GEMINI
8-M Telescopes
Project

TN-O-G0004

Optical Surface Figure Evaluation of an 8-m Primary Mirror

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ABSTRACT

A parametric study was performed to investigate the effects of the surface RMS error with respect to the spacing between data sampling points. As a reference surface figure for all the optical analyses, a 20 NM RMS surface error was used which was specified for the Gemini 8-m primary mirror. Structural function was utilized in order to quantify the optical surface distortion of a high order spatial frequency. The objective of this study is to specify the optical surface quality by the surface RMS error as a function of separation distance as well as by the overall surface RMS over the aperture.

INTRODUCTION

The surface figure of the Gemini primary mirrors should meet a maximum RMS surface error of 20 NM. The specified RMS error describes the overall optical surface quality for a 'mathematical' surface. It does not take into account the fact that the RMS may be affected by either the severity of surface distortion or the number of data sampling points over the aperture.

The optical surface figure needs to be sufficiently smooth so that high order frequency errors such as localized print-through bumps and cyclic ripples are minimized. Due to these high spatial errors, the optical surface figure may degrade the image quality and establish the intensity of the satellite images. There are occasions when the image quality is not desirable, but the surface figure meets the overall surface RMS error requirement.

In order to avoid the undesirable circumstances, an optical surface description using sub-aperture interferometry is often used. The description specifies the optical quality in terms of the surface P-V and/or RMS errors of the sub-apertures at several distinct locations over the entire mirror. A mathematical expression can be utilized more systematically for the surface errors as a function of data spacings. Structural function for atmospherical turbulence is a description to demonstrate astronomical applications.

STRUCTURAL FUNCTION

Structural function was introduced initially as a description of atmospheric turbulence. It calculates the mean-squared velocity differences between two points in space separated by a displacement vector. The structural function defined by the atmospheric velocity between two points separated by a displacement vector s is given as:

$$D_v(s) = < [v(r + s) - v(r)]^2 > \qquad (1)$$

where v(r+s) is the velocity at a point displaced by s from the reference point location r. This shows an entity described by a variance of velocity at a certain point in space. The entity can be analogous to the optical surface variance. Structural function for the optical surface variance as a function of the distance of separation becomes:

$$D_\delta(s) = < [\delta(r + s) - \delta(r)]^2 > \qquad (2)$$

where $\delta(r + s)$ is the surface height at a point displaced by s from the reference point r. $D_\delta(s)$ represents the square sum of the surface height differences between two points separated by a distance s. Operating Equation (2) for every point r over the aperture yields the surface RMS with respect to separation s.

A program was developed to evaluate the optical surface errors as a function of separation at every 12.87 (90/7) degree angular increment. The program imports an interferometric (INT) file and exports a MACRO file for CODE-V to plot a structural function.

OPTICAL SURFACE EVALUATION

A number of sampling optical surfaces were synthesized to quantify their optical surface errors. Each of these is a combined surface using the following three baseline surfaces: (1) CASE I - the residual surface figure of a meniscus mirror corrected by 140 axial actuators in ZENITH; (2) CASE 2 - the residual surface figure of a honeycomb structured mirror corrected by 141 axial actuators in ZENITH; and (3) CASE 3 - an optical surface representing a characteristic Zernike surface (36 characteristic Zernike surfaces were generated).

The baseline optical surface figures are plotted in **Figure 1.** Figure l(a) shows an optical surface map for CASE 1, and Figure l(b) illustrates CASE 2. Characteristic Zernike surfaces for Astigmatism and fifth order Coma are shown in Figures I (c) and (d), respectively.

A linear combination of these baseline figures, with a set of proper scaling factors, was made to generate sample optical figures. The combination scheme used in this study was:

$$\delta_c = K[A\delta_l + B\delta_2 + C\delta_3] \qquad (3)$$

where δ_c is the combined surface figure with scaling parameters of A, B, and C for CASE 1, 2, and 3, respectively. K is a global scale factor. These scaling parameters were introduced to force the surface figure to be a normalized overall RMS error of 20 NM for each sample surface.

