X-Ray Microscope Mirror Characterization

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Project Report

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Abstract

Kirkpatrick-Baez (KB) microscopes are used in inertial confinement fusion research to obtain images of plasma x-ray emission. Current KB microscopes used on OMEGA produce a four-image output. A new 16-image KB system is being designed for implementation on OMEGA. Mirror components of the 16-image KB optic were characterized by measuring their precise dimensions, surface roughness, and radius of curvature. A KB optic with a fundamentally smooth surface, built to proper dimensional specifications with an ideal radius of curvature, will allow the mirrors to not only fit into place in the existing microscopes, but also will allow the microscope itself to capture images at optimum focusing performance with minimized aberration. Results have been obtained by using an optical micrometer-measuring microscope, a Taylor Hobson Form Taly Surf 2.0 Profilometer, and a Zygo NewView 5000 white-light interferometer. Raw data output obtained from these instruments has been analyzed using the PV-Wave programming language.

I. Introduction

Inertial confinement fusion (ICF) physics is the study of matter in the plasma state, at ultra-high densities and temperatures, produced by compressing a target (generally comprised of deuterium) using high intensity laser or particle beams[1]. To gain a greater understanding of the physical properties of ICF plasmas, direct observation is essential. First developed by physicists Kirkpatrick and Baez in 1948[2], the Kirkpatrick-Baez (KB) x-ray microscope has since been adapted for use in laser plasma research. On the University of Rochester's OMEGA laser system, KB microscopes are used as a primary means for imaging laser plasma x-ray emission[3,4,5]. The high density and small scale of the imploding fusion target places unique demands on x-ray diagnostics. An imaging system such as the KB microscope having sufficient spatial resolution, is ideal for understanding the behavior and characteristics of the compressed ICF target core (i.e. density, shape and size.) These instruments are able to produce images of target implosions resulting from ablation of the target outer surface by the intense ultraviolet laser illumination. The KB's currently used on OMEGA produce a four images of target x-ray emission[3,4,5]. Each x-ray image is produced by the reflection of x rays, striking pairs of perpendicular KB mirrors, which focus the image in both the x and y dimensions, respectively (Fig. 1). For optimum focus to be reached for a given x-ray image, the equation

$$\frac{1}{p}+\frac{1}{q}=\frac{2}{R\sin i} \tag{1}$$

must be satisfied, where p is the source-to-mirror distance, q is the mirror-to-image distance, R is the mirror radius of curvature and i is the angle of incidence of incoming x rays[2]. For enhanced efficiency during optic manufacturing, each mirror is produced with an identical radius of curvature, thus requiring an offset to be introduced between the two mirrors[3].

Without additional instrumentation, the KB microscope would produce an output of four identical x-ray images. More useful information may be obtained, however, by using an x-ray framing camera[6]. An x-ray framing camera is able to introduce temporal resolution to the KB system, thereby allowing each of the four images to be resolved on x-ray film or a digital charged coupled display (CCD) in a chronologically increasing fashion. Consequently, each image is able to directly portray a different discrete stage of the evolution of the target implosion. This is essential to directly observe and record information relating to the dynamically changing implosion process.

Recent efforts at the Laboratory for Laser Energetics have resulted in the design of a KB microscope capable of producing 16-images of the target implosion process[7]. This KB design employs an optic, constructed to dimensions able to replace the existing optical assembly, (Fig. 2). As with the four-mirror system, each mirror is produced with an identical radius of curvature, again making it necessary for a slight offset to be introduced between each pair, with reflective surfaces perpendicular to one another, as illustrated in (Fig. 3). This will allow the images to be cofocal. This design will also incorporate an x-ray framing camera and will require modification to the existing design that can frame four KB images[8]. Mirrors forming the KB x-ray optic must be precisely constructed in order to obtain well-focused images. This work describes the ideal mirror specifications, method of characterization, and resulting measurements gathered throughout the investigation.

II. Characterization of the 16-Image KB Microscope Mirror

Mirror characteristics such as dimension, radius of curvature and surface roughness must all be determined when constructing a functional mirror system for the 16-image KB microscope. For this reason, direct measurement and characterization of each of the 32 KB mirrors is essential.

A. Mirror Dimensions

An optical micrometer-measuring microscope was used to measure the mirror dimensions. This microscope, with its three adjustable axes and lighted stage, permitted focusing on the mirror through its plastic container. Viewing the mirror surface through the ocular, the x- and y-axes of the stage were adjusted until the ocular crosshair was centered above a given vertex of the mirror. The specific x and y coordinate values of that mirror vertex were then recorded from the primary and vernier analog measurement dials of the microscope. Figure 4 depicts the coordinate labels given to each of the mirror vertices. The mirror side BC refers to the mirror's curved reflective surface. To ensure that this measuring microscope would offer reasonable results, initial coordinate data for a mirror with known dimensions was gathered. Using these coordinates, length measurements for the dimensions of the mirror were calculated using the equation:

