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Optical Measurement of Φ750 mm Telescope System

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Abstract: For detecting space debris in the high orbit, a telescope with wide field of view (4°), large relative aperture (1 : 1.32) and broad wavelength (500 nm to 800 nm) is obtained. The telescope, whose clear aperture is Φ750 mm, consists of primary mirror and refractive corrector group. The surface type of primary mirror is parabolic, and the refractive corrector group includes one ellipsoid lens and three spherical lenses. The advanced methods of optical elements measurement and whole system are introduced respectively. Firstly, the figure error of spherical lens is measured using template method. A compensation test method of null lens is used to test the hyperbolic primary mirror and ellipsoid corrector lens. Next, when the corrector lens group is aligned, the whole corrector lens group is tested making use of a new spherical mirror method. And at last, it is adopted to measure the optical telescope with collimator test in the room and with nature star observation outdoors. All of the measurement results are satisfying the requirement of design. The figure errors of spherical lenses are less than 0.1 fringe in the first step, the figure errors of primary mirror and ellipsoid lens are less than $\lambda/30$ (RMS), and the wavefront error at the third step is less than $\lambda/30$ (RMS). After measuring the whole telescope optical system in the room, the 80% encircled energy is within 2 pixels, at the side of that, when observing the stars outdoors, the 80% encircled energy is also within 2 pixels in the whole field of view, 4° diagonal.

Key words: Telescope; Optical measurement; Compensator; Collimator test

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0 Introduction

At present, the space debris of universe become more and more important for individuals, organizations and the countries. For the detecting of space targets, the magnitudes are much lower and the energy become much weaker, so that we need the large relative aperture of the detecting telescopes[1-2].

Most of ground-based telescope whose apertures are larger than 500 mm, almost use purely reflective optical system so as to eliminate the chromatic aberration. Among most of the on-axis reflective optical systems, Cassegrain system[3-4] and Ritchey-Chretien system are the most applicable. But the former couldn't eliminate coma aberration of large field of view, and the latter couldn't remove astigmatism aberration of large field of view (FOV). So it is difficult for enlarging the FOV of detecting optical system, and ensuring the excellent image quality at the same time[5].

The Changchun Institute of Optics and Fine Mechanics and Physics (CIOMP) developed an excellent ground-based telescope of detecting space targets in the high orbit, which has small spot diagram, and small 80% encircled energy diameter and good modulation transfer function (MTF)[6-7]. The system focal length of telescope is 990 mm, whose clear aperture is Φ750 mm, so it is a slow optical system. The quality of system mostly depends on the figure errors of all optical elements, so the issue is how to measure the figure errors and what precision could be obtained.

1 Methods of measuring all elements

1.1 The optical system

The optical system involves five optical elements, one of which is hyperboloid reflective mirror, and the others are refractive lenses whose surface types are spherical. The type of this optical system is prime-focus, so the detector is front of

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the telescope tube, especially, front of the optical elements.

The field of view of telescope is 4° diagonal, and the wavelength band is from 500 nm to 800 nm. With the obscuration of detector, the energy which the telescope would collect is less than the whole Φ750 mm, but it is enough for detecting the objects of the high orbit. The satellites and other unidentified flying object above 10 000 km are the main targets for the telescope, and the most of them are weaker than 16 Mv.

The imaging quality of telescope consists of spot diameter, encircled energy, and modulated transfer function, etc. The pixel size of detector is 24 micrometers, and the spot diameter is less than 25 micrometers, the diameter of 80% encircled energy is less than 28 micrometers, the modulation transfer function is higher than 0.6 at 21 lp/mm, the Nyquist sampling frequency of the detector. All of these depend on optic design, elements manufacture, optical measurement, optic alignment, but the optical measurement is the most important factor of all the process.

1.2 Parameters and requirement

According to the Fig. 1, the primary mirror is positive power, and the lens group is negative power, which lead to the whole optical system is positive power. Table 1 gives the parameters of optical elements.

