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Computer Controlled Polishing of the Off-axis Aspheric Mirrors

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Abstract: In this paper, the manufacturing and testing procedures to make large off-axis aspherical mirrors are presented. The difficulties in polishing and testing for both circular aperture and rectangular aperture mirrors are previewed, and a possible solution is given. The two mirrors have been polished by means of CCOS, and the final accuracy is 25nm rms for 770mm × 210mm rectangular mirror and 20nm rms for Φ600mm circular mirror. These results just meet the optical tolerances specified by the designer, and the manufacturing and testing procedures presented here show good ability to make the large off-axis aspherical mirrors.

Key words: asphere, computer-controlled polishing, optical testing
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1 Introduction

To obtain good resolution and wide FOV, many optical designers chose TMA off-axis aspherical configuration for the next generation space telescopes. However, the designs have not been made applicable until the significant progresses recently took place in optical design, computer controlled optical manufacturing and testing, and computer aided alignment^[1]. For large precision aspheric mirror fabrication, computer-controlled small tool grinding/polishing has been proved to be a reasonable approach to this issue^[2,3]. This is true for two reasons. First, the small tool can maintain good fit between the tool and the workpiece as it moves along the asphere surface. Secondly, computer control makes grinding/polishing process repeatable and efficient.

CIOMP is now under a contract to make two pieces of off-axis aspherical mirrors. One has circular aperture, and the other has rectangular aperture. This paper presents the manufacturing and testing procedures for this task, such as a new profiler used in grinding stage, a proposed method to

separate manufacturing errors and misalignment errors during interferometric test. The two mirrors have been polished by a CNC polisher, and the final accuracy is 25nm rms for the rectangular mirror and 20nm rms for the circular mirror. These results just meet the optical tolerances specified by the designer, and the manufacturing and testing procedures presented here show good ability to make large off-axis aspherical mirrors.

2 Measurement of the off-axis mirrors grinding stage

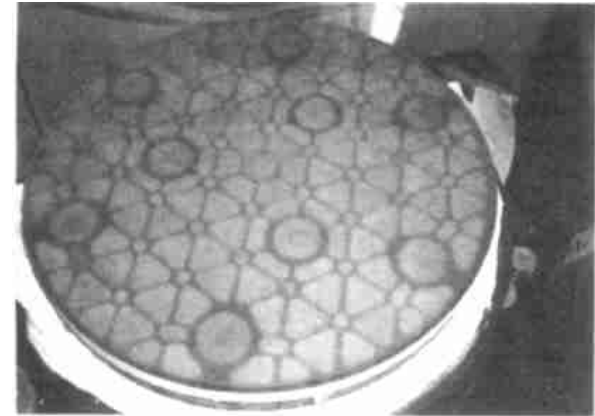
2.1 Choosing the best fit sphere

CIOMP is now under a contract to make two off-axis aspherical mirrors. Mirror A is a segment of prolate ellipsoid with diameter of 600mm, which has a circular aperture and is centered 460mm off-axis. Mirror B is a segment of oblate ellipsoid with a rectangular aperture of 770mm × 210mm, which is centered 173mm off-axis. Fig. 1 is the photograph of the two mirrors. Since the asphericities for both mirror A and B are small enough, we decide to start the figuring from the best-fit sphere.

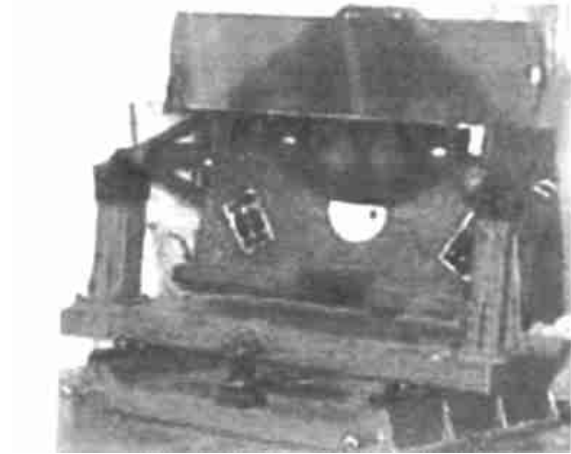
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To determine the radius of the best-fit sphere, there are two considerations. In the first case we consider the off-axis piece as a part of the rotational symmetric parent mirror and have the coordinate origin coincided with its parent axis. In the second case we have the coordinate origin coincide with the geometrical center of the off-axis segment. Fig. 2 shows these two configurations.