$$L = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2} \quad (2)$$

where L is the distance between two vertices, x_2 is the x-coordinate of the first vertex, y_2 is the y-coordinate of the first vertex, x_1 is the x-coordinate of the second vertex, and y_1 is the y-coordinate of the second vertex. Upon confirmation of reasonable mirror coordinate values, the remaining 38 mirrors were measured. With these coordinate values, a fitting program was developed to analyze the measurements written in the PV-Wave computer programming language[9]. This program fit a set of ideal mirror coordinates to the input measured data. This was accomplished first by translating the ideal coordinates such that the midpoint of the base AD was superimposed over the measured base midpoint. This midpoint was determined using the equation:

$$m = ((\frac{x_1 + x_2}{2}),(\frac{y_1 + y_2}{2})) \quad (3)$$

where m is the midpoint between two vertices, and (x_1, y_1), (x_2, y_2) are as defined above. The midpoint of BC was also determined using Equation 3. The ideal coordinates were then rotated a determined angle found using the equation:

$$\theta = \arctan\left(\frac{y_t - y_c}{x_t - x_c}\right) \quad (4)$$

where θ is the angle to be rotated, y_t is the y-coordinate of the midpoint of BC, y_c is the y-coordinate of the midpoint of AD, x_t is the x-coordinate of the midpoint of BC, and x_c is the x-coordinate of the midpoint of AD. Finally, the position of the ideal data was adjusted to minimize the deviation between the measured and ideal coordinates. This was accomplished by using the PV-Wave NLINLSQ function, which uses a modified Levenberg-Mardquardt algorithm[10] to solve the non-linear least squares problem. The algorithm takes as input the estimates of the three parameters x_c, y_c, and θ, and minimizes the square deviation between the points. The least squares deviation is determined using the equation:

$$\sigma^2 = \sum_{i=1}^{4} \left| (f_i - x_i)^2 + (g_i - y_i)^2 \right| \quad (5)$$

where f_i and g_i are given by:

$$f_i = x_i \cos\theta - y_i \sin\theta + x_c \quad (6)$$

$$g_i = x_i \sin\theta + y_i \cos\theta + y_c \quad (7)$$

With this calculation, the deviation of each measured mirror from ideal specification was determined.

B. Radius of Curvature:

Given a fixed image plane, any variation from the ideal mirror radius of curvature will degrade the apparent resolution of the microscope. Geometrical object resolution was determined for mirrors of various radii of curvature, using the ray tracing software Zemax[11]. Figure 5 shows the object resolution for a mirror with an ideal radius of curvature of 25.6 meters, as well as the degraded resolution for a mirror with a 5% deviation in radius of curvature, with the other focus parameters held fixed (i.e. same source and image distance.) The importance of keeping the mirror curvature the same for multiple pair KB microscopes, such as the 16-image KB, is evident. Two instruments were used to measure radius of curvature of the KB mirrors: a Taylor Hobson Form Taly Surf 2.0 Profilometer[12], and a Zygo NewView White Light Interferometer[13]. A sample of 16 mirrors were selected for measurement. The mirrors were placed in a protective fixture that was constructed to expose only the desired surface of each mirror to be measured. The Taylor Hobson profilometer measures the surface depth by moving a precision diamond-tipped stylus across the surface of the mirror. These measurements were analyzed using a PV-Wave program designed to fit this data to a curve. Using the PV-Wave routine NLINLSQ (see section II(a)) this program was able to determine deviation of the measured radius of curvature from the ideal, through the equation:

$$\sigma^2 = \frac{1}{N-}\sum_i f_i^2 \tag{8}$$

where σ^2 is the calculated curvature deviation from ideal, f_i is defined by the function:

$$f_i = R^2 - (x_i - x_c)^2 - (y_i - y_c)^2 \tag{9}$$

where R is the ideal radius of curvature, x_i is the x value of a measured mirror coordinate, x_c is the x value of the calculated center of curvature, y_i is the y value of a measured mirror coordinate, and y_c is the y value of the calculated center of curvature. The Zygo interferometer was used to verify these results. Using the connected Zygo MetroPro software program[13], the depth measurements obtained from the surface scan could then be displayed. An internal software function was then used to determine a calculated radius of curvature value for the scanned mirror surface (circular.) While both of these instruments offered reasonable results for the mirror radius of curvature measurements, the Zygo interferometer was deemed a superior measuring tool for mirror radius of curvature, as it offered a non-contact method of measurement and also displayed results that were accurate to the one Angstrom level for vertical resolution, while the Taylor Hobson Profilometer was accurate to the 12 nm level (120 times less resolution).

C. Surface Roughness

In order to attain good image focus, microscopic surface features of the KB microscope's reflecting surface must be taken into account. Any deviations from a constant radius of curvature found on the surface of the mirror, could degrade image quality. The Zygo NewView 5000 white light interferometer with a 20x ocular was used to measure the surface roughness of each mirror. The larger magnification revealed a higher degree of detail regarding the surface roughness. Through the built in Zygo MetroPro software[13], the root mean squared (rms) value of the degree of surface roughness was generated, again accurate to the one Angstrom level. This rms value represented the mean degree of deviation of each surface scan from an ideal curve (circular).