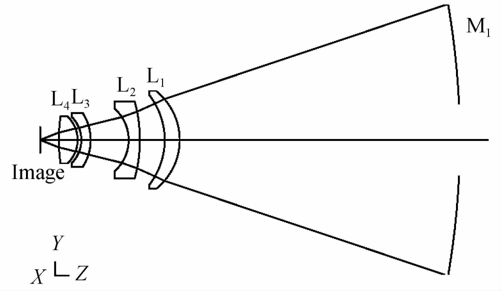


Fig. 1 The telescope optical system

Table 1 Parameters of the optical system

Number	M_1	L_1	L_2	L_3	L_4
Type	Hyperboloid	Spherical	Spherical	Spherical	Spherical
Material	ZERODUR	N-BK7	N-FK5	N-SF4	N-FK5
Aperture/mm	750	270	234	154	130
First radius/mm	2 227.53	163.26	383.71	147.58	95.74
Second radius/mm	/	191.24	111.65	94.88	381.99

The system measurements involve four steps of elements, which are all spherical lenses test, reflective mirror test, lens group test and the whole optical system test. And the second is the most difficult step, the after is the third, others are relative easy to achieved sometimes.

Table 2 gives the test requirement of optical elements. The estimation standard of the fourth step is different from the other three steps, because for this detecting telescope, it adopts diameter of 80% encircled energy to evaluate the whole system, and for the element or elements group, the figure error or wavefront error can be as the evaluation.

Table 2 Test requirement of measurement for optical system

Element number	Figure error (RMS)	Diameter of 80% encircled energy
M_1	$\lambda/30$	/
Single lens surface	$\lambda/30$	/
Corrector group	$\lambda/30$	/
The whole telescope	/	$\leqq 48\ \mu m$
$\lambda=632.8$ nm, pixel size $=24\ \mu m$		

2 Measurement and result

In this paper there are four different methods to test the figure error or wavefront error. The first and fourth steps don't need compensators, others have compensators necessary[8].

2.1 Lens figure error measurement

Three of all lenses are meniscus shape, the last one is bi-convex shape, Fig. 2 indicates the all lenses during fabrication, and all of the four lenses are spherical. So for the concave surface, it uses laser interferometer to test the figure errors, the test method is shown in Fig. 3.

Fig. 2 The lenses of corrector group

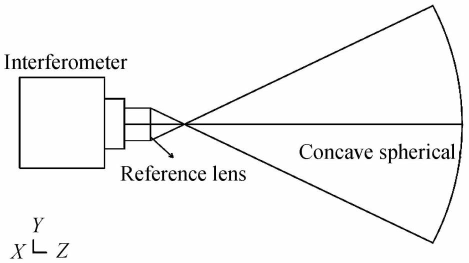


Fig. 3 The test method for concave spherical surface

The interferometer sends out parallel beam, and which is converged by the reference lens. The focus of reference lens coincides with the center of concave of the measured concave surface. So the divergency beam will be reflected by the concave surface and then return along the original optical path, which is collimated by reference lens and interfere with the reference beam. The difference is the figure error of the measured concave surface.

For the convex spherical surface, the test method is template test. In this measurement, it needs a concave reference spherical surface that has the same radius of curvature with tested convex surface, which has the RMS figure error less than 10 nm. Then it uses the reference surface as the template to measure the convex surface.

At last, five unique templates are needed to test the five convex surfaces, and the other three concave surfaces are measured with 4D dynamic laser interferometer. Table 3 indicates the eight test results of four lenses. According this, the best surface is concave surface of L_2, the figure error of which is 12 nm(RMS); and the worst surface is convex surface of L_1, the figure error of which is 20 nm(RMS).

Table 3　Test results for every surface of four lenses

Surface	L_1-1	L_1-2	L_2-1	L_2-2	L_3-1	L_3-2	L_4-1	L_4-2
Figure error	$\lambda/32$	$\lambda/40$	$\lambda/34$	$\lambda/52$	$\lambda/36$	$\lambda/43$	$\lambda/36$	$\lambda/39$

$\lambda=632.8$ nm

2.2　Primary mirror figure error measurement

Primary mirror is a hyperboloid mirror with a hole in the center. Because of the concave surface, it is relatively easy to measure the figure error with auto-collimated interferometry. For composing the test system, it is necessary to design and manufacture the compensator accurately.

