

Figure measurement of a large optical flat with a Fizeau interferometer and stitching technique

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Abstract

Large flat mirrors can be measured by using subaperture Fizeau interferometer and stitching the data. We have implemented such a system that can efficiently and accurately measure flat mirrors several meters in diameter using a 1 meter sub-aperture instantaneous Fizeau interferometer, coupled with sophisticated analysis software. The 1-m aperture optical system uses a fused silica test plate, reflective collimator, and commercial instantaneous interferometer. Collimator errors, mapping distortion, surface errors in the test plate, and other systematic effects were measured and compensated for individual measurements. Numerous individual maps were stitched together to determine the global shape of a 2-m class flat.

Key words: optical testing, Fizeau interferometry, optical flat, stitching

1. Introduction

We made a 2-m class flat mirror at the University of Arizona College of Optical Sciences. We used an instantaneous phase-shifting Fizeau interferometer¹ to test it. The largest reference flat available to us was 1 in meter diameter which was not big enough to measure the full-aperture of the test flat. To measure the full aperture we made multiple sub-aperture measurements and then stitched them together using software^{2,3}. A diverger lens and an off-axis parabolic (OAP) mirror were used to expand and collimate the beam from the interferometer. The testing system is described in Section 2. The OAP collimator used was diamond-turned and has high-frequency figure errors which are visible in the interference fringes and had to be filtered out. We describe the steps taken to filter out the high frequency error in Section 3. The particular interferometer we used deliberately introduces tilt between the reference and test beams. As a result, the OAP collimator introduces different amount of aberrations to the two beams. We can switch reference and test beams to average out the field errors. This method is detailed in Section 4. The sub-aperture measurement has slight mapping distortion due to the use of the OAP collimator. We present the distortion correction method in Section 5. The reference flat is not perfect and we estimate the figure error using a maximum likelihood estimate⁴ and corroborate the estimate with another estimate obtained using Parks' method⁵. The error due the reference surface is then subtracted from each sub-aperture measurement. In Section 6, we briefly describe the method used and present the map of the reference surface. The stitching software that we used, MBSI from MB Optique^{2,3}, required that each sub-aperture measurement was translated only relative to another measurement and not rotated. In our case, the test optic was rotated and it was necessary to rotate the individual sub-aperture measurements back to the correct positions on the parent surface before stitching. Section 7 explains how this is done. Then in Section 8 we present the stitched full-aperture surface map.

Detailed analysis for this testing method will be submitted for publication elsewhere.⁶

2. Fizeau test of a large optical flat

Figure 1 shows the layout of the testing system. The interferometer is an Intellium H1000 made by ESDI¹ which is an instantaneous phase-shifting interferometer employing polarization technique. The interferometer sends out two collimated beams with orthogonal polarizations and a small tilt angle between them. A diverger lens focuses the beams

and a small flat folds the beam to the OAP mirror which collimates the beam again. The collimated beams which are now 1m in diameter reflect off the reference and test flats and come back to the interferometer. One beam from the reference mirror is internally combined with the orthogonally polarized beam from the test mirror to form fringes. The diverger lens is a standard Fizeau reference sphere, but it is slightly tilted so that the beams reflected off the internal reference surface do not make it through the field stop.