III. Results

A. Mirror Dimensions

The root mean square (RMS) output of the PV-Wave dimensional best-fit program, both cumulative and for individual vertices, is found in Table 1. Here, it is found that mirror C06 was the least in deviation from ideal, with a RMS of 21.8 microns while mirror B18 was greatest in deviation with a RMS value of 43.0 microns. Cumulative measured mirror coordinate offsets from ideal are also depicted in Fig. 6. A contributing source of measurement error was noticed that the mirrors were measured with their protective casings on, leading to distortion.

B. Radius of Curvature

As was described in section II(B), a 16-image KB mirror with a precise radius of curvature is necessary for ideal x-ray image focus and resolution. The 16-image KB microscope, is designed with a mirror radius of curvature of 25.6 m. A larger four-image KB mirror with a sufficient curvature to be measured by both the Taylor Hobson and the Zygo was used to substantiate the measurements of the new mirrors (Fig. 7). It was therefore concluded that the measurements from these instruments were indeed reliable. When test 16-image mirror measurements were completed, varied results were obtained. Using the PV-Wave NLINLSQ curve-fitting program, the test measurements obtained by the Taylor Hobson Profilometer for mirror B08, offered a radius of curvature of 25.65 m, which is nearly ideal. However, the Zygo interferometer produced a surface profile not spherical in nature, with a much smaller radius of curvature (Fig. 8.) Due to this inconsistancy, the usefulness of these mirrors has been brought into question. As a result, a sample mirror (KB_B08) was returned to the manufacturer (Research Electro-Optics[14]).

C. Surface Roughness

As was mentioned in section II(C), a fundamentally smooth reflective mirror surface is needed for optimum image resolution. With the 16-image KB mirror, surface roughness should not exceed 5.0 Angstroms. The RMS roughness values that were measured using the Zygo interferometer generally fell within a range to the order of 5.0 Angstroms or less. As a result, it was concluded that these mirrors were sufficiently smooth and within specification.

IV. Conclusions

The Kirkpatrick-Baez x-ray microscope is an essential instrument for laser driven ICF diagnostics. While current KB microscopes in use on OMEGA produce four-images of the target x-ray emission, a new design produces a 16-images, which can be used for high resolution, temporally resolved (framed) imaging of target implosions. This work describes the method and results of characterizing mirrors that comprise the 16-image microscope (i.e. measuring the dimensions, radius of curvature, and surface roughness.) The microscope used has sufficient resolution to determine the dimensions to $\pm$ 5 μm. Mirror curvature was determined using both a white light interferometer and a surface profilometer. The interferometer had superior resolution and could best determine the curvature and surface roughness. Deviation of the mirrors from the desired ideal concave surface was significant and means that they may not produce usable images. This will require further investigation, both at the University of Rochester and Research Electro-Optics.

Acknowledgements

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Figure Captions

FIG. 1. Isometric view of a four-image KB optic.

FIG. 2. Isometric view of a four-image KB microscope assembly as used on OMEGA.

FIG. 3. Schematic diagram of a completed 16-image KB mirror pair. (a) Offset mirror pair with reflective surfaces at a perpendicular. (b) Side view of KB mirror pair with mirror offset indicated.

FIG. 4. Schematic diagram of a single 16-image KB mirror with measured coordinates A, B, C, and D labeled. Note: BC indicates the mirror reflective surface location.

FIG. 5. ZEMAX ray tracing simulations of KB image resolution. Solid line indicates resolution of mirrors with an ideal radius of curvature. Dotted lines indicates resolution of mirrors with a +/- 5.0 % radius of curvature deviation.

FIG. 6. Frequency histogram of mirror dimensional root mean square (RMS) offset from ideal.

FIG. 7. Surface profile of four-image KB mirror. (a) 3D surface profile of mirror measured using a Zygo NewView 5000 white light interferometer. (b) Plot of mirror surface profile obtained using a Taylor-Hobson Form Taly Surf 2.0 profilometer; fitted to an ideal curve using PV-Wave NLINLSQ command.

FIG. 8. Surface profile of 16-image KB mirror. (a) 3D surface profile of mirror measured using a Zygo NewView 5000 white light interferometer. (b) Plot of mirror surface profile obtained using a Taylor-Hobson Form Taly Surf 2.0 profilometer; fitted to an ideal curve using PV-Wave NLINLSQ command.

Table Captions

Table 1. Table of measured 16-image KB mirrors individual and cumulative deviation from ideal coordinate dimensions.