Typical combined sample surfaces are shown in **Figure 2,** and their corresponding parameters are listed in **Table 1.** Model x04-2 in Figure 2(a) has a strong influence of Astigmatism, whereas model x04 **-** 3 in Figure 2(b) has a dominant print-through effect. Model x11-2 (Figure 2(c)), on the other hand, shows the effect mostly from the fifth order Coma. Figure 2(d) shows model zerxp, which is a real surface figure generated during polishing process at NOAO. The surface was translated into an INT file in terms of several Zernike coefficients.

Overall RMS Error Description

As previously mentioned, the mathematical description of the overall surface RMS does not fully account for either severity of surface distortion or the grid sampling points. This may not be sufficient to specify the optical surface figure, because in practice the surface error will be quantified by a data sampling points accomplished by either real measurements or by numerical manipulation.

Two sample surfaces were selected to demonstrate the effect of the RMS errors due to the grid size variation. A simple, smooth surface defined as Zernike 4th aberration, Astigmatism, was studied as a first model (see Figure l(c)). RMS errors of the Zernike surface for a variety of the grid sizes ranging from 10 to 500 are listed in **Table 2**. A normalized RMS of 20 NM was applied for all cases. Distribution of the RMS variations is fairly uniform; therefore, the overall RMS specification is applicable for this model.

The second sample model studied was surface CASE 1 (Figure l(a)), which has higher order spatial aberrations due to the support print-through bumps. In this case, a relative surface displacement at certain point may be significantly different from that evaluated from a point in its neighbor. RMS surface errors of the surface with respect to the grid sizes were evaluated and listed in **Table 3.** A maximum of 30 percent variation in the overall RMS was observed. This implies that the overall RMS is not sufficient to specify the surface quality, especially for surfaces with a high irregularity. For the cases with a large grid size (smaller grid spacing), however, the RMS converges to its reference value. Hence, in addition to the overall RMS a systematic description is required to specify a generic optical surface quality.

Structural Function Description

Structural function defined by Equation 2 evaluates RMS errors as a function of separation distance between data points. In order to faithfully describe the optical surface, a proper size of the data points over the aperture should be determined in advance. A number of structural functions for several optical surfaces were calculated with a variety of the grid sizes. A typical set of plots for the structural function of CASE I is shown in **Figure 3.** It was found that the shapes of the function become reasonably consistent when the size exceeds values greater than 64. A uniform grid size of 128 by 128 over the aperture was adopted for the evaluation of structural functions.

In order to demonstrate the performance of the structural function, the combined surface models were used in Figure 2. For illustrative purposes, the structural functions were plotted only for a maximum separation distance of 2000 mm. For model x04-2 (Figure 4(a) - same as Figure 2(a)), the structural function was calculated and plotted in Figure 4(b). It represents the surface RMS with respect to the separation distance. For example, the structural function shows a surface RMS of 3.6 NM at a separation distance of 125 mm. Plots of the point spread function and the encircled energy distribution for the model are also shown in Figures 4(c) and 4(d), respectively.

A similar investigation was conducted for model x04-3 and model x11-2, and their structural functions along with the optical evaluation plots are shown in **Figures 5 and 6**. Additionally, for model zerxp the structural function was calculated, and the plots for encircled energy and point spread function were made (shown in **Figure 7**). The results of the optical surface evaluation for the combined surfaces with the reference RMS of 20 NM at a wavelength of 632.8 NM are summarized in **Table 4**. The sizes of the diameter of the encircled energy concentration as well as the structural function are listed. Current specifications of the Gemini primary mirrors are as follows: (1) Diameter of encircled energy should be less than 0.0217 mm for 50% concentration and 0.03 1 0 mm for 80%, and (2) RMS surface error should be 3 NM for a separation distance of 20 mm and 5 NM for a separation of 40 mm.