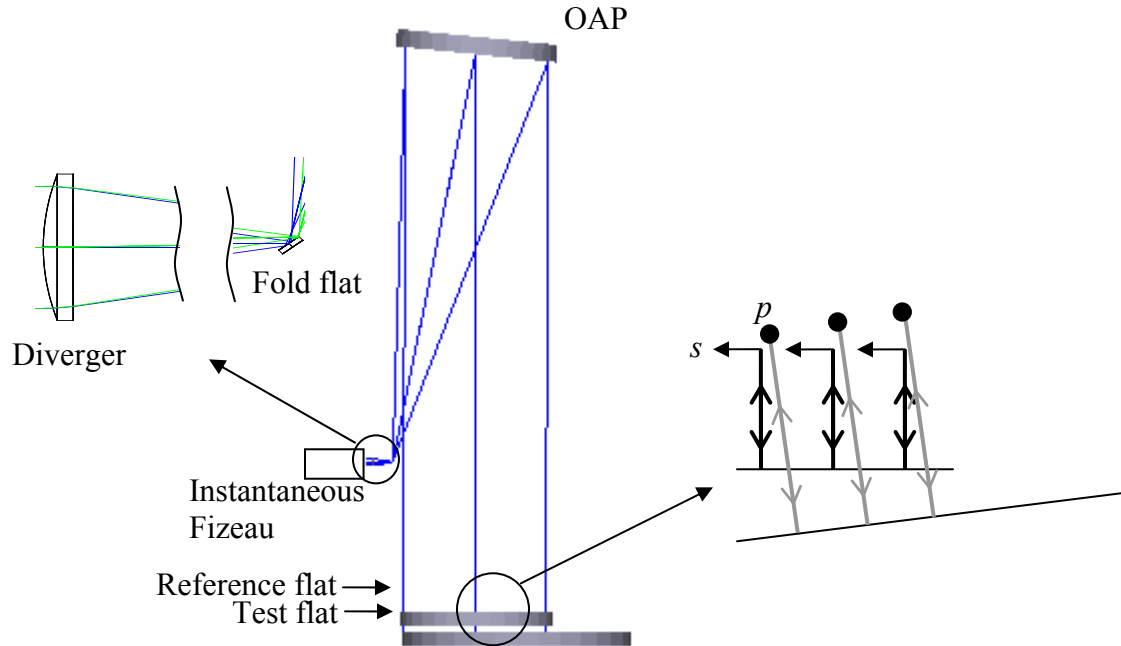


Figure 1. Layout of the Fizeau test for sub-aperture measurement of the large flat. The reference and test beams are orthogonally polarized and separated by a small angle. One can choose s polarization as reference beam and p polarization as test beam as shown above, or vice versa.

The ratio of the sizes of reference and test flats determines that a minimum of 8 measurements are needed to cover the whole test flat. Figure 2 shows the sub-aperture measurements it takes to cover the whole mirror.

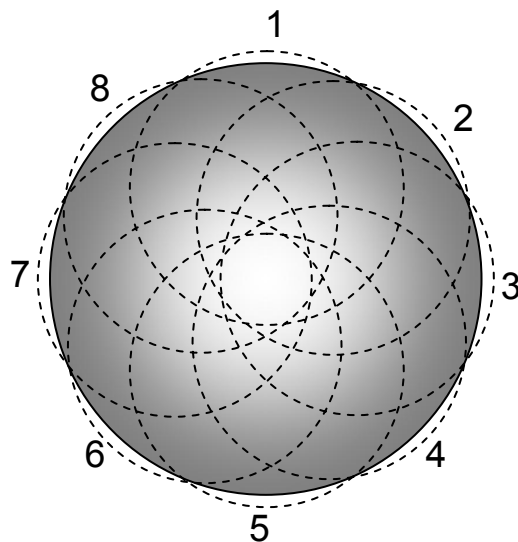


Figure 2. Sketch of the 8 sub-aperture measurements needed to cover the whole surface of the test flat.

3. Removal of high frequency errors on OAP

The OAP was diamond turned. The tool marks are clearly visible in the interferogram and cause high frequency errors in the calculated surface map (See the original surface map in Figure 3). To filter out the high frequency errors, we take the Fourier transform of the measured map, identify and filter out the noise frequency components. Then inverse Fourier transform it to get the clean map. Since this is a fixed pattern noise, the same filter is applied to all sub-aperture measurements. Figure 3 illustrates this process step by step.