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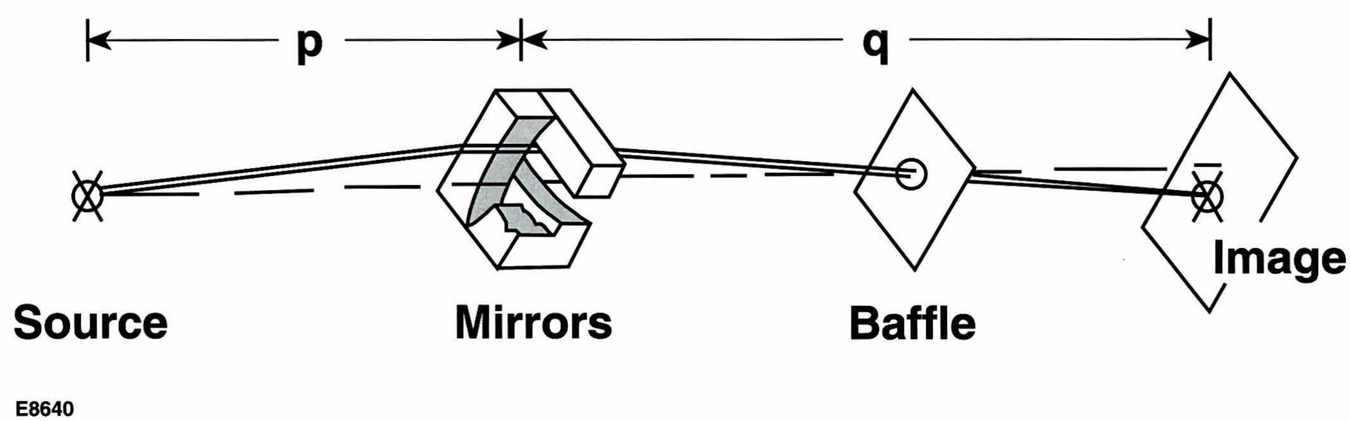
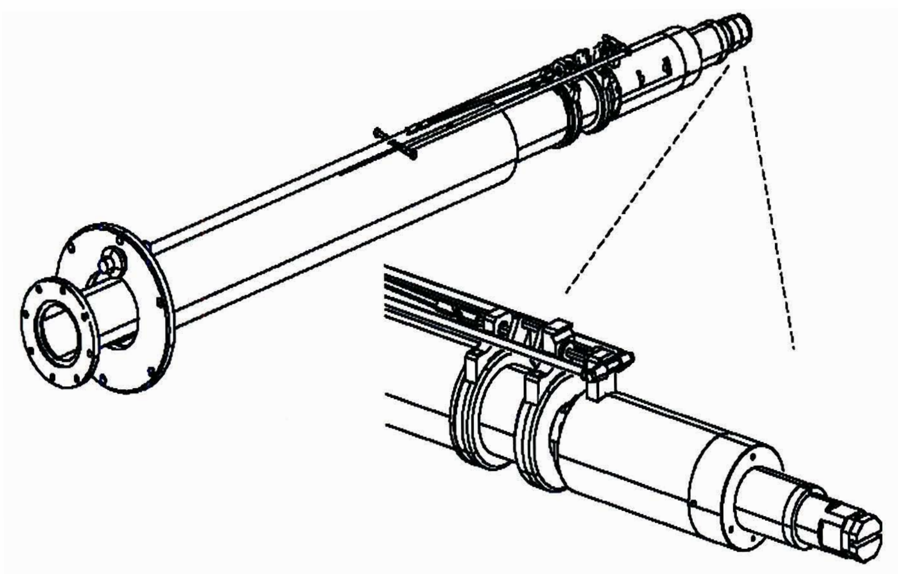
Fig 1

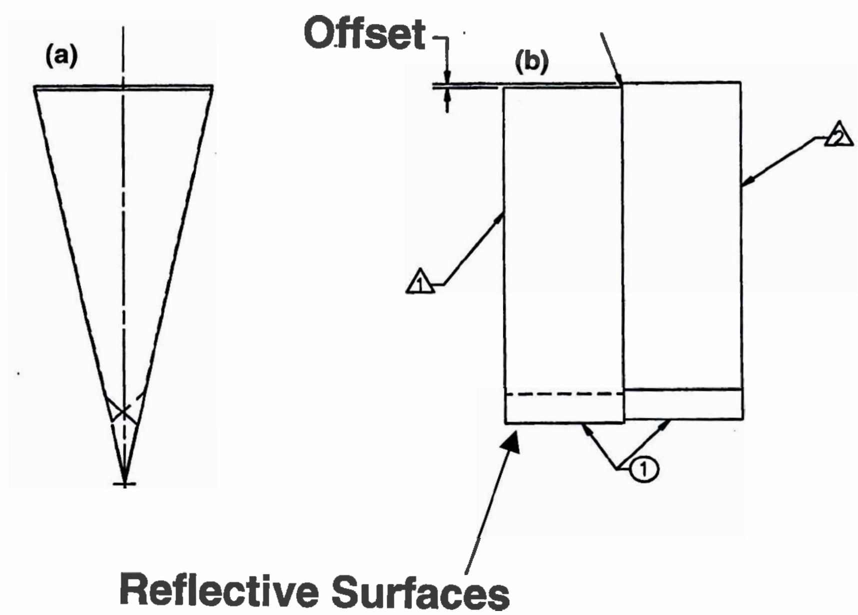


(Figure 2)