From Fig. 4, the interferometer sends out parallel beam, through the compensator, which changes plane wavefront into aspheric wavefront that is the same as the wavefront of primary mirror. Then the divergency beam is reflected by primary mirror and returns along optical path originally. The return beam interfered with the reference beam, so the difference between the two beams that is obtained by interferometer is the figure error of primary mirror. The compensator is the key element for the whole test optical system, it is correct only the compensator has high accuracy. In this optical system for measurement, the compensator consists of two small aperture lenses, and the worst figure accuracy is less than 10 nm, so it is precise enough to test the primary mirror.

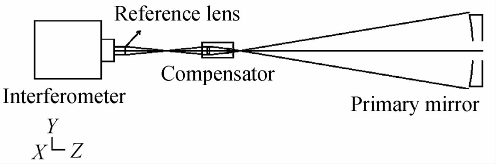


Fig. 4　The optical layout of measurement for primary mirror

In this test system, it used 4D dynamic laser interferometer. And the primary mirror is tested with support. Fig. 5 is the practical optical system for measurement.

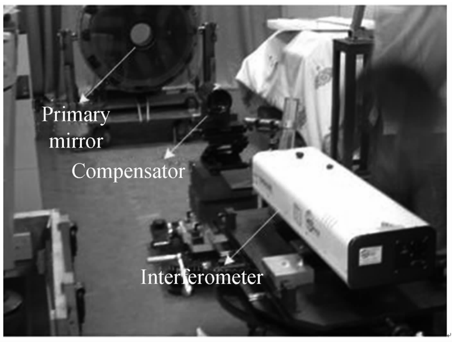


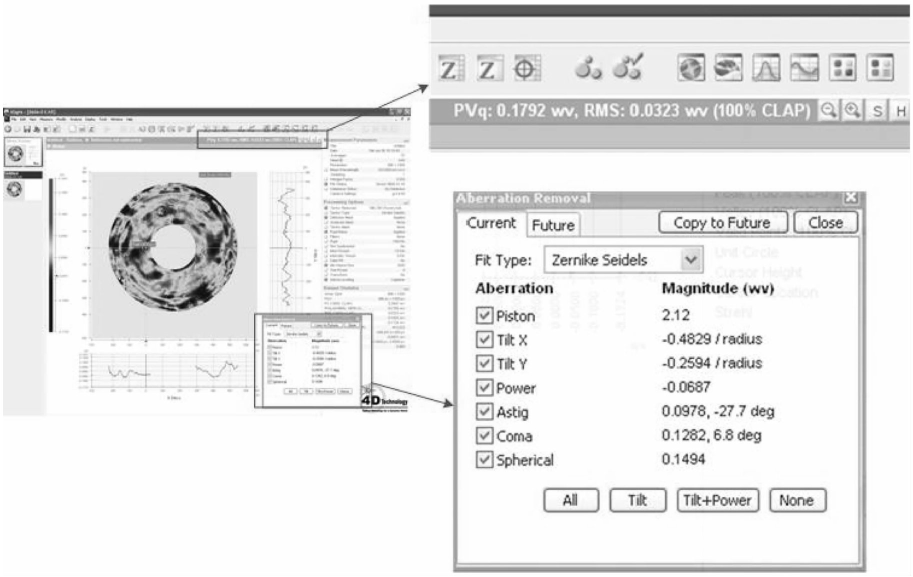
Fig. 5　The practical test process of primary mirror

According to Fig. 6, the measurement result of primary mirror is accurate enough to optical system of the Φ750 mm telescope, and the figure error is 20.44 nm(RMS), which is better than requirement of measurement in the section 2.

2.3　Corrector group measurement

The two sections above have completed the measurement for single optical element, and now the task is to test the corrector group after alignment. The corrector group is not an independent optical system with good image quality, so it is impossible to measure the group wavefront directly when it is aligned. It must also need a simple and precious compensator. Based on the requirement, the engineers design a compensator that is different from that of primary mirror test optical system, it is a standard spherical mirror.