SUMMARY AND CONCLUSIONS

Through performing a parametric study on the evaluations of the optical surface distortion, the following conclusions were drawn:

(1) A program was developed to evaluate the optical surface RMS errors as a function of separation at every 12.87 (90/7) degree angular increment (structural function).

(2) The overall RMS is an adequate index for a smooth surface, but it is not sufficient for a surface with higher spatial aberrations. (see Tables 2 and 3) .

(3) A uniform gird size of 128 by 128 is sufficient to demonstrate both the overall RMS surface errors and structural function evaluation (Figure 3).

(4) The slope of the structural function represents the irregularity of the surface; therefore, the stiffer it is, the higher the irregularity of the surface.

(5) The optical performance evaluation for the models slightly exceeded the current primary mirror specifications.

(6) A direct correlation between the structural function and the encircled energy does not exist in surface quality specification (see Table 4).

(7) A detailed study should be performed to faithfully describe the optical surface quality to account for the specifications of encircled energy and structural function.

REFERENCES

1. Catalan, G., et al., "Theoretical Study of the Image Quality of an 8M Primary Mirror Having Print-Through Undulations Over the Mirror Surface", Gemini report RPT-O-G0001, 1991.

2. "CODE VI', Optical Research Associates, Pasadena, California, 1991.

3. Tyson, R. K., "Principles of Adaptive Optics", Academic Press Inc., 1991.

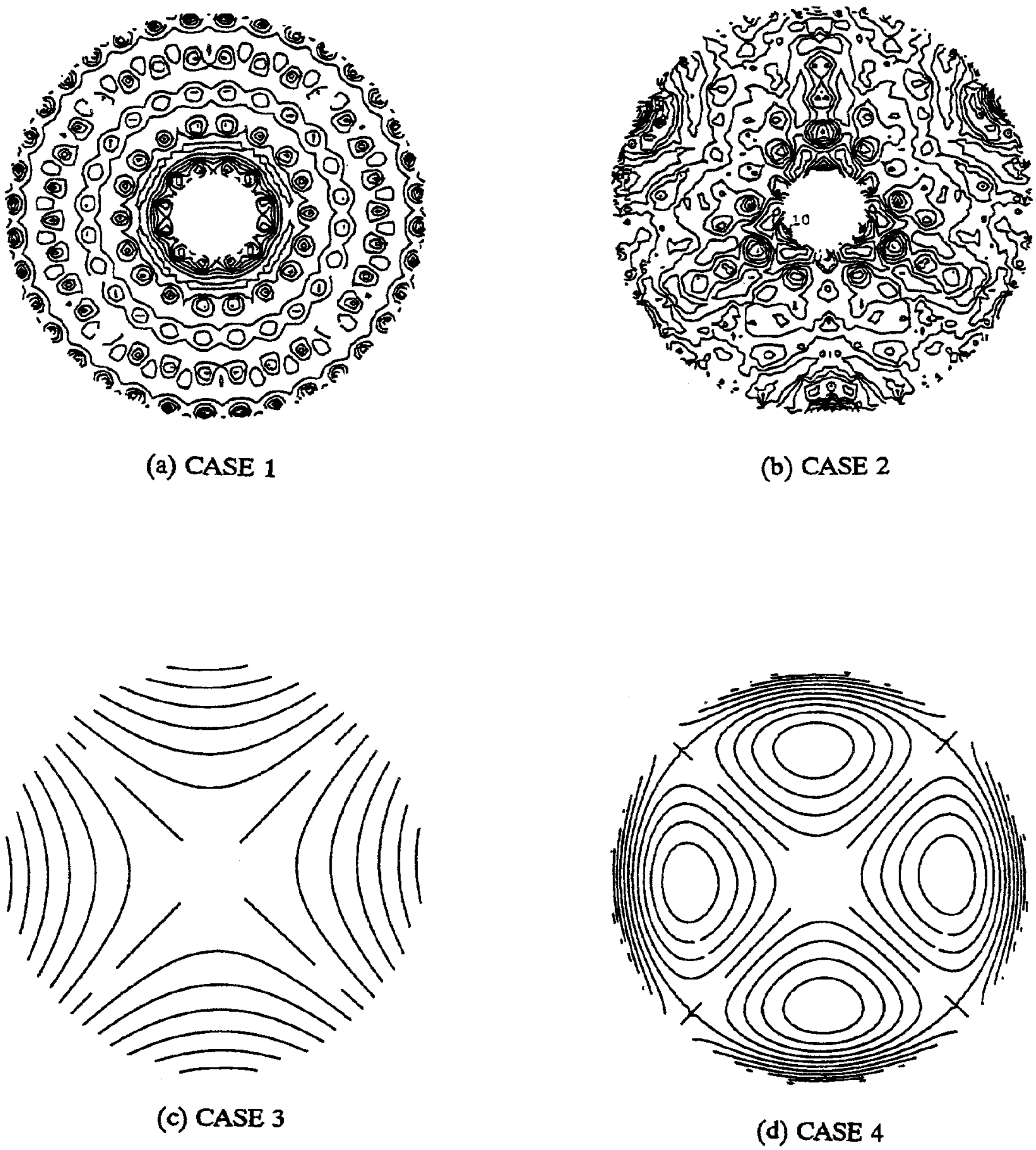
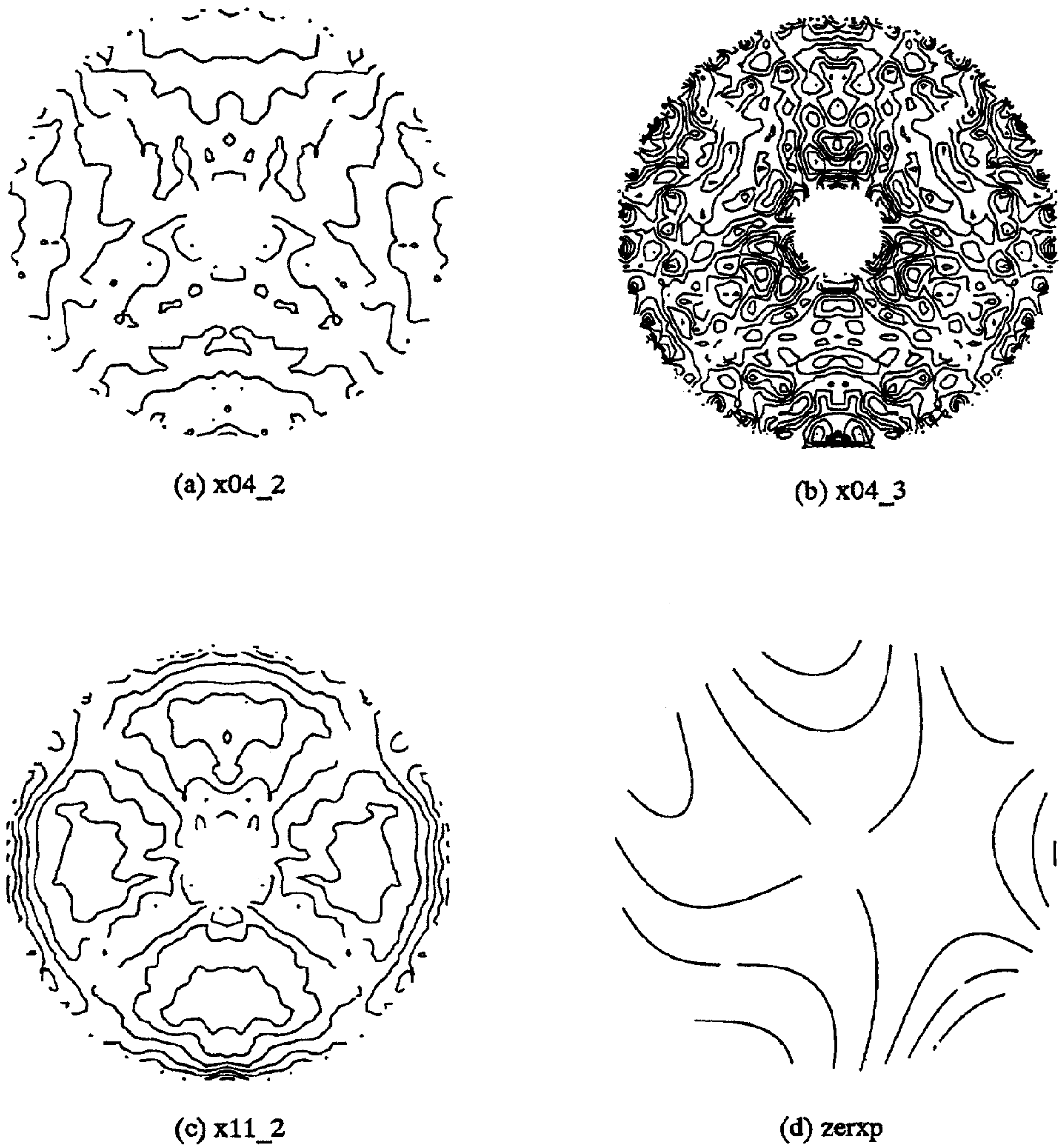