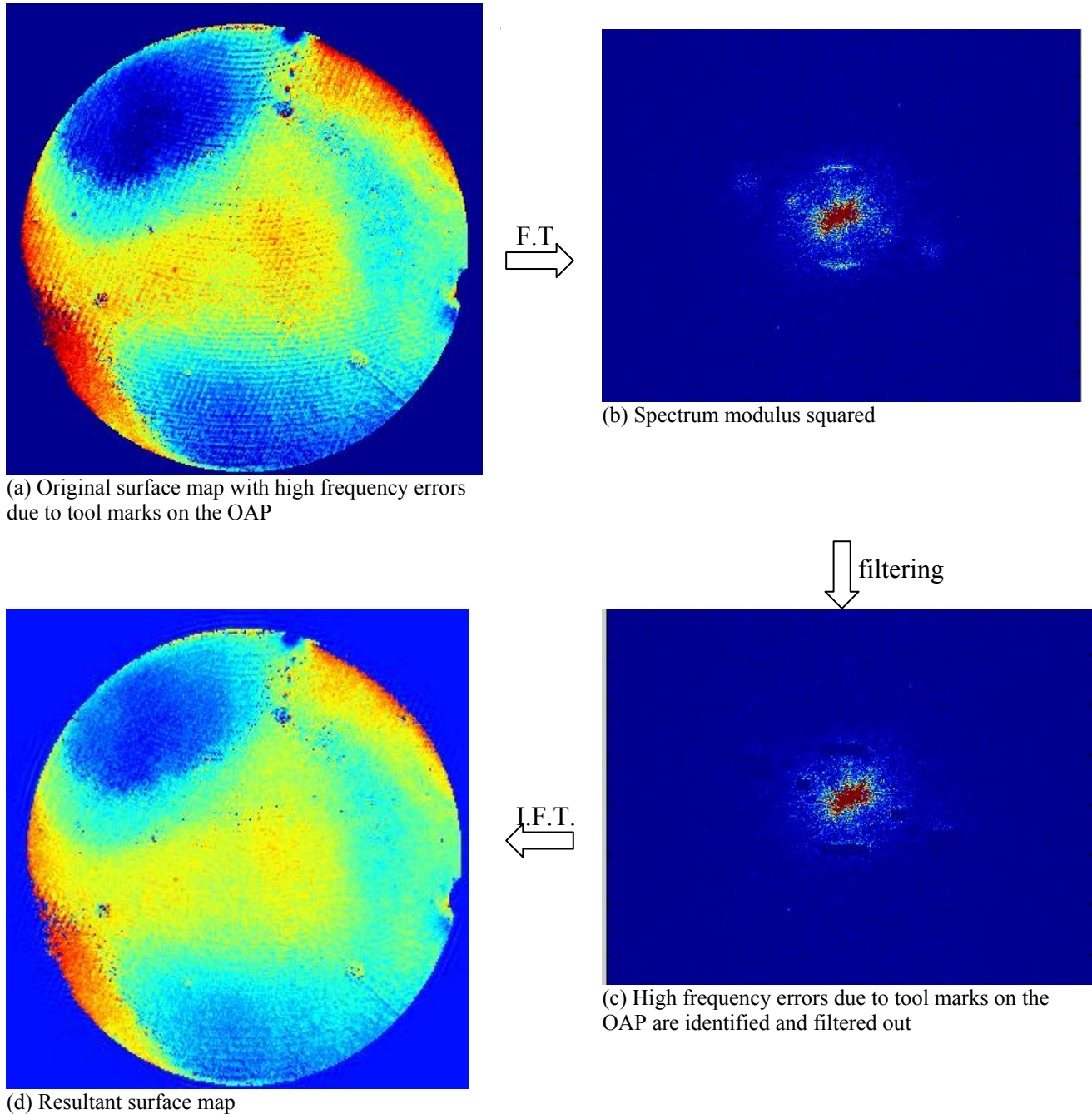


Figure 3. The procedure for filtering out the high frequency errors caused by the tool marks on the OAP collimator.

4. Elimination of field errors

Two orthogonally polarized beams, s and p , exit the interferometer with a small tilt angle between them, as shown in Figure 1. The interferometer can be used in two configurations. Either polarization s will reflect off the reference and polarization p off the test optic, or vice versa. The OAP introduces different amount of aberrations to the two beams. So strictly speaking, this Fizeau interferometer is not perfectly common path. The different aberrations introduced to reference and test beams inevitably lead to measurement errors which we call the field error. The field error can be eliminated if we make a measurement in each configuration and then average them (see table 1).

Table 1. The sub-aperture measurements can be made in two configurations with reference and test beams switched.

Configuration	Description	Measured surface map
A	s as reference, p as test	a
B	s as test, p as reference	b

The averaged map ,

$$\text{Avg} = (a+b)/2, \quad (1)$$

is free of filed error. By taking the difference map,

$$D = a-b, \quad (2)$$

the field error can be corrected using only one measurement:

$$\text{Avg} = a - D/2 = b + D/2. \quad (3)$$

Figure 4 shows the two surface maps measured in two configurations, the averaged map which is free of field error, and the difference map which is twice the field error.