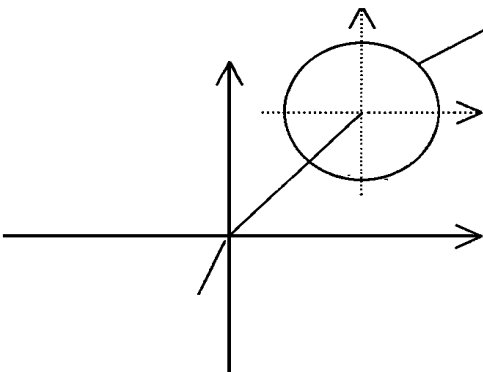


Mirror A

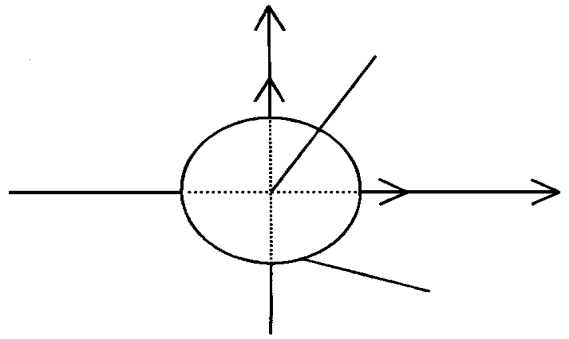


Mirror B

Fig. 1 Photograph of the two off-axis mirrors

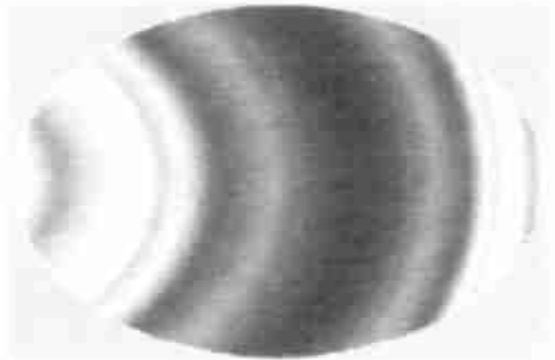


(a) Case A

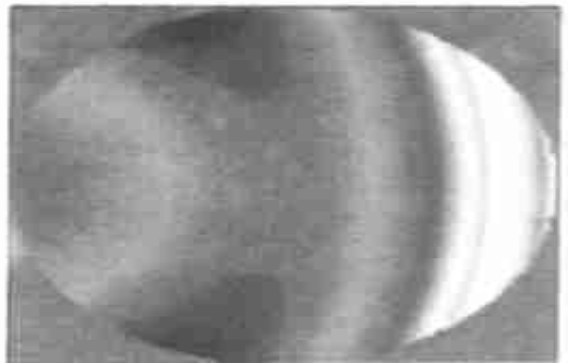


b) Case B

Fig. 2 Two configurations to choose best-fit sphere



a) Case A, P- V: 220 μ m



b) Case B, P- V: 270 μ m

Fig. 3 Departure of the best fit sphere from the asphere

Fig. 3 shows the departure of the best-fit sphere from the asphere for the two configurations. Here we use mirror A as an example. Because the CNC grinding/polishing machine with travel longer than 800mm is not available, we will choose the second configuration to begin with, even though

the departure in the first case is $50\mu\text{m}$ less than in the second case.

2.2 Profilometry testing of the off-axis mirrors

For CNC grinding/polishing, quantitative measurements are needed to guide the material removal. This feature distinguishes CNC grinding/polishing from conventional grinding/polishing. Usually, surface errors from grinding to polishing may vary from $20\text{--}40\mu\text{m}$ rms to $10\text{--}20\text{nm}$ rms. Using only one test instrument can not cover this big span, test devices with various resolutions are needed to measure the surface errors in different stages.