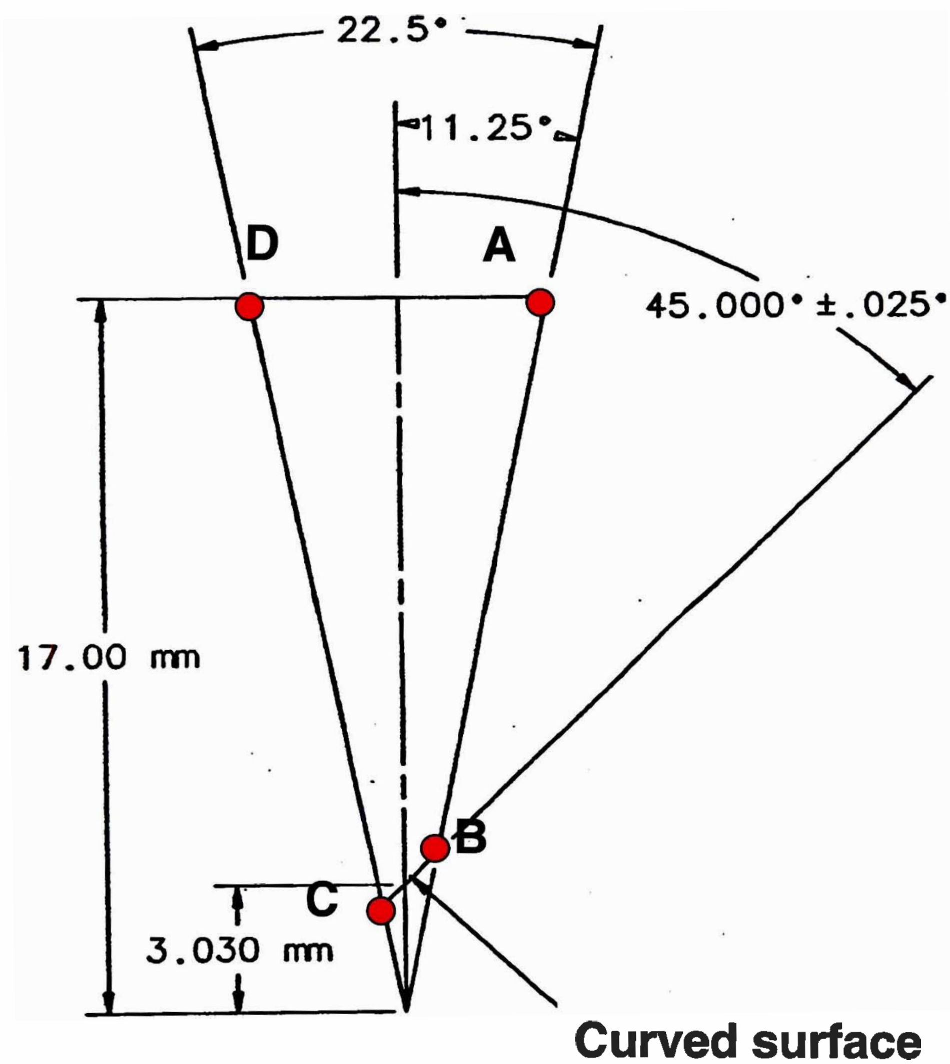


4-image KB optic

