Optics ellipticity performance of an unobscured off-axis space telescope

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Abstract: With the development of astronomy, more and more attention is paid to the survey of dark matter. Dark matter cannot be seen directly but can be detected by weak gravitational lensing measurement. Ellipticity is an important parameter used to define the shape of a galaxy. Galaxy ellipticity changes with weak gravitational lensing and nonideal optics. With our design of an unobscured off-axis telescope, we implement the simulation and calculation of optics ellipticity. With an accurate model of optics PSF, the characteristic of ellipticity is modeled and analyzed. It is shown that with good optical design, the full field ellipticity can be quite small. The spatial ellipticity change can be modeled by cubic interpolation with very high accuracy. We also modeled the ellipticity variance with time and analyzed the tolerance. It is shown that the unobscured off-axis telescope has good ellipticity performance and fulfills the requirement of dark matter survey.

OCIS codes: (220.3620) Lens system design; (220.0220) Optical design and fabrication.

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1. Introduction

The start of the century has seen rapid progress in the study of weak gravitational lensing [1]. Gravitational lensing is the deflection of light from distant objects by all matter along its path, including dark matter. This is one of the most promising aspects in astronomy. Scientists believe they can find the basics of nature from the survey of dark matter. They build up giant telescopes to complete the survey of large areas of the sky. Recently the Euclid mission is going to detect dark matter in space where there is no atmosphere. Several projects like WFIRST, LSST etc are under discussion or construction and will be delivered soon.

However, weak gravitational lensing is rather challenging to detect because it induces only percent level correlations in the observed ellipticities of galaxies, which is called cosmic shear. The shear signal is typically ~0.01, which is far smaller than the galaxy intrinsic ellipticities (~0.3) and even the optics ellipticities of the PSF (point spread function). Different programs have been planned to improve the accuracy of weak gravitational lensing measurement [2]. Wide field survey data are used to analyze the shear signal in large scale structures. It is rather encouraging that we are achieving 10% statistical errors and more recently 5% in weak lensing [3].

With the increasing accuracy demand of weak lensing and decreasing statistical errors, we must control the systematic errors well, the most important of which is the PSF ellipticity uncertainty. S. Paulin-Henriksson pointed out that the PSF ellipticity uncertainty should be less than 0.001 with systematic errors 1e-7 [4]. In the Euclid mission, the ellipticity knowledge requirement is even more demanding by 2e-4 [5]. To acquire such high accuracy, we must first find out a robust method to model the optics PSF and measure its ellipticity. Then we have to find the origins of PSF ellipticity and make constraints on these parameters to control the optics ellipticity. The constraints of ellipticity on optical systems are more rigorous than those of MTF (modular transfer function) or wave-front error (WFE) so it is rather challenging.

With the development of space optics, we are now able to build an unobscured off-axis space telescope. Off-axis telescopes have many advantages over co-axis ones, such as easy stray light control, low-scattering property, filled pupil for wave-front sensing, room for adaptive optics, larger throughput, and so on [6]. It has also got simpler and sharper diffraction pattern, which means not only higher resolution but also some advantages in ellipticity performance. This paper describes the characteristic of optics ellipticity of an unobscured off-axis telescope. It is shown that the unobscured off-axis telescope has good ellipticity performance and is fit for dark matter survey.

2. Ellipticity

Different methods are used to characterize the anisotropy of a galaxy [7,8]. The most widely used method for weak lensing analysis is the KSB + method [9]. It is defined as a function of weighted quadrupoles:

$$Q_{ij}^{W} = \frac{\int I(x,y)\, x_i x_j W(x,y)\, dxdy}{\int I(x,y)\, W(x,y)\, dxdy} \tag{1}$$

Where W(x,y) is a Gaussian weight function of scale length r_g, and r_g is some measure of PSF size such as the half-light radius and $x_1 = x - \bar{x}$, $x_2 = y - \bar{y}$. An ellipticity e and its size R is defined from these weighted moments using Eq. (2):