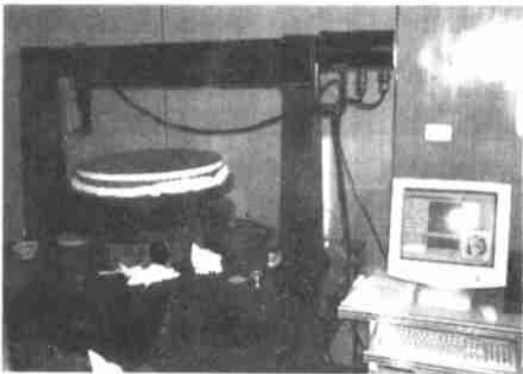
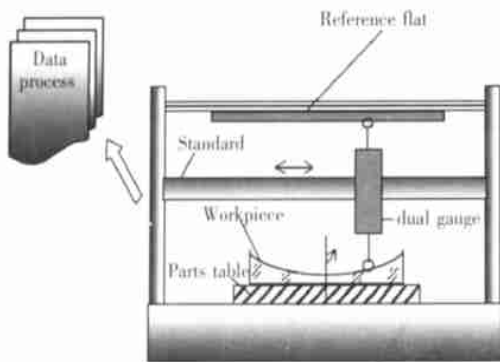
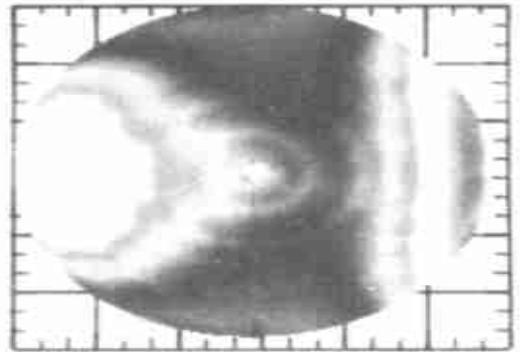


Fig. 4 Scheme and photograph of the newly built profiler

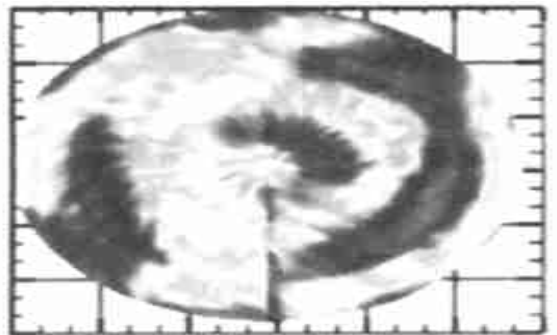
Because CNC grinding is of rapid material removal, the efficiency of the whole manufacturing process is greatly affected by grinding efficiency.

Therefore, quantitative measurement with good repeatability and accuracy is required to guide rapid material removal in CNC grinding. Such measurement can be implemented using IR interferometer, which diagnoses the non-specular surface by lowering the sensitivity. However, the expensive IR detectors and invisible operation make small optical workshop hesitate to use IR interferometer. We built a new profiler, AP-100, as shown in Fig. 4, the linear motion error of the slide is canceled due to the use of dual gauge plus a reference flat.

Fig. 5 a) shows the test result of mirror A after being ground to its best-fit sphere. The mirror was then ground on FSGJ-1 for 20 hours, as shown in Fig. 5. b), the rms error reduced from $32\mu\text{m}$ to $5\mu\text{m}$. When applying the local interpolation algorithm, the radius of curvature was also well controlled within the tolerance required.



a) Original error map, rms: $32\mu\text{m}$



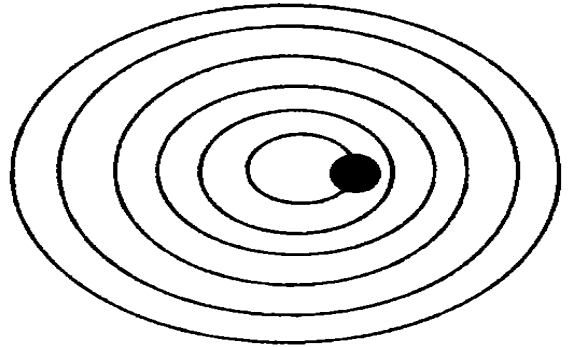
b) Error map after 20h grinding, rms: $5\mu\text{m}$

Fig. 5 Contour map of the surface error for mirror A

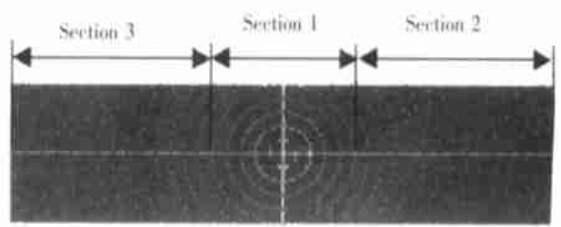
3 CNC grinding and polishing of the off-axis mirrors

3.1 CNC grinding of the two mirrors

The grinding was performed on FSGJ-1 CNC machine built by CIOMP. The figure error distribution function measured by the AP-100 was transformed into a control file for the FSGJ-1 machine. A local interpolation was employed based on Shepard algorithm to improve the control accuracy^[4]. For mirror A, a spiral tool path was chosen due to its circular shape. For mirror B, the segment was divided into three sections, as shown in Fig. 6. In section 1, the spiral tool path was chosen. In section 2-3, the workpiece swung left and right, while the tool moved in the radial direction.