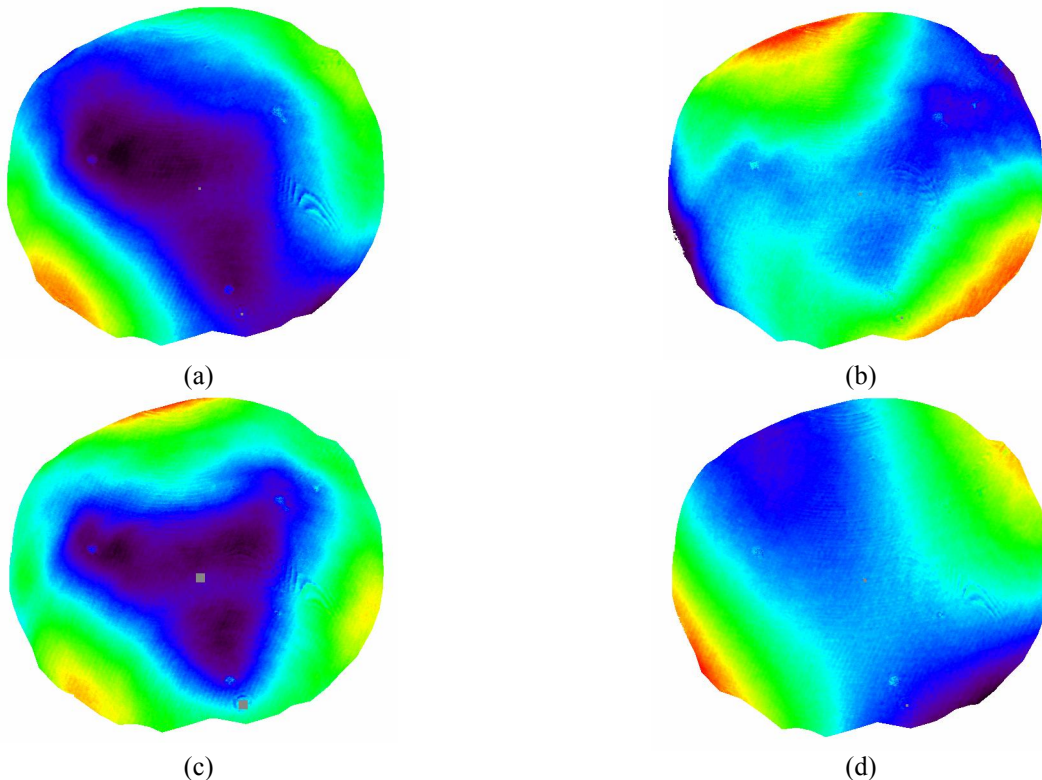


Figure 4. (a) The surface map measured in Configuration A. (b) The surface map measured in Configuration B. (c) The average of surface maps measured in Configurations A and B where the field error is eliminated. (d) The difference of the surface map measured in Configuration A and B which is twice the field error map.

The field error is constant since the system up to the OAP is fixed once aligned. So the field error can be characterized once and backed out from measurements performed in only one configuration. Eq. (4) can be made general:

$$\text{Field_Error_Corrected_Map} = \text{Map_measured_in_Configuration_A} - D/2. \quad (5)$$

5. Correction of mapping distortion

The use of an off-axis parabolic mirror to collimate the beam causes a slight mapping distortion between the flat surface to be tested and the phase map obtained through camera. When the beam size is 500 pixels in diameter on the camera, the maximum distortion is around 2 pixels. The small mapping distortion can be corrected using polynomials. With 3rd order polynomial fitting, the maximum error is less than 0.01 pixel; with 2nd order polynomial fitting, the maximum error is about 0.5 pixel. The mapping relationship is defined as the following⁷:

$$\begin{aligned} X &= \sum u_{ij} x^i y^j \\ Y &= \sum v_{ij} x^i y^j \end{aligned} \quad (6)$$

where

- (X, Y) is the normalized pixel coordinate of a fiducial mark on camera;
- (x, y) is the normalized coordinate of the corresponding fiducial mark on the test flat;
- (u_{i,j}, v_{i,j}) are the coefficients of the polynomials.

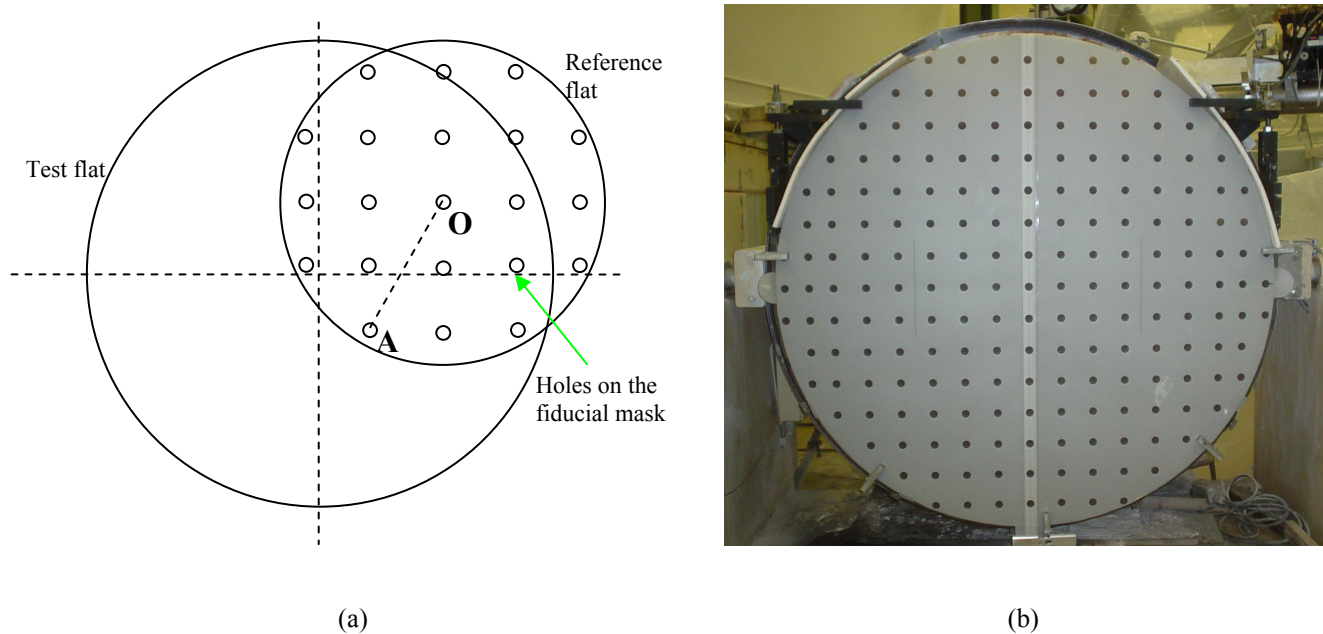


Figure 5. (a) The mask configuration for correction of the mapping distortion in this test. Fiducial O is chosen as the origin of the coordinate system and all the coordinates are normalized to the length of OA for fitting the mapping relations. (b) An example fiducial mask with regularly spaced holes. This is NOT the mask used in this test.