Fig. 7 is the test layout of corrector group, the designed wavefront error is less than $\lambda/200$ (RMS), which is too small to influence the whole test result. The aperture of compensator is Φ260 mm, the radius of curvature is 917.15 mm, the figure error is $\lambda/100$ (RMS), and the distance between corrector group and standard sphere is about 533.47 mm.



Fit Type: Zernike Seidels

Aberration	Magnitude (wv)
☑ Piston	2.12
☑ Tilt X	-0.4829 / radius
☑ Tilt Y	-0.2594 / radius
☑ Power	-0.0687
☑ Astig	0.0978, -27.7 deg
☑ Coma	0.1282, 6.8 deg
☑ Spherical	0.1494

Fig. 6 The test result of primary mirror

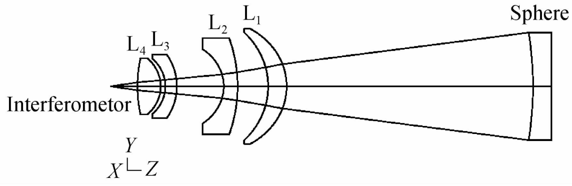
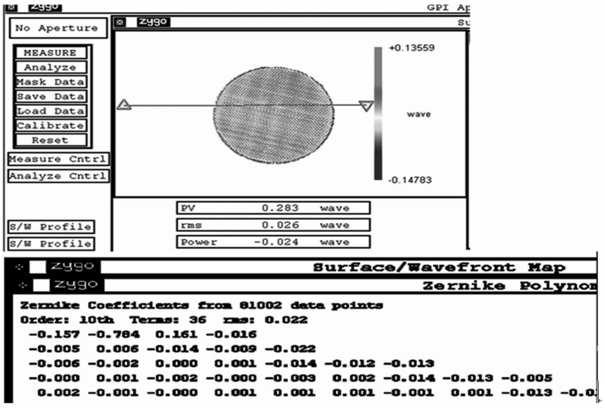


Fig. 7 The test optical system of corrector group

In this measurement, they use the ZYGO GPI interferometer to measure the wavefront error of corrector group as the 4D dynamic interferometer is busy. In this measurement, interferometer sends out convergent beam, which is changed into divergent beam after focus. Then the beam goes through the corrector group and it will be reflected by reference mirror. The returned beam transfers along the optical path originally, and at last which interferes with the reference beam. The difference between their interference is the whole wavefront error of the correct group. Fig. 8 gives the interference pattern as the result of measurement, the wavefront error of whole corrector group after alignment is less than λ/38 (RMS). For the telescope, the result is accurate enough.



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PV        0.283   wave
rms       0.026   wave
Power    -0.024   wave
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Zernike Coefficients from 81002 data points
Order: 10th  Terms: 36  rms: 0.022
 -0.157 -0.784  0.161 -0.016
 -0.005  0.006 -0.014 -0.009 -0.022
 -0.006 -0.002  0.000  0.001 -0.014 -0.012 -0.013
 -0.000  0.001 -0.002 -0.000 -0.003  0.002 -0.014 -0.013 -0.005
  0.002 -0.001 -0.000  0.001  0.001  0.001 -0.001  0.001 -0.013 -0.0
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Fig. 8 The result of measurement for the corrector group

2.4 The whole system measurement

Now the final work is testing the whole telescope when the corrector group is aligned with primary mirror. The paper gives two processes to get the final image quality. In the room, a collimator is used to simulate the starlight from space; then the telescope is moved to observe stars and satellites outdoors[9-10].

First, it is important to testing the whole telescope system in the room. It adopts a collimator whose focal length is 11 m to send parallel light beam. The azimuth and elevation angles could change expediently to achieve the large field of view. According to the designed image quality, the standard of image evaluation for the telescope is the diameter of 80% encircled energy. Fig. 9 is the process of measurement in the room, a spot hole whose diameter is 0.01 mm is arranged at the focus of the collimator. Then a point source transmits light and after through the spot hole, the light is reflected by the parabolic mirror of the collimator and becomes collimated beam, from Fig. 1, the telescope receives collimated beam and imaged in the detector. In the final result of this measurement , the diameter of

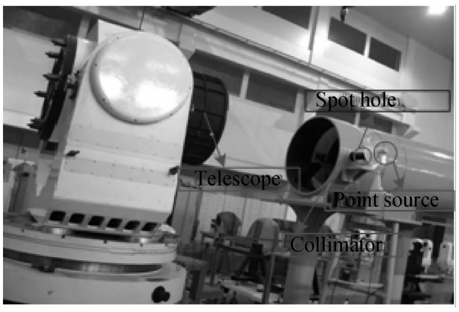

Fig. 9 The measurement of the whole telescope in the room

80% encircled energy is within two pixels，and less than 48 μm.