Mirror A



Mirror B

Fig. 6 Tool path for grinding/polishing mirror A and B

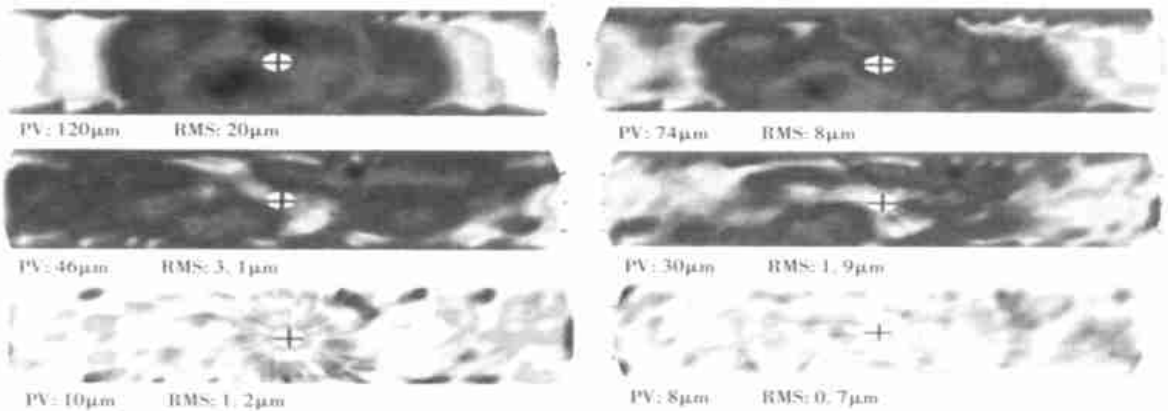


Fig. 7 Figure error convergence of mirror B

Fig. 7 shows the progress of the error reduction for mirror B. We kept CNC grinding until the figure error was less than $1\mu\text{m}$ rms, and we believed that surface with errors in this level can be resolved by visible light interferometer after polishing. Fig. 8 shows the interferogram of mirror B after polishing.

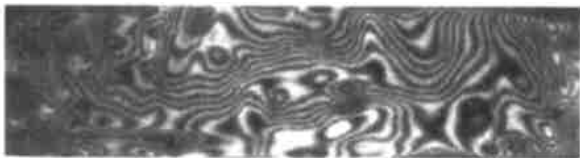


Fig. 8 Interferogram of mirror B polished right after CNC grinding

3.2 CNC polishing of the two mirrors

The polishing was also performed on FSGJ-1 machine by means of CCOS. Here the interferometry test was conducted to reduce data for the CNC machine. Fig. 9 (a) and (b) show the progress of figure error convergence for mirror A and B.

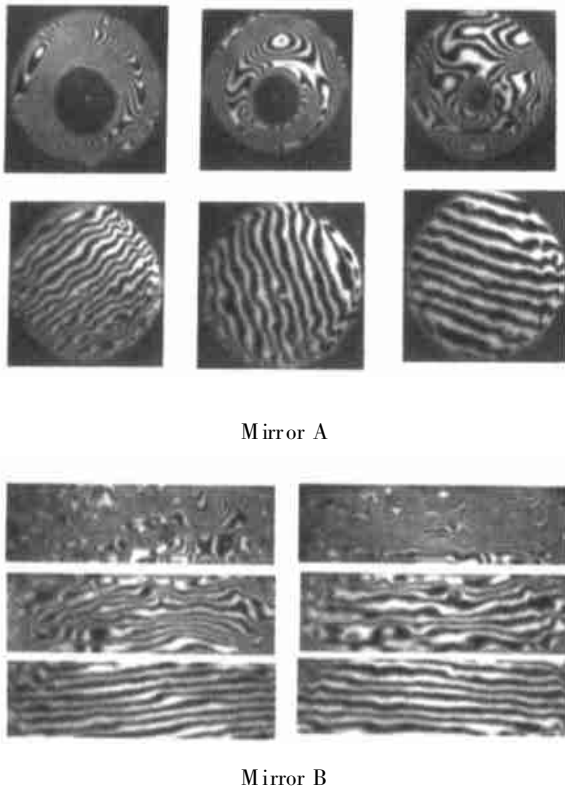


Fig. 9 Figure error convergence for mirror A and B during CNC polishing

3.3 Method to separate the manufacturing errors and misalignment errors

Interferometric null test will be employed to test the off-axis mirrors during polishing. The configuration is shown in Fig. 10.