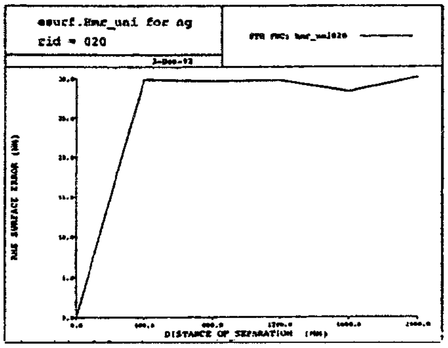
Figure 1. Baseline optical surface figures.



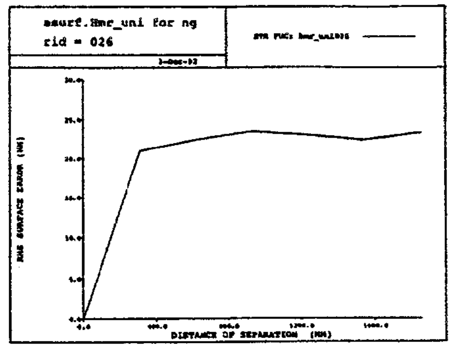
(a) x04_2 (b) x04_3

(c) x11_2 (d) zerxp

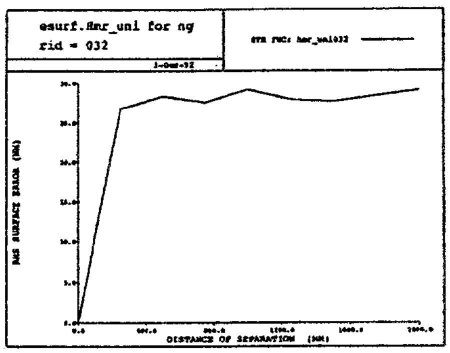
Figure 2. Combined optical surface figures.