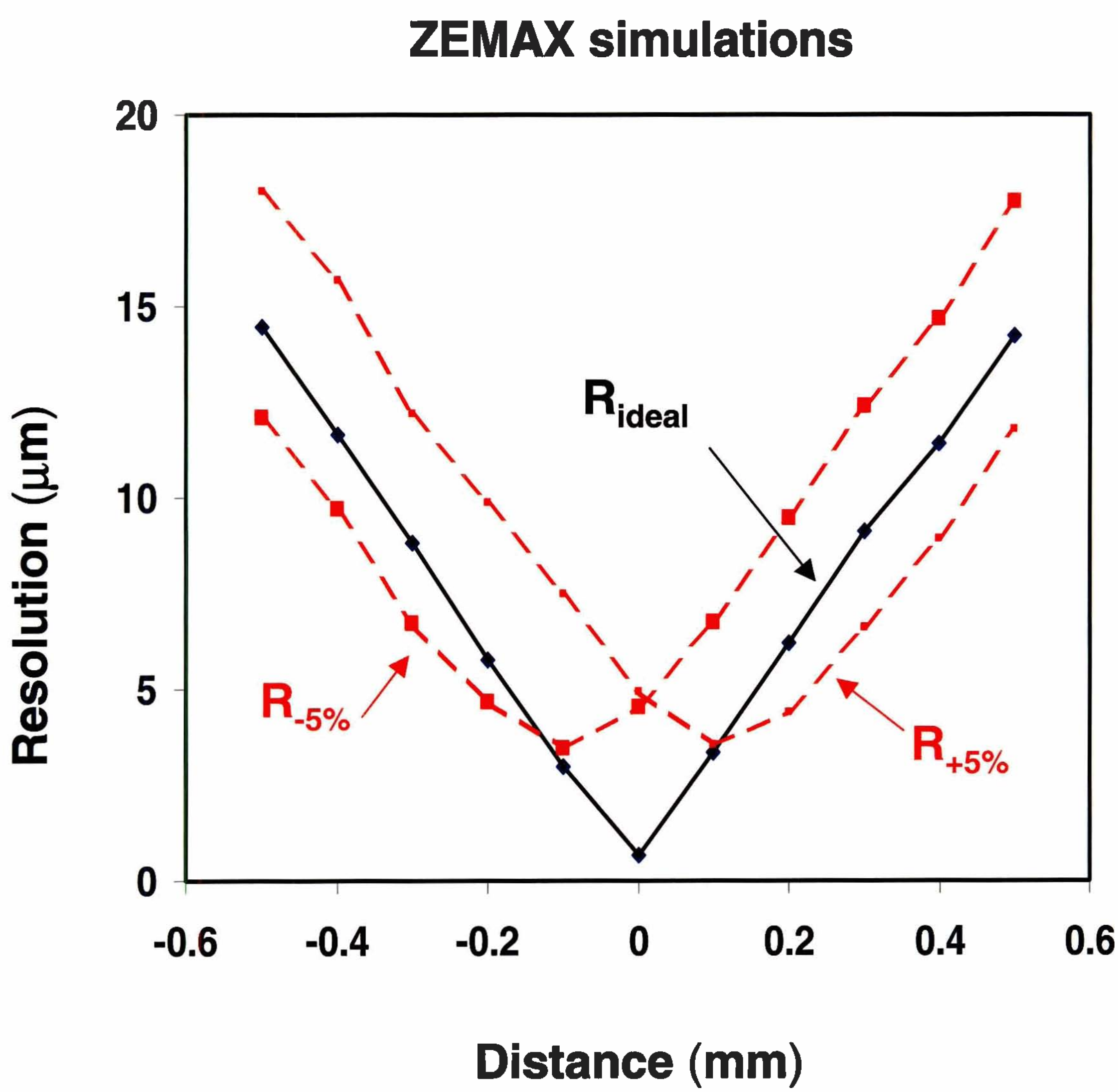
(Figure 3)



(Figure 4)