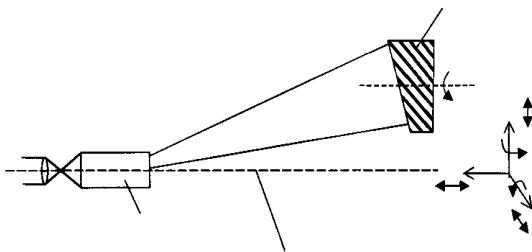


Fig. 10 Configuration of null test for the off-axis mirror

The observed interferogram includes both manufacturing errors and misalignment errors. It is the former errors that need to be removed by CNC grinding/polishing, and we must be able to separate the manufacturing errors from the misalignment errors when analyzing the interferogram. For

on-axis conics, coma is a sign to be used to correct the rigid-body misalignment. However, for off-axis section, it is not simple. Under certain circumstances, coma can appear as astigmatism centered on the sub-aperture affecting the conjugate null test's ability to measure mirror shape^[5]. Fig. 11 shows two examples of these situations.

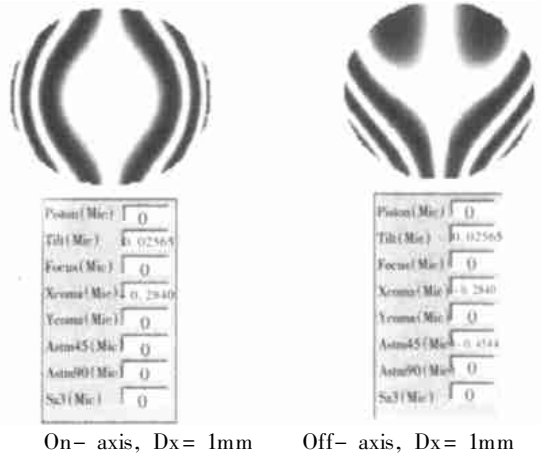


Fig. 11 Examples of the rigid body misalignment induced aberrations

Eric W. Young and Gregory C. Dente developed an algorithm to separate misalignment errors and misfigure errors for testing off-axis parabolic mirrors^[6]. We here extend this algorithm to any general off-axis aspheres. The wavefront aberration $W(x, y)$ of an interferogram in null test can be expressed as a function of x and y , which represents the position of a point on the mirror. It contains both manufacturing errors $W_m(x, y)$ and misalignment errors $W_a(x, y)$:

$$W(x, y) = W_m(x, y) + W_a(x, y) \quad (3-1)$$

$W_a(x, y)$ is introduced by the rigid-body motion of the off-axis mirror and should be removed from the test result.

As shown in Fig. 10, $W_a(x, y)$ can be expressed as:

$$W_a(x, y) = -2 \cdot \left(\delta \cdot \frac{\tau}{n} \right) \cdot \left[1 + \left(\frac{\partial z}{\partial x} \right)^2 + \left(\frac{\partial z}{\partial y} \right)^2 \right]^{-1/2} \cdot \left[-\frac{\partial z}{\partial x} \cdot \delta dx - \frac{\partial z}{\partial y} \cdot \delta dy + \delta z \right] \quad (3-2)$$

Where, Z is the sag height of the asphere:

$$z = f(x, y) = \frac{c \cdot p^2}{1 + \sqrt{1 - (k + 1) \cdot c^2 \cdot p^2}} + al \cdot p^4 + a2 \cdot p^8 + \dots$$

$$p^2 = x^2 + y^2 \quad c = \frac{1}{R} \quad k = -e^2$$

R is the radius of curvature of the vertex, k is conic constant, and n is the unit normal to the mirror surface, δl is the displacement of a point on the surface of the mirror:

$$n = \left[1 + \left(\frac{\partial z}{\partial x} \right)^2 + \left(\frac{\partial z}{\partial y} \right)^2 \right]^{-1/2} \cdot \left(-\frac{\partial z}{\partial x}, -\frac{\partial z}{\partial y}, 1 \right) \quad (3-3)$$