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$$e = \frac{Q_{xx}^W - Q_{yy}^W + 2iQ_{xy}^W}{Q_{xx}^W + Q_{yy}^W} = e_1 + ie_2, R = \sqrt{Q_{xx}^W + Q_{yy}^W} \quad (2)$$

Although this definition is simple and easy to implement, it is dependent on parameters such as sampling area, sampling distance and Gaussian radius r_g. Different people use different parameters and will get quite different results. These parameters can be defined by practical requirement. Once determined, they should be used constantly without change, or the result will not have exactly the same meaning and is not well defined.

In order to achieve high accuracy, PSFs are largely sampled in the image plane. Normally we sample every 0.1 micron to get a 2048 × 2048 matrix and compute ellipticity in a 67.9 microns (0.5″) radius circle centering its centroid. The Gaussian weighting can be omitted as it is used to depress noise which in not included in our model. The small sampling step in the image plane is desired to improve ellipticity accuracy but we cannot depend too much on it because sampling in the pupil plane is also important. Pupil sampling decides the accuracy of wave-front and contributes to ellipticity accuracy. To balance between pupil sampling and image sampling we can improve the centroiding algorithm by iterative method [10]:

$$x_0 = \frac{\int xIW(x - x_0)dxdy}{\int IW(x - x_0)dxdy}, y_0 = \frac{\int yIW(y - y_0)dxdy}{\int IW(y - y_0)dxdy} \quad (3)$$

SExtractor and IMCAT software both use this algorithm for centroiding and it is believed to have an accuracy of < 0.001 sampling step. This is very helpful because it improves the calculation accuracy greatly while reduces the need of oversampling in the image plane, which contributes dramatically to computation efficiency improvement. With a sampling step of 0.4 micron, we only need a 512 × 512 matrix to get a PSF with 200 microns width, which means 16 times reduction in hard disk space and calculation time. With this centroiding algorithm, most computation time is saved and we can do more analysis on the behavior of ellipticity. Therefore we will use as small matrix as we can to implement large amount of calculation and as large matrix as we can to evaluate the accuracy we can achieve.

3. The optical system and the PSF

Although the system is reflective, the PSF size is dependent on wavelength (according to the Airy disk radius $\theta \approx 1.22\lambda/d$, longer wavelength has larger PSFs). For simplicity, we just consider monochromatic PSF of our system (Fig. 1). It is a 2 meter F/14 cook TMA telescope with a 1.1° × 1° field of view. This unobscured system with wide field of view system has the ability to complete the survey of the sky in a short time and detect dark distant objects with high signal noise ratio. For such a large system the optical performance is quite important. The average RMS WFE is 21 nm or λ/30. So it is a diffraction limited system with very competent performance.

This system is specially designed for dark matter survey. Therefore there is a very high requirement on its performance in ellipticity. To achieve ellipticity measurement accuracy of 0.001 (based on Euclid analysis [11]), the requirement on optics at the design phase is as follows:

a) The full field ellipticity must be under 0.15;

b) The EE80 (Encircled Energy = 80%) radius must be under 0.13 ″ (17 microns);

c) The ellipticity interpolation error across one detector must be under 2e-4;

d) The ellipticity variation between two consecutive exposures must be under 5e-3.

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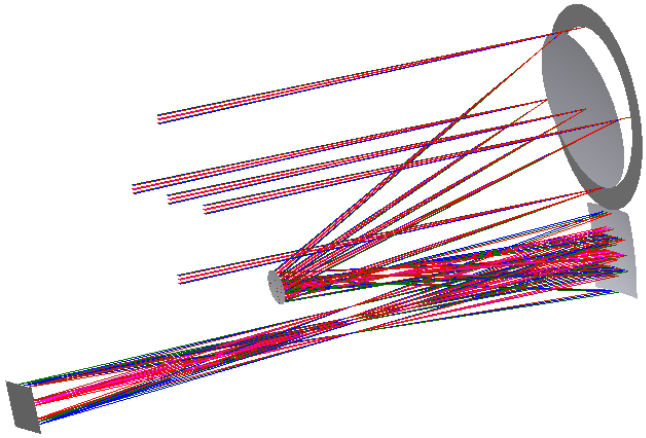