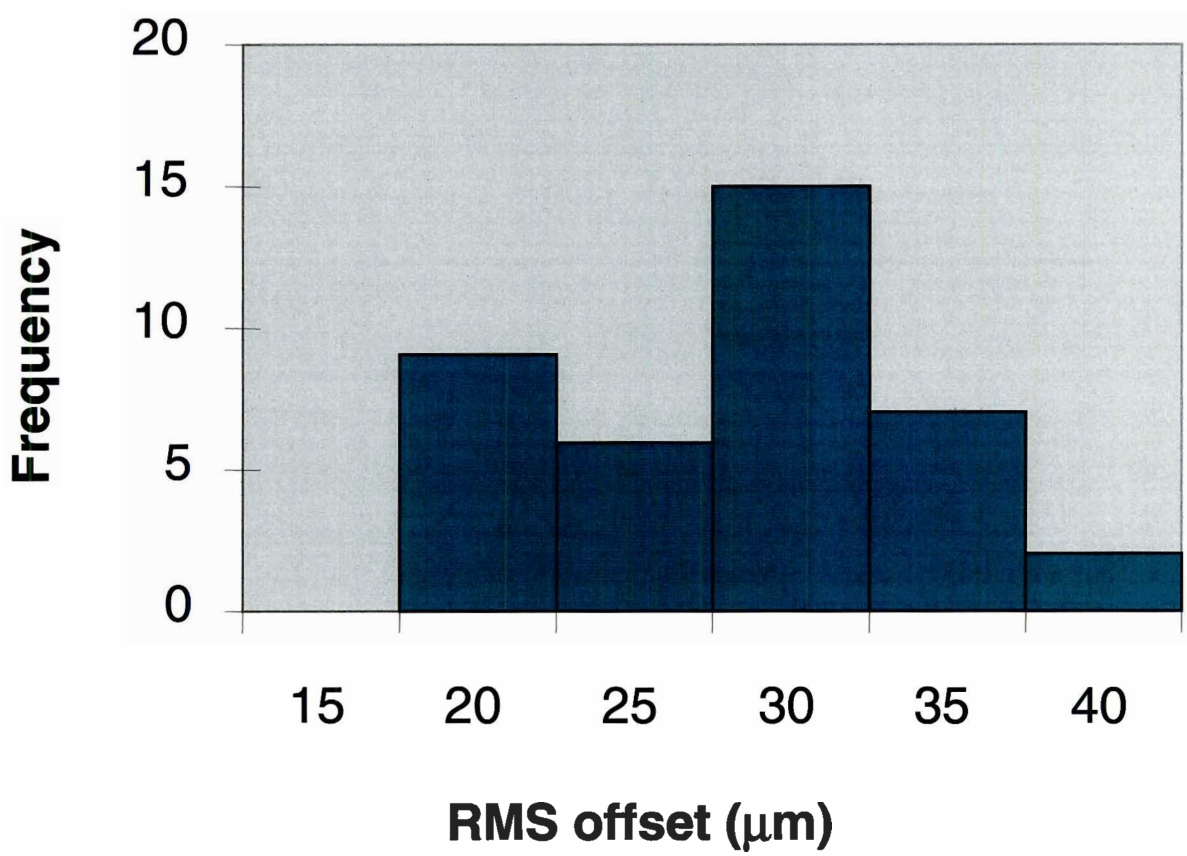


(Figure 5)

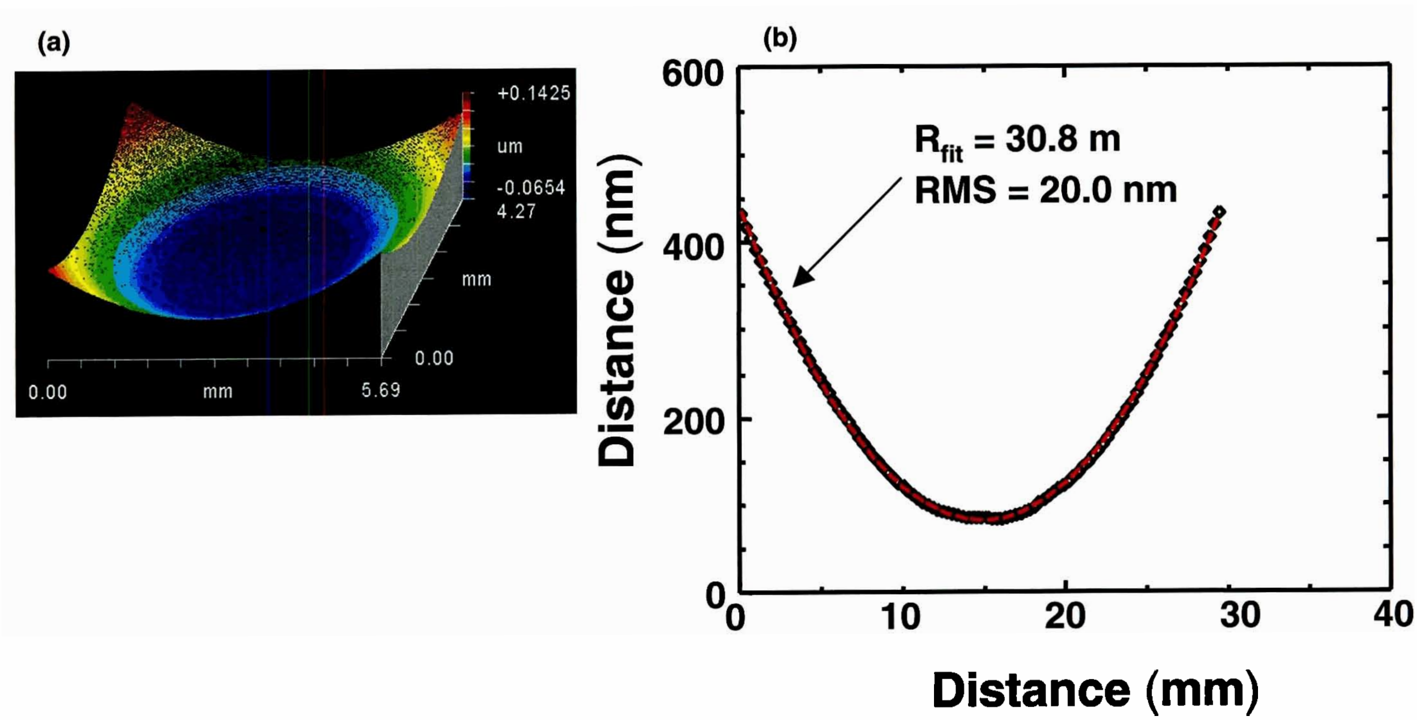


ZEMAX simulations
20
15
10
5
0
Resolution (μm)
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
Distance (mm)
R_ideal
R_-5%
R_+5%

