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# *Application of Wavefront Imaging Detection System in Astronomy*

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***Keywords:*** Wavefront Imaging, Defocusing Distance, Astronomy

***Abstract:*** Fast measurement of light source orientation is one of the research hotspots in the field of photoelectric tracking telemetry and command. In terms of the current light source detection technology, the multi-point detector layout is adopted, the intensity difference of incoming light is obtained by different detectors, then the direction of the light source is resolved. The technical route of wavefront imaging detection is studied from the perspective of practical application in this paper, and the calculation method of focal length, defocusing distance, and other parameters are provided, which provides a theoretical basis for the practical application and optical design of azimuth detection system based on wavefront imaging.

## 1. Introduction

Fast measurement of the orientation of incoming light source is one of the research hotspots in the field of photoelectric tracking telemetry and command. For the current detection technology of incoming light sources, a multi-point detector layout is adopted, the intensity difference of incoming light is obtained through different detectors, then the orientation of incoming light is resolved[1]. The azimuth measurement accuracy of this technology depends on the number and layout of multi-point detectors and the measurement accuracy between different detectors. It is difficult to get high-precision azimuth information, because of the limitations of current technology. A high-precision light source azimuth detection technology based on wavefront detection is developed in this paper, which can make a fast response through quickly perceiving the complex laser source and determining the laser source azimuth. It is always a research hotspot to explore the high precision and real-time light source azimuth detection system, which has wide prospects and demand in astronomy and other fields[2].

## 2. Astronomical Requirements for Azimuth Detection of Optical Targets

There is a very wide range of applications in practice for wavefront directiondetection systems. However, the wavefront direction detection system is still a long way from practical application, because of the small angle incidence, and not considering many ideal conditions such as astigmatism[3]. The actual wavefront direction detection is a very large and difficult problem to solve.

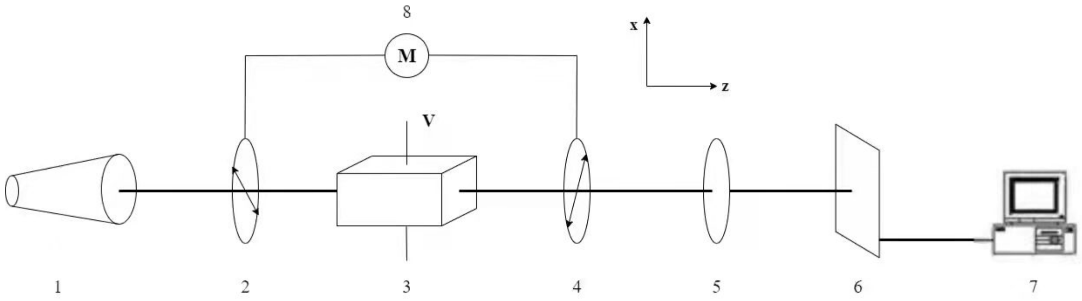

Figure 1: Application of azimuth detection based on wavefront imaging in astronomical system