Fig. 1. The optical layout (y-z plane) of the unobscured off-axis telescope

The requirement on ellipticity is in fact requirement on PSF because it is calculated from PSF and its characteristic is decided by PSF variation over time and space. Therefore we must model PSF correctly before we calculate ellipticity [12,13]. The PSF can be defined by [14]:

$$PSF = \left|FFT\left(P\right)\right|^2, P = Ae^{(2\pi iOPD/\lambda)} \tag{4}$$

Where P is the pupil function, A is the aperture function, OPD is the optical path difference and λ = 632.8 nm is the main wavelength.

From this definition we know that the PSF characteristic of an unobscured system is mainly decided by the OPD because the aperture is nearly a constant circular area for all fields. The ellipticity induced by pupil projection is quite small and can be ignored in our system. For an obscured system like HST, the diffraction pattern is mainly decided by the aperture function, which can be very complex and field dependent. Therefore for an obscured system one has to compute both aperture function and OPD to calculate the PSF. For our system we do not need to compute the aperture function. This means that the ellipticity model is simpler and the ellipticity control is easier than that of an obscured one because ellipticity changes only with aberration. This is a great advantage of an unobscured off-axis system.

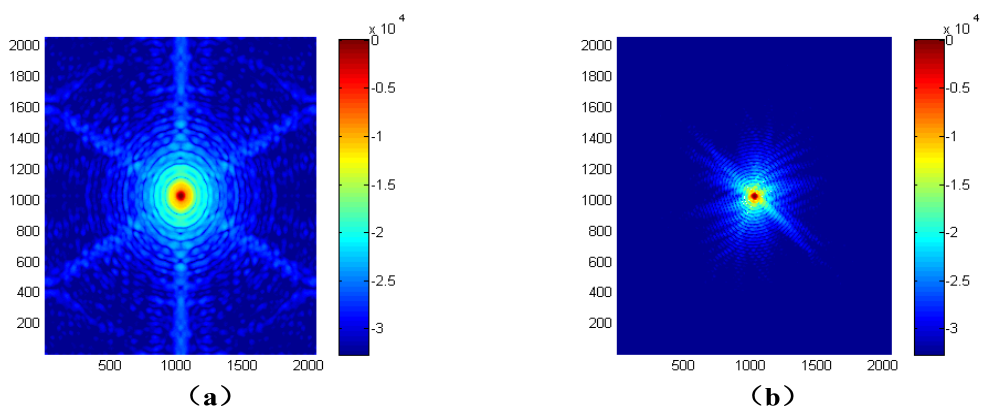

Fig. 2. The typical PSF (in logarithmic scale) of: (a) an obscured telescope; (b) the unobscured off-axis telescope (maximum normalized to 1)

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The system has a focal length of 28 meters and pixel size of 10 microns with a pixel scale of 0.074″. The typical PSF of the system is in Fig. 2 (with comparison with that of an obscured telescope like Euclid). It is a very sharp point with a FWHM (Full Width at Half Maximum) only 0.034″, which is smaller than half pixel size. The *R* of ellipticity is 0.018″, which is about half FWHM. The airy pattern is 0.080″ in radius. The EE80 radius is less than 0.088″. The diffraction pattern is small and simple. The energy is very concentric and the energy drops rapidly outwards. The PSF has no spiders caused by second mirror supporting vanes obscuration. It also has lower wings and hence smaller size because of the absent of central obscuration.