We use a mask with equally spaced holes so that that physical coordinates are known (see Figure 5). We put this mask on the reference flat and take a measurement. We then obtain the distorted positions of the holes in the camera space. A fiducial point near the center of the camera is chosen as the origin of both distorted and undistorted coordinate systems. The fiducial coordinates are normalized to the largest distance from the origin in both distorted (camera space) and undistorted (physical space) coordinate systems. This normalization defines the scale of the distortion corrected map. Therefore, the exact coordinates of the undistorted fiducials are not important as long as the relative positions are correct, i.e. scale, rotation and shift do not matter. With the known coordinates of the fiducials, we can fit the coefficients u_{i,j} and

v_{ij} in Eq. (6). Then, in the distortion corrected map, each pixel corresponding to a point on the test flat is mapped to a pixel in the camera space (distorted map) whose phase value is known. If the calculated distorted pixel coordinate is fractional, a bilinear algorithm is used to calculate the phase value.

6. Estimate figure error of the reference flat

The reference flat has significant surface figure errors in it and must be subtracted from each measurement. There was no direct measurement of the reference flat and we had to estimate the figure error. Peng Su and Jim Burge developed a maximum likelihood method⁴ to estimate the reference errors from 13 measurements with the test flat rotated 8 times at 45 degrees apart and the reference flat rotated 6 times at 60 degrees apart. Figure 6 shows the reference surface map estimated with the maximum likelihood method. To corroborate the measurement, we also used Parks' method⁵ to estimate the reference surface map. The Parks' method retrieves no information about the axi-symmetric terms. With the axi-symmetric terms removed, the estimated reference map of maximum likelihood method agrees well with that of the Parks' method, as shown in Figure 7.

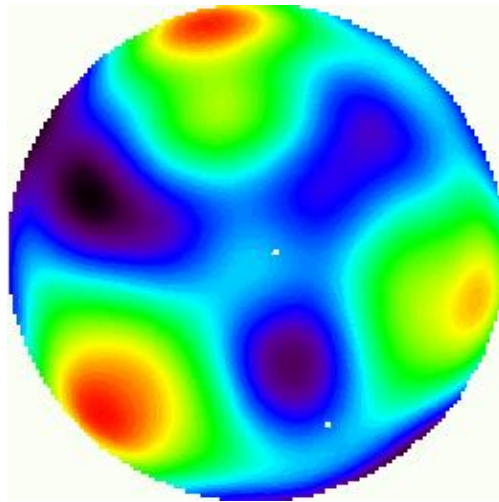


Figure 6. The reference surface map estimated with the maximum likelihood method. PV: 141nm, RMS: 40nm.

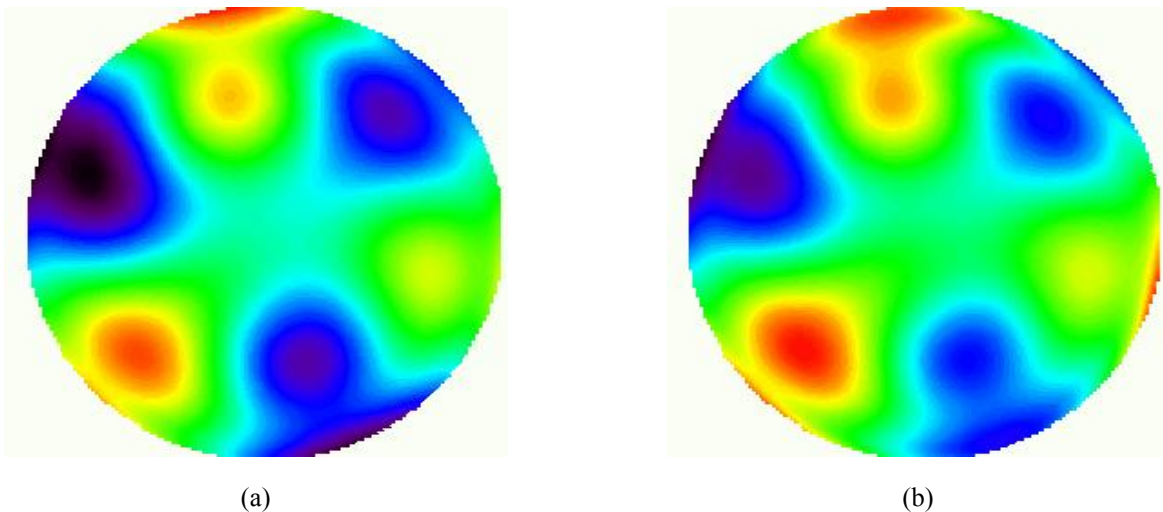


Figure 7. Comparison of the reference surface map estimated from two different methods. (a) Result of the maximum likelihood method with axi-symmetric terms removed. PV: 156nm, RMS: 36.6nm. (b) Result of Park's method as a corroboration. PV: 155nm, RMS: 36.8nm.