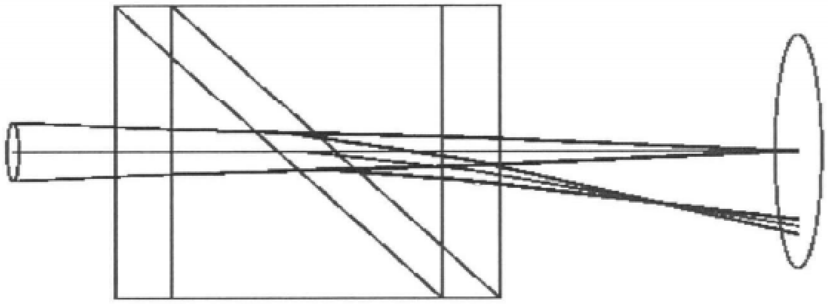

Figure 2: Generation of defocusing distancein practical optical systems

The optical system and telescope are often used to realize azimuth detection of astronomical targets in the field of astronomy, the schematic diagram of the device is shown in Figure 1. The o and e light beam inevitably separate, resulting in wavefront distortion, focal and defocused images, as shown in Figure 2. The reason is atmospheric turbulence, telescope difference, and large angle incidence, etc. In practical applications, two CCDs are usually used to collect the focus image and defocus image at the same time, or the method of controlling the light path is adopted to put the focus image and defocus image on a CCD. Combined with the basic principles of the different influences of the induced refractive index and the change of light intensity and other factors of the micro-electric field, the azimuth detection of the wavefront can be realized by analyzing the light intensity of the focus image and defocusing the image[4].

Therefore, in practical application, the collection of defocusing distance and focus image plays a decisive role in the construction of an optical system. The formulas of some parameters are proposed based on the actual optical system, which provides a theoretical basis for the optical design of the light source azimuth detection system[5].

## 3. Cutoff Frequency and Cutoff Frequency Multiplier

The image quality in the actual optical system is limited by both the optical system and the digital detector. Since thediffraction exists, even if the Rayleigh criterion is considered for the system without aberration, when the center of the intensity distribution pattern of Airy disk generated by one point light source happens to fall on the first-order zero of Airy diskgenerated by another light source, the system can distinguish these two points[6]. Therefore, there is a spatial diffraction limit.

From the perspective of wave optics, the light field incident to the lenscan be regarded as conducting Fourier transform, and the two-dimensional Fourier transform of the light field is formed on the back focal plane of the lens, i.e., spatial spectrum. At the focal plane, with the middle as the fundamental frequency, the farther away from the optical axis, the higher its frequency.In the practical optical system, only part of the low-frequency components is passed through,while the high-frequency components are cut off, because of the limited aperture. Therefore, there is a cut-off frequency, which is determined by the aperture size D, and the relationship is as follows:

The cutoff frequency of an imaging system with aperture D and focal length F is as follows, when the working wavelength is $\lambda$.

$$\nu=D/\lambda F$$

The detector converts objects projected onto it from light signals to electrical signals by means of an optical lens. The detector is a discrete component, the optical signal received is continuous, but the electrical signal output is discrete. This is because the discrete structure of the detector determines its sampling frequency. The sampling frequency $\nu$ _CCD of a CCD camera withpixel size a (a is also called detector pixel interval) can be calculated based on the following equation.

$$\nu\_ccd=1/a$$

The cutoff frequency of the CCD camera is higher than that of the optical system, that is, the CCD camera should fully sample or over-sample the optical image.

The sampling theorem must be satisfied in the practical imaging process. The process of CCD imaging is equivalent to spatial digital sampling of the analog image produced by the lens. Nyquist sampling theorem means that in the process of conversion between analog and digital signals, only when the sampling frequency is at least two times higher than the highest frequency in the signal, can the sampled digital signal completely retain the information in the original signal. The sampling frequency is usually guaranteed to be 5 ~ 10 times the highest signal frequency in practice, aiming to meet the requirements of sufficient sampling.After considering the sampling theorem, the cut-off frequency of the camera is expressed as follows:

$$\nu\_ccd=1/2a$$

$\nu$_ccdand$\nu$satisfy the following relation:

$$\nu\_ccd=M\nu$$

Where M is the cutoff frequency multiplier, and M>1.

## 4. The Focal Length of the Actual Optical System

Considering the relationship between the optical system’s cutoff frequency and the CCD camera’s cutoff frequency,the focal length F of the optical mirror in the actual system (it is the objective lens of the telescope for the astronomical system) can be calculated after the actual parameters such as CCD pixel size and cutoff frequency are known:

$$F=D/\lambda\nu=MD/〖\lambda\nu〗\_ccd$$

The atmospheric turbulence degradation image simulation system is taken as an example, if the CCD with pixel size a=11μm, cutoff frequency $\nu$ _CCD =29.7 lp is selected, at the same time thecenter wavelength ofthe imaging system is 0.6μm, the cutoff frequency multiplier M is 7, imaging system aperture D is 1000mm, then the cutoff frequency$\nu$ and focal length F of the imaging system can be obtained, i.e., $\nu$=4.24 lp, and F= 10432.1mm.As can be seen from the above examples, reasonable optical design schemes can be proposed after specific requirements are given.