The sharp PSF of an unobscured system is desired for weak lensing. First it means higher resolution and smaller galaxies can be resolved because the system PSF is small. Second the system PSF has small ellipticity because there are no spiders caused by supporting structures. Last a bright star has low wing and will not cover its neighborhood, so the system can achieve high signal noise ratio (SNR). This feature will be critical for detecting of dark distant galaxies. Therefore, the system is expected to have high performance for dark matter survey.

4. Ellipticity performance

The main concern about the optics ellipticity is its value, the PSF size, and spatial and time stability [11]. As we can see from Fig. 2, the PSF size is small and there are no diffraction patterns which are caused by central obscuration or spider. Here we omit the calculation of PSF size since it is good enough for an unobscured system. To model the ellipticity, we consider mainly the full field ellipticity and spatial and time stability.

4.1 The full field ellipticity

With Eqs. (1)-(3), we can calculate the full field ellipticity (Fig. 3). The 41 × 41 PSFs are generated by CODE V. The PSF is sampled on a 2048 × 2048 grid with an image sampling step of 0.1 micron, pupil sampling step of 89.5 mm. The sampling is intensive on the detector because the PSF is small and this sampling will introduce ellipticity model error less than 1e-4. We can see from the meshes that the ellipticity change is quite smooth across the field of view, indicating small model errors. For an obscured system with a complex pupil shape, we will need much larger sampling in the pupil to ensure ellipticity map continuity [11]. The unobscured off-axis telescope therefore has a unique advantage in ellipticity modeling.

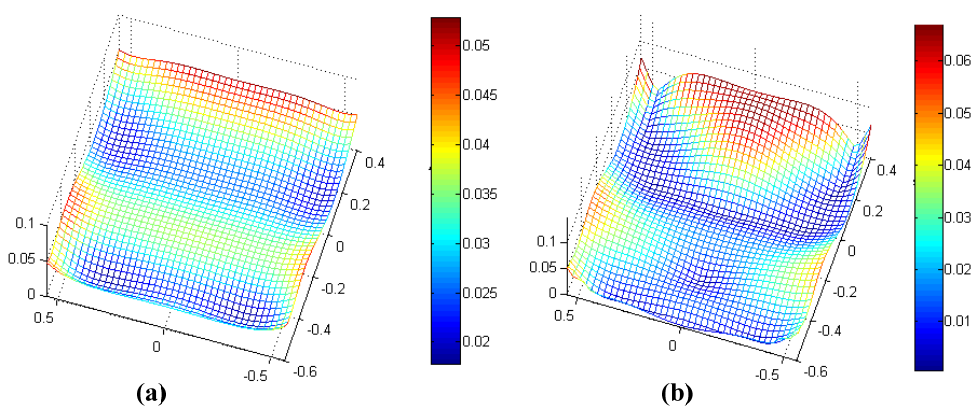

Fig. 3. The WFE and ellipticity distribution: (a) WFE map (in wavelength); (b) ellipticity map.

From Fig. 3 we can see that the full field WFE is less than 0.055 λ and full field ellipticity is less than 0.07. And there is a strong correlation between WFE map and ellipticity map.

#213928 - $15.00 USD Received 16 Jun 2014; revised 13 Sep 2014; accepted 1 Oct 2014; published 8 Oct 2014

This shows that we may be able to control optics ellipticity by constraining the WFE of the system. From section 3 we know that the PSF shape is mainly decided by OPD which can be described by a combination of Zernike polynomials for an unobscured system. To find how much each aberration contributes to ellipticity we do a numerical calculation.

The calculation is done as follows. We add only one kind of Zernike aberration to the PSF once and do 36 calculations for the first 36 Standard Zernike polynomials (CODE V) The RMS WFE is 30 nm or 60 nm, of which 0, 20%, or 40% is defocusing error. Defocusing errors are added because some aberrations are nonsymmetrical only with some defocus. As most of the aberrations are symmetric and do not contribute to ellipticity, we list just the aberrations which contribute most to ellipticity in Table 1.