Based on the equation of (3- 1) through (3- 4), we can obtain “null” fringe, or in another word, remove the misalignment errors by properly adjusting $Dx, Dy, Dz, \theta_x, \theta_y$. This can be done by means of a least square optimization method. The procedure is as follows:

$$\rho = \begin{bmatrix} Dx - \theta_y \cdot z \\ Dy + \theta_x \cdot z \\ Dz + \theta_y \cdot x - \theta_x \cdot y \\ 1 \end{bmatrix} \quad (3-4)$$

1) Take an interferogram with aberration of



Mirror A

$W(x, y)$

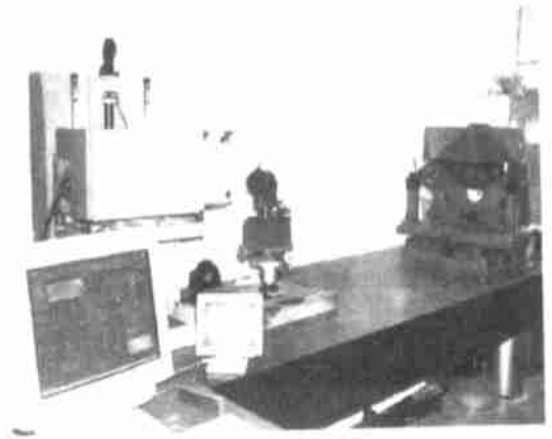
2) Let $S = W(x, y) - W_a(x, y)$

3) Find $Dx, Dy, Dz, \theta_x, \theta_y$ to make S^2 a minimum, equally solve the following equation system:

$$\begin{cases} \frac{\partial S^2}{\partial Dx} = 0 \\ \frac{\partial S^2}{\partial Dy} = 0 \\ \frac{\partial S^2}{\partial Dz} = 0 \\ \frac{\partial S^2}{\partial \theta_x} = 0 \\ \frac{\partial S^2}{\partial \theta_y} = 0 \end{cases} \quad (3-5)$$

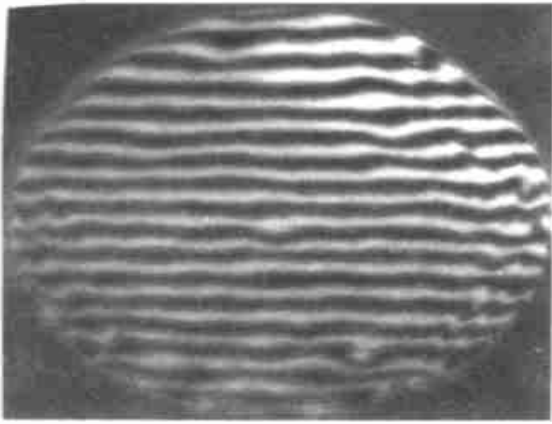
4) Adjust the relative position between the null lens and the mirror using the solved $Dx, Dy, Dz, \theta_x, \theta_y$. If obtain a null fringe then stop, otherwise go back to step 1) and continue.

Fig. 12 (a) is the photograph of the test set up for measuring the mirror A and B. Fig. 12 (b) is the final results for these two mirrors. Note that the null fringes without coma and astigmatism are obtained by using the above- proposed method.

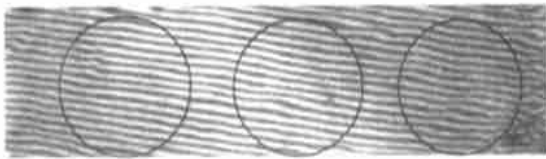


Mirror B

a) Photograph of the test set up for measuring mirror A and B



Mirror A, 20nm rms



Mirror B, 25nm rms

b) Interferograms of mirror A and B after fine polishing

Fig. 12 Testing the two off-axis aspherical mirrors

4 Summary

The manufacturing and testing procedures for making two off-axis aspherical mirrors are introduced. Some developments such as a new profiler used in grinding stage, proposed methods to separate manufacturing errors and misalignment errors during interferometric test are also presented. The two mirrors have been polished by means of CCOS, the final accuracy is 25nm rms for the rectangular mirror and 20nm rms for the circular mirror. These results just meet the optical tolerances specified by the designer, and the manufacturing and testing procedures presented here show good ability to make the large off-axis aspherical mirrors.

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