## 5. The Defocusing Distance$\Delta$z of Optical System

The separation of focal and defocused images is calleddefocusing distance $\Delta$ Z.The defocusing distanceis a very important parameter in the designing process ofthe practical optical system, which is closely related to phase iteration and focal length[7]. We have learned that the wavefront distortion caused by atmospheric turbulence can be described by Zernike polynomials in the astronomical field.In fact, Zernik polynomials are not the best polynomials to describe wavefront in all cases, and their practical application value is very high in this astronomical system. The defocusing distance can be calculatedbased on the following formula:

$$\Delta z=8\delta\lambda(FM/D)^2$$

Where $\Delta z$ is the defocusing distance, $\delta$ is the Peak -to-valley (P-V) value generated by wavefront distortion of defocus image. F is the effective focal length of a telescope. M is the magnification ratio of the objective lens for amplifying the focal and defocus images (the focus image and defocus image are often too close to each other to be distinguished in the actual system,thus the focus image and defocus image are magnified on a CCD by an external objective lens). D is the telescope diameter. Generally, the magnitude of $\delta$ is between 0.8 and 1, which is considered to be ideal. The fourth-order expression of Zernike's coefficient is as follows:

$$\Delta\varphi_d (x,y)=A_4 Z_4 (\rho,\theta)$$

$$Z_4 (\rho,\theta)=\sqrt{3}(2\rho^2-1)$$

Where $A_4$ is the fourth-order expression of the Zernike coefficient, $Z_4$ is the fourth-order orthogonal basis function of the Zernike polynomial.$\Delta\varphi_d (x,y)$ is also used to describe the defocusing distance, because the fourth-order expression of the Zernike coefficientdescribes defocusing degree. Therefore, the following relationships are obtained.

$$\delta=2\sqrt{3} A_4 \lambda=\Delta z/(8 (FM/D)^2)$$

Thus, it can be concluded that the defocus coefficient$A_4$ of Zernike polynomials satisfies the following equation:

$$A_4=\Delta z/(16\sqrt{3} \ (\lambda(FM/D))^2 )$$

$\lambda$ is the central wavelength of the operating band. When the aperture and focal length of the telescope is determined, there is a clear correspondence between $\Delta Z$ and $A_4$ in practice. Therefore, when designing an optical system based on the polarization characteristics of crystal in practical application, the size of Zernike coefficient $A_4$ given by optical design software can be used to judge whether the required defocusing distance meets the requirements, guiding the design of the optical system.

There is an important relationship between the defocusing distance and the thickness of the crystal and the surface inclination of the smooth surface. The defocusing distance mainly comes from two parts. The defocusing distance partly comes from the optical path difference between the e light and the o light in the crystal, which is related to the thickness of the crystal and the actual incident angle. Another source of defocusing distance is the inclination of the crystal surface. The effect of Zernike's fourth-order coefficient can be studied by changing the tilt angle of the crystal surface to obtain the desired defocusing distance. If the tilt angle is not reasonable, aberration will be introduced. The reasonable choice of tilt angle can not only obtain the defocusing distance but also reduce the astigmatism and improve the accuracy.

## 6. Conclusions

According to the understanding of the actual situation, the specific calculation method of focal length, defocusing distance, and other parameters is proposed in this paper, which provides a theoretical basis for the optical design and practical application of azimuth detection system based on wavefront imaging. Although the actual wavefront detection system involves many fields such as optical design and automation design, the simple wavefront detection system proposed in this paper can realize wavefront detection to a large extent after making appropriate adjustments such as adding CCD, which is a feasible approach for application in the field of astronomy.

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