Table 1. Ellipticity of different Zernike aberration

RMS WFE	Defocus percentage	Zernike aberration type					
		1st-ast	1st-coma	2nd-ast	2nd-coma	3rd-ast	3rd-coma
30nm	0	0.000	0.071	0.000	0.159	0.000	0.203
	20	0.029	0.067	0.023	0.153	0.012	0.195
	40	0.056	0.05	0.047	0.121	0.027	0.159
60nm	0	0.000	0.202	0.000	0.305	0.000	0.325
	20	0.101	0.192	0.051	0.297	0.006	0.320
	40	0.192	0.147	0.113	0.256	0.026	0.290

From Table 1 we can see that coma especially high order coma contributes most to ellipticity. Astigmatism only contributes to ellipticity with some defocusing. As defocusing and WFE increases, astigmatism contribution to ellipticity increases. So to reduce ellipticity one has to control coma, astigmatism and the RMS WFE. And ellipticity will be constrained to under 0.15 if there is 30 nm RMS WFE, 0.3 if 60 nm RMS WFE (as long as high order coma are controlled well enough). The system ellipticity can be decided by RMS WFE because aberration distribution is predicable. For our system, we limit the RMS WFE to be less than 30 nm if the ellipticity requirement is less than 0.15.

4.2 The spatial stability

The image of a galaxy on the detector plane is convolved by the PSF of the optical system. So the ellipticity of the galaxy is changed by the optics of the system. In order to counteract this effect, the ellipticity of the PSF at the position of the galaxy must be modeled correctly. This can be done by interpolation. Bright stars are used as sources of PSF seeds to predict optical PSF ellipticity at the position of galaxies. With a capability of detecting 24.5 mag objects, the system has about 166 bright but not saturated stars between 10 mag and 17 mag in a detector region of 40 square arcmin, which fulfills the calibration requirement of PSF interpolation.

In order to implement interpolation on PSF ellipticity, there are strict constraints on its spatial stability, which means that ellipticity across the image plane must be smooth. For our system, assume the single detector size to be 50 mm × 50 mm, we sample every 10 mm to get a 6 × 6 grid. Sampling the center of these 36 grids will get another 5 × 5 grid (as shown in Fig. 4). The system requirement is that the grid center ellipticity error calculated from grid point ellipticity by cubic interpolation is less than 1.4e-4.

#213928 - $15.00 USD Received 16 Jun 2014; revised 13 Sep 2014; accepted 1 Oct 2014; published 8 Oct 2014

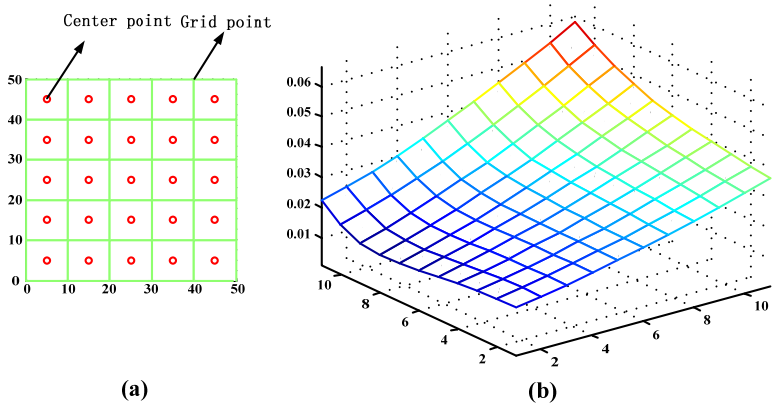

Fig. 4. The interpolation method: (a) sampling grid, (b) interpolation map.

With our modeled system, we do the interpolation over nine equally distributed areas. As the system is axial symmetric, we chose the right half plane x > 0. The chosen field of view is (0/0.275/0.55, 0.4/-0.1/-0.6) (in degrees). The worst interpolation ellipticity map (0.55, –0.6) is shown in Fig. 4. Even this map fulfills the requirement of the spatial stability. We listed the field point ellipticity and field area (50 mm × 50 mm) interpolation error in Table 2.