According to the result of room measurement，the image quality satisfied the requirement of design. So it is proved that the primary mirror and the corrector group have been aligned very well. Because of the satisfied result，the next step which is the last measurement step will be carried out. So the telescope is transported outdoors to get the first observation of nature sky. In this step the starlight is the collimated beam from sky，which will be received by telescope and image in the detector，too. It also uses the diameter of 80% encircled energy as the image standard. Fig. 10 is a section of detector image，at the field of ±2°，the diameter of 80% encircled energy is smaller than two pixels，and many images of stars only hold one pixel.

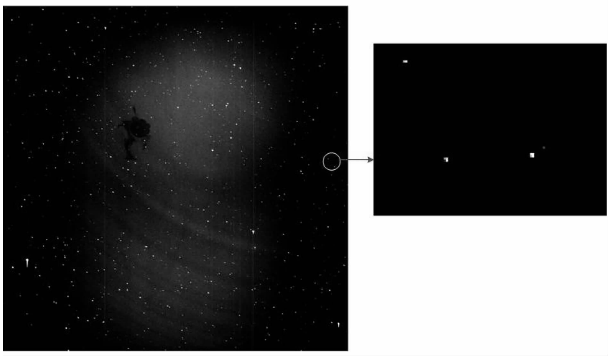

Fig. 10　The image of observation outdoors

3　Conclusions

For detecting more weak objects and search more debris on the high orbit，CIOMP developed a Φ750 mm prime focus telescope that has 4° field of view and whose relative aperture is 1∶1.32. The telescope optical system consists of hyperboloid mirror and corrector groups. During the development all of elements，the corrector group and the whole optical system should be test. The paper introduces four steps of measurement for the telescope，which gives their principles of measurement，and with the test，it obtains the practical figure errors and wavefront errors. The figure errors of all lenses are less than $\lambda/30$ (RMS)，and the figure error of primary mirror is $\lambda/31$(RMS). After completing the measurement of all single optical element，this paper tests the corrector group after alignment，the wavefront error of that is $\lambda/38$ (RMS). At last，it use collimator to measure the diameter of 80% encircled energy of the whole telescope，and move it to observe the nature stars and satellites，both of results are less than two pixels，which proves the method and process of all the measurement.

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Φ750 mm口径望远镜光学系统的检测

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摘 要：为了探测更高轨道的空间目标，研制了一台通光口径为Φ750 mm的望远镜．该望远镜为主焦点光学系统，由一片二次非球面反射元件和四片透射元件组成，具有大视场（4°），大相对孔径（1∶1.32）和宽光谱（500～800 nm）的特点．本文以该望远镜的研制为基础，介绍了其光学系统各个元件的单独检测和系统装调完成后的整体检测方法和过程．采用样板法对系统中的球面透射元件进行了单独检测，采用透射无像差补偿器法对二次非球面反射镜进行了单独检测，采用反射无像差补偿器法对组合起来的透射校正镜组进行了检测，并且对系统装调对准之后的光学系统进行室内平行光管和室外对星观测两种方法进行检测．测量结果均满足设计要求，其中球面透镜的面形误差小于0.1个光圈，反射元件和透射元件非球面表面的面形误差均优于$\lambda/30$（$\lambda=632.8$ nm），透射校正镜组的波像差优于$\lambda/30$（$\lambda=632.8$nm）．光学系统整体检测结果表明，室内和室外检测结果一致，其像面的80％能量集中度直径在4°的全视场范围内均小于2个像元，达到了设计的成像要求．

关键词：望远镜；光学检测；补偿器；平行光管测量