Trefoil is dominant in the estimated reference surface map, which is reasonable since the 60% of the weight is supported at three points as show in Figure 8. When the reference error is not backed out, each sub-aperture measurement shows significant trefoil. After the reference error is backed out, trefoil is not so visible which indicates trefoil comes primarily from the reference flat (see Figure 9).

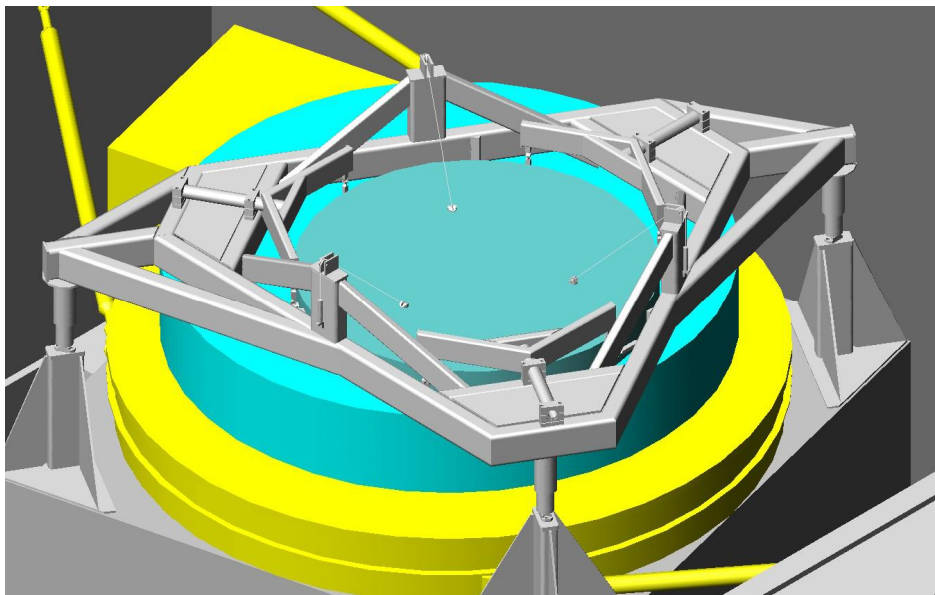
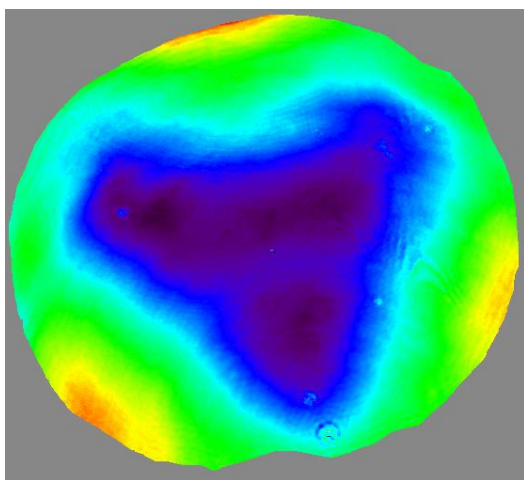
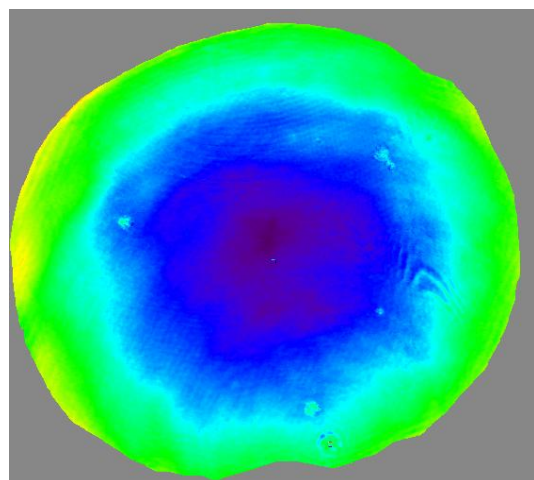


Figure 8. Support structure for the reference flat. 60% of the weight is supported at the bonded attachments on the top surface, which accounts for the trefoil in the fitted reference surface map.



(a)



(b)

Figure 9. A sub-aperture surface map (a) before subtracting the reference, and (b) after subtracting the reference.