Table 2. Ellipticity and maximum interpolation error of nine fields over the image plane

Field	1	2	3	4	5	6	7	8	9
e	0.06	0.07	0.06	0.01	0.01	0.04	0.00	0.02	0.06
e_1	0.06	0.01	0.06	–0.01	–0.01	0.00	0.00	–0.01	0.03
e_2	0.00	–0.06	0.02	0.00	–0.01	–0.04	0.00	–0.01	–0.05
$\delta e(\times 10^{-05})$	2.43	6.04	3.90	3.02	2.29	2.53	4.45	4.44	5.58
$\delta e_1(\times 10^{-05})$	2.43	2.24	4.87	3.05	2.30	3.02	5.73	4.39	5.42
$\delta e_2(\times 10^{-05})$	4.84	5.81	4.77	1.60	2.13	2.56	2.22	5.03	6.86

From Table 2 we can see that the ellipticity interpolation error is less than 7e-5 for an off-axis telescope. This is not unusual because of the smooth distribution of ellipticity over the whole image plane. For obscured telescopes the situation is much more complex. We have also designed an obscured on-axis telescope with the same optical parameters and made the same analysis. Although on-axis systems have smaller RMS WFE and ellipticity, the ellipticity map is coarse and the interpolation error is about two magnitudes larger. The reason is that higher sampling in the pupil is needed to model the ellipticity of an obscured system, which is beyond the capability of CODE V. Therefore, the ellipticity of an unobscured off-axis telescope is easier to model and has good spatial stability. For obscured telescopes, the effect of pupil shape and pupil sampling should be considered carefully and will need further study.

4.3 The time stability

Because of changes of temperature, vibration, stress, etc. the optics alignment will change with time. There will be significant change in ellipticity even with very small change in the optics. The optics alignment can be controlled by proper optical, mechanical and thermal design. However the time stability of ellipticity is very demanding to ensure shear measurement accuracy. For example, the Euclid mission requires ellipticity change to be less than 5e-3 in 8 consecutive exposures. Therefore, we must put strict requirement on optics alignment tolerances to ensure the time stability of ellipticity.

#213928 - $15.00 USD Received 16 Jun 2014; revised 13 Sep 2014; accepted 1 Oct 2014; published 8 Oct 2014

We do the simulation of time stability with two steps. For the first step, we do an analysis of the ellipticity change with large tolerances to find the range of ellipticity change. At this step, the RMS WFE change is limited to 8 nm or 0.013 waves. We chose the same nine fields as in Table 2, and calculated their ellipticity in 30 Monte Carlo simulations. The result is shown in Fig. 5.

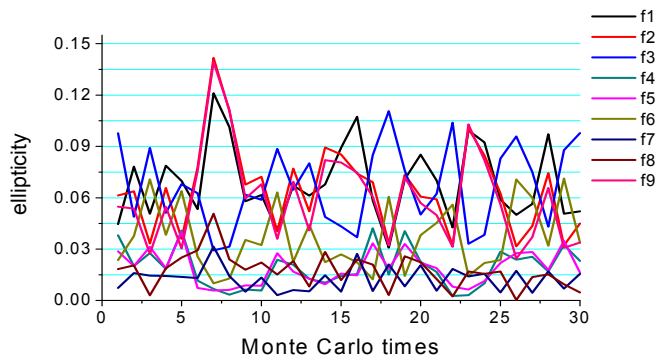

Fig. 5. Ellipticity simulation

As we can see in Fig. 5, the ellipticity change is about RMS 0.026 for field 2. The ellipticity of some occasions is nearly 0.15. This is within the range of ellipticity requirement. Although the 0.013 λ RMS WFE change is not necessarily the final optics tolerance, it is strongly recommended that the optics WFE change should be controlled within this range.