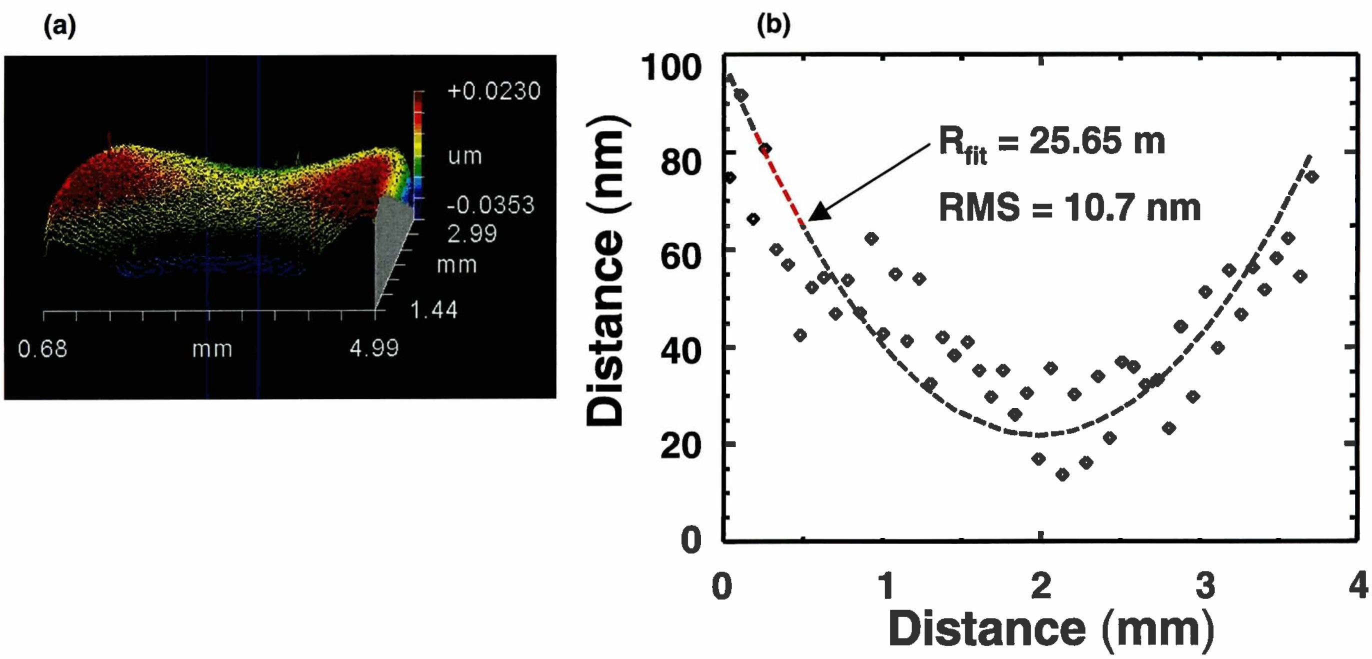
(Figure 6)



(Figure 7)


(a)
+0.1425
um
-0.0654
4.27
mm
0.00
0.00
mm
5.69
(b)
600
400
200
0
0
10
20
30
40
Distance (nm)
Distance (mm)
R_{fit} = 30.8 m
RMS = 20.0 nm

(Figure 8)


(a)
+0.0230
um
-0.0353
2.99
mm
1.44
0.68
mm
4.99
(b)
R_{fit} = 25.65 m
RMS = 10.7 nm
Distance (nm)
Distance (mm)
0
20
40
60
80
100
0
1
2
3
4

(Table 1)

Deviation of Measured Coordinates from Ideal Coordinates (microns)					
Serial #	Deviation from A	Deviation from B	Deviation from C	Deviation from D	Root Mean Square
C06	22	21	22	23	21.8
C17	24	10	26	26	22.3
C10	20	17	30	20	22.4
A05	18	23	31	18	23.0
C01	14	23	36	12	23.2
C15	22	23	30	19	24.0
C18	31	20	24	20	24.2
B08	12	18	30	32	24.4
C03	25	14	35	20	24.8
B12	17	20	39	22	25.9
B17	28	16	30	29	26.4
C08	24	14	41	21	26.8
B04	22	24	36	30	28.3
C02	32	20	35	25	28.5
A11	30	24	34	26	28.7
B11	26	20	42	28	30.1
C04	19	30	41	25	30.1
B10	31	17	41	28	30.1
C05	36	13	35	35	31.3
B07	25	29	41	28	31.5
C09	34	22	35	35	31.7
C14	34	30	37	25	31.8
B06	36	16	41	30	32.2
C12	37	22	40	27	32.3
B13	29	19	41	35	32.3
B14	33	16	42	34	32.7
A16	32	27	35	37	33.1
A06	30	31	46	24	33.6
C13	17	33	55	18	34.2
A12	37	22	45	30	34.6
C11	23	49	39	24	35.3
B01	43	15	38	40	35.5
B15	38	28	47	36	38.0
B05	26	34	56	30	38.2
B03	44	26	45	36	38.5
A07	34	33	55	30	39.1
B16	44	18	55	33	39.8
B09	39	24	59	36	41.7
B18	36	15	67	38	43.0