higher UV transmittance is found, this design would be a good candidate for upgrading current WFCAT.

## 4 Davies-Cotton design for WFCAT

For the sake of avoiding light losses caused by refracting of the Fresnel lens, the original structure of telescope must be substantially changed. If there is an enough optical space, rather than reducing the light collecting efficiency, we can adopt the Davies-Cotton design $[4, 8, 9, ]$ which has been serviced well in many large IACT for the wide FOV telescope.

### 4.1 The layout of Davies-Cotton design

Based on the dimension of our container, the diameter of reflector maintains 2380 mm for the maximum light collecting efficiency. In order to achieve the wide FOV, F/2 is chosen for telescope. According to Davies-Cotton design, all facet mirrors are identically with 9520 mm radius of curvature and are mounted on a spherical surface with 4760 mm radius. The focal plane is at the center of curvature of the spherical surface; however, for the purpose of balancing imaging quality, the camera may be defocused a little. The reflector can be segmented into smaller mirrors with 0.1 tessellation ratio. Hence, for this structure, the container must be lengthened or extension arm may be helpful.

### 4.2 Performance characteristics of Davies-Cotton design

Because the behavior of Davies-Cotton design resembles much that of a parabolic reflector [5], for simplicity, the Davies-Cotton design can be evaluated directly by simula-

tion of a parabolic reflector. The spot diagrams for on-axis rays and $8°$ incidence rays are shown in Fig.4 and corresponding rms point spread is up to $0.04°$ for on-axis rays while $0.24°$ even for fringe rays. Angular resolution is much more precise than the expected value over full FOV. The enclosed energy is almost $100\%$ for on-axis rays and $57\%$ for fringe rays corresponding to 15 mm active diameter.
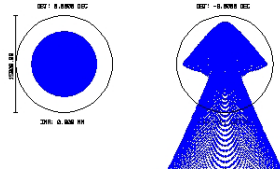


Figure 4: Spot diagram of Davies-Cotton design for 2 filed positions, left for $0°$ and right for $8°$. The circle in black with diameter 15 mm is active size of a pixel

It can be seen clearly from the Seidel coefficients listed in Table 3, the Davies-Cotton design is free of the gross spherical aberration on the optic-axis. Its imaging aberrations, mainly consisting of coma, astigmatism, and field curvature, are within acceptance.

| Component | SPHA | COMA | ASTI | FCUR | DIST |
|-----------|------|------|------|------|------|
| 1:mirror | -0.0 | -4.7 | 5.5 | -5.5 | 0.0 |
| 2: camera | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Total | -0.0 | -4.7 | 5.5 | -5.5 | 0.0 |

Table 3: Seidel aberration coefficients of Davies-Cotton design($Unit : mm$).

Comparing to the Fresnel design, the Davies-Cotton design has better imaging quality, even perfect for on-axis rays. Because of only prime mirrors, there is no refracting loss which has a great influence on the Fresnel design. However, the dimensions of the camera become larger than the one of the Fresnel design. On these parameters, the diameter of the camera is up to $1340$ mm. That means the reduction of the light collecting efficiency by large obscuration of camera. Simulation indicates that the efficiency will drop off $15\%$ for $0°$ incident rays. A larger camera also brings cost question resulting from needs of more PMTs with certain dimension.

## 5   Conclusions

The main purpose of this paper was to study the potential of future WFCTA upgrading designs, using third-order optical aberration theory and ray-tracing simulations. According to the parameter requirements and constraints of WFCTA, the Fresnel lens correction design and the Davies-Cotton design have been examined. The Fresnel lens telescope, F/0.95, partly correcting aberrations is compact and portable at the expense of refraction loss. The Davies-Cotton design with F/2 exhibits best off-axis performance of the conventional designs and can provide $16°$ full FOV. But the dimension of the camera and the focal length must be increased. The optical spot size is designed to be similar as the dimension of selected size of pixels in the focal plane camera for both designs and angular resolution is superiors than expected.

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