The second step is the optics stability tolerance for ellipticity. This is used to constrain the ellipticity change between and during exposures. To achieve ellipticity time stability of 5e-3, the RMS WFE change should be very small. The most sensitive tolerance of the system is the M1-M2 distance. We therefore tested the sensitivity of ellipticity on this parameter. The tolerance limit is 500 nm. The 30 Monte Carlo simulation results are shown in Fig. 6.

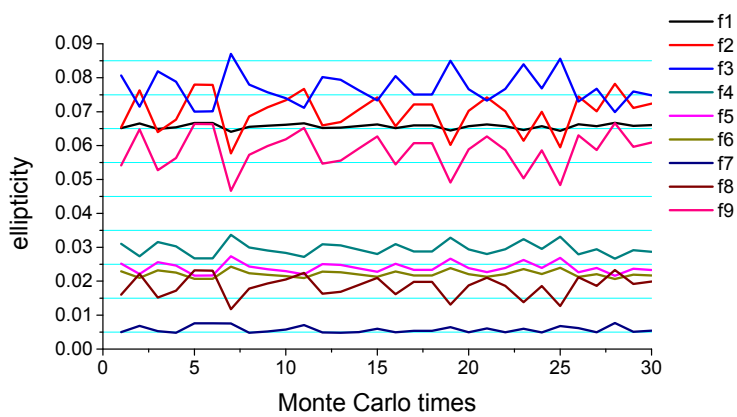

Fig. 6. Ellipticity time stability

As in Fig. 6, the RMS ellipticity change is less than 5e-3, which is within the range of requirement. With a closer examination, we find that the RMS WFE change is 0.003 waves or 2 nm. For a more complete analysis, we also tested the sensitivity of other tolerances. The result shows that the other tolerances are at least twice larger than this. This means that we have to pay special attention to M1-M2 distance stability in order to get high performance in time stability. By a suitable assignment of tolerance budget of 2 nm RMS WFE change, we can achieve the requirement of 5e-3 ellipticity stability between exposures.

#213928 - $15.00 USD Received 16 Jun 2014; revised 13 Sep 2014; accepted 1 Oct 2014; published 8 Oct 2014

However, we should notice that such high requirement on system stability is very hard to achieve, especially for low-earth orbit space telescopes. The HST gives us a good example. It has focus change mainly caused by thermal effect and truss shrink [14]. Therefore it is strongly recommended that the space telescope should be located at L2 or nearby orbit where there is little light or heat from the sun and is extremely benign.

5. Conclusion

Off-axis telescopes have many advantages over co-axis ones, the most important of which is the small and stable PSF desired for weak lensing. The PSF of an unobscured system is decided mainly by OPD. Therefore it is easy to model and analyze. In this article we make a complete analysis of the PSF property and ellipticity performance of an off-axis telescope.

Ellipticity is extremely sensitive to sampling parameters. In order to find out the ellipticity performance of an unobscured off-axis telescope, we modeled the optics PSF and adopted proper algorithm to calculate the optics ellipticity with proper sampling parameter. As a result, the unobscured optical system needs fewer sampling, which leads to high accuracy and efficiency in ellipticity modeling.

With careful choice of sampling parameter, we calculated the ellipticity of the unobscured system. With average RMS WFE of 21 nm, the full field ellipticity is less than 0.07. The EE80 radius is less than 0.088″. The spatial stability is under 7e-5 by cubic interpolation. The time stability of 5e-3 can be achieved with RMS WFE change tolerance less than 2 nm. The good ellipticity performance can meet the requirement of dark matter survey.

It is shown that the ellipticity performance of an off-axis telescope is closely related to the RMS WFE of the system. One can control the full field ellipticity by small WFE design and proper aberration balancing. With strict tolerance of the system RMS WFE change, the optics ellipticity stability can be controlled within the range of system requirement. There are still many other disturbances that have not been considered, such as spectrum, jitter, and noise. Therefore, more work is needed to make the system meets the final requirement.

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