7. Rotation of the sub-aperture map

Since the test flat is rotated for each sub-aperture measurement, the part on the test flat corresponding to each individual sub-aperture measurement is not only translated relative to another measurement, but also rotated as shown in Figure 10. The stitching software does not correct for rotation^{2,3} and the distortion corrected map must also be rotated before stitching.

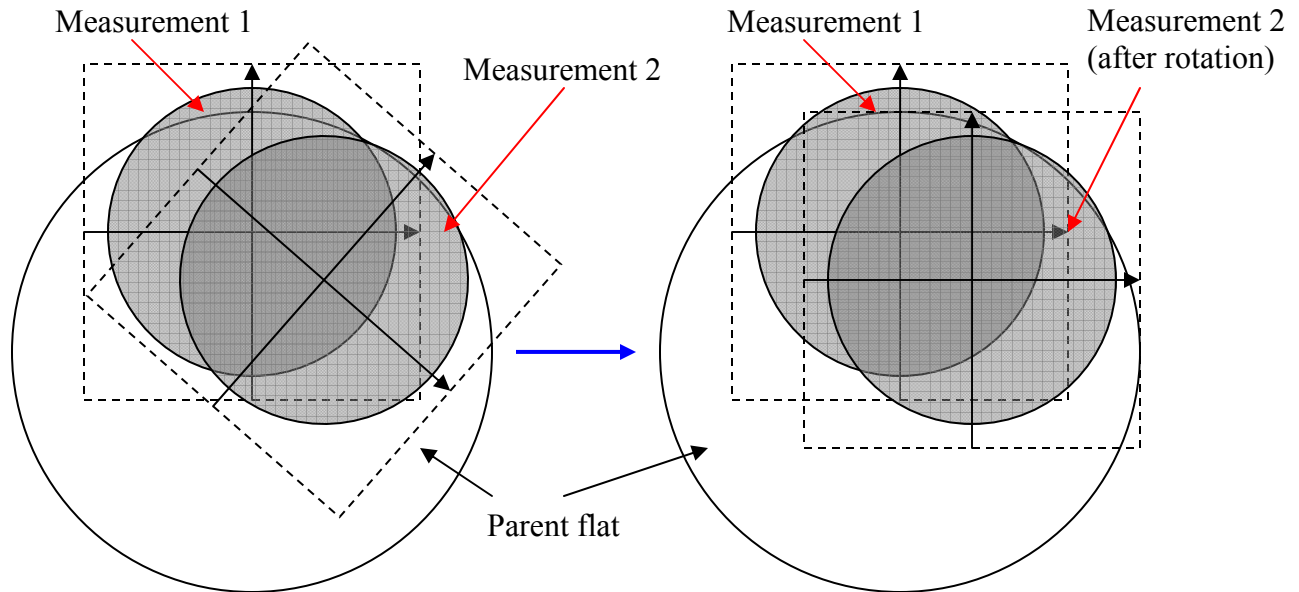


Figure 10. Illustration of the need for rotating the sub-aperture measurement in order that the stitching software can stitch them together. (a) Before rotation, a sub-aperture measurement is both translated and rotated relative to its neighbor. (b) After rotation, all sub-aperture measurements are just translated relative to each other.

The stitching software must know the relative positions of each sub-aperture measurement. A convenient position is the center of rotation since it does not move under rotation. We choose the fiducial that we used as the origin of the coordinate system in the distortion correction process as the center of rotation since its also remains its position after distortion correction. Figure 11 shows two sub-aperture measurements, one of which is rotated 45 degrees.

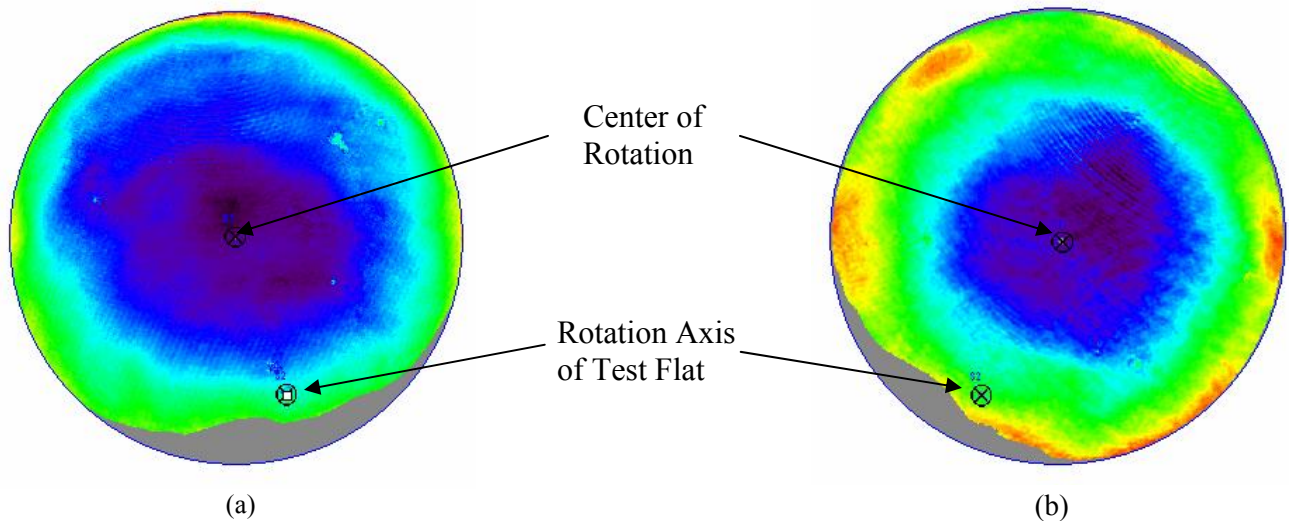


Figure 11. (a) Sub-aperture measurement at 0 degree (no rotation needed). (b) Sub-aperture measurement at 45 degree after rotation.

8. Stitching of sub-aperture measurements

After we finished all of the sub-aperture measurements, we processed the data following the procedure outlined in Sections 3-7. We filter out the high frequency errors in the OAP, back out the field error, correct the mapping distortion, subtract the reference surface map and rotate each sub-aperture measurement. Finally, we stitch the final sub-aperture maps together. Figure 12 shows the stitched map of 12(a) sub-aperture measurements. After subtraction of power and

astigmatism, the RMS surface error is 7.5nm. The stitching error in any overlapped area is about 2nm. For comparison, the estimated surface map from the maximum likelihood estimate has an RMS of 5.9nm and shows the same ring features as the stitched map. Obviously, the stitched map retains higher order information.

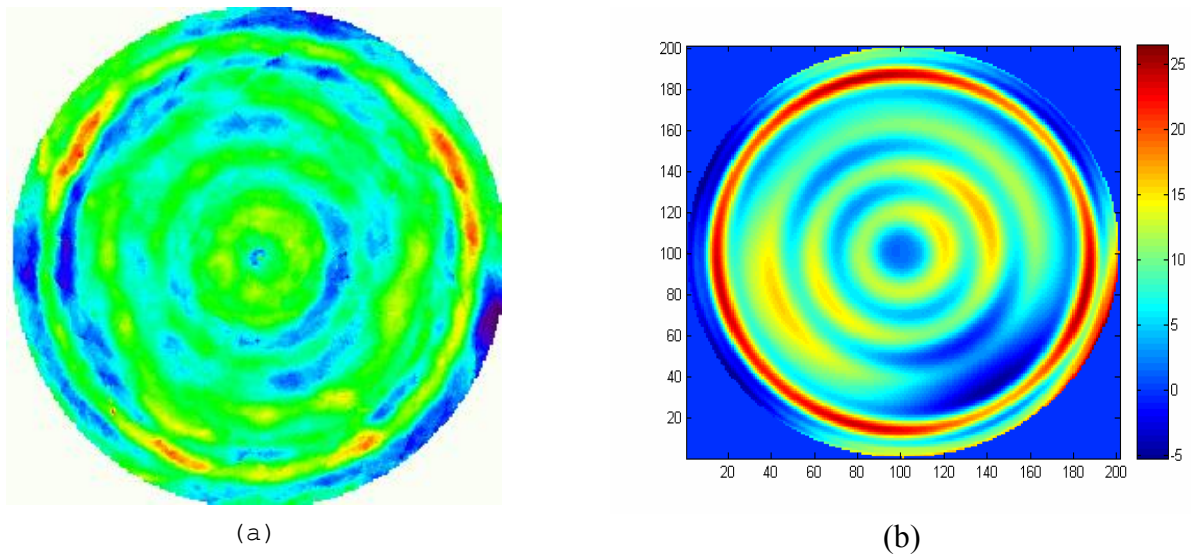


Figure 12. Measured full aperture surface map of the test flat. (a) Stitched map with focus and astigmatism subtracted. (b) Surface map fitted with the maximum likelihood method, with power and astigmatism subtracted.

9. Conclusion

We tested a large flat mirror successfully using an instantaneous phase shifting Fizeau interferometer and stitching techniques. We made the sub-aperture measurements of the flat with the Fizeau and an external 1m diameter reference flat. The test flat was rotated for each sub-aperture measurement. We filtered out the high frequency errors caused by the tool marks on the OAP collimator, corrected the field error due to the separation of reference and test beams, corrected the mapping distortion, estimated the reference surface and subtracted it from each sub-aperture measurement, rotated each sub-aperture measurement, and finally stitched the resultant sub-aperture measurements together to get the full surface map of the large flat. The final surface map agrees with the surface map obtained using a maximum likelihood estimate.

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