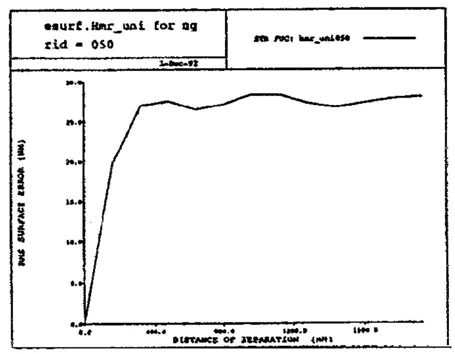
(a) ngrid=20



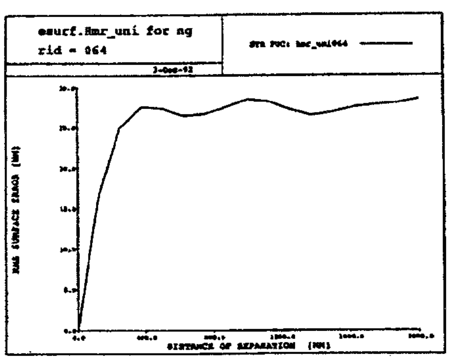
(b) ngrid=26



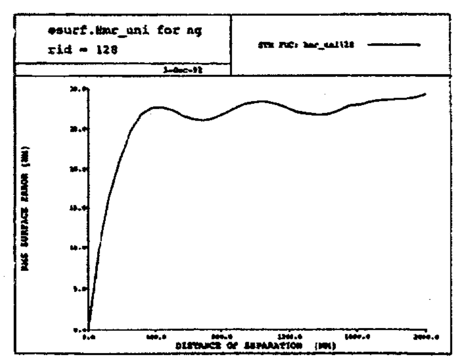
(c) ngrid=32



(d) ngrid=50

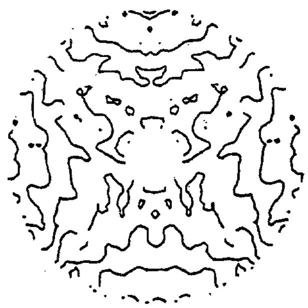


(e) ngrid=64

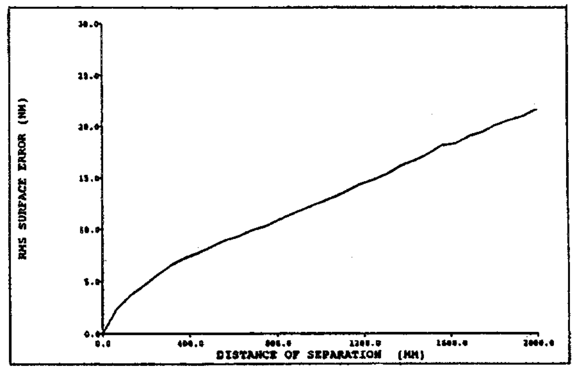


(f) ngrid=128

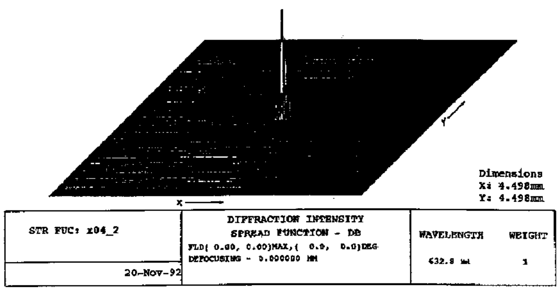
Figure 3. Structural functions of CASE 1 for various grid sizes (ngrid).



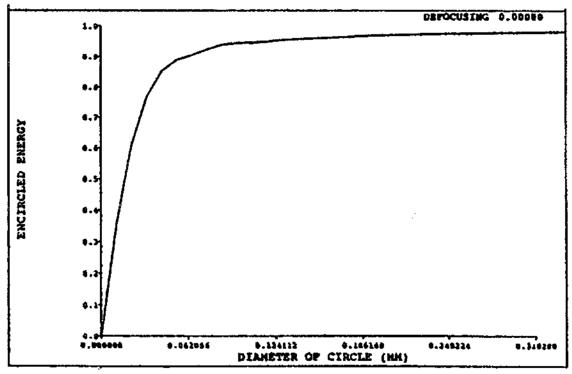
(a) Surface figure



(b) Structural function



(c) Point spread function



(d) Encircled energy concentration

Figure 4. Evaluation of surface figure for model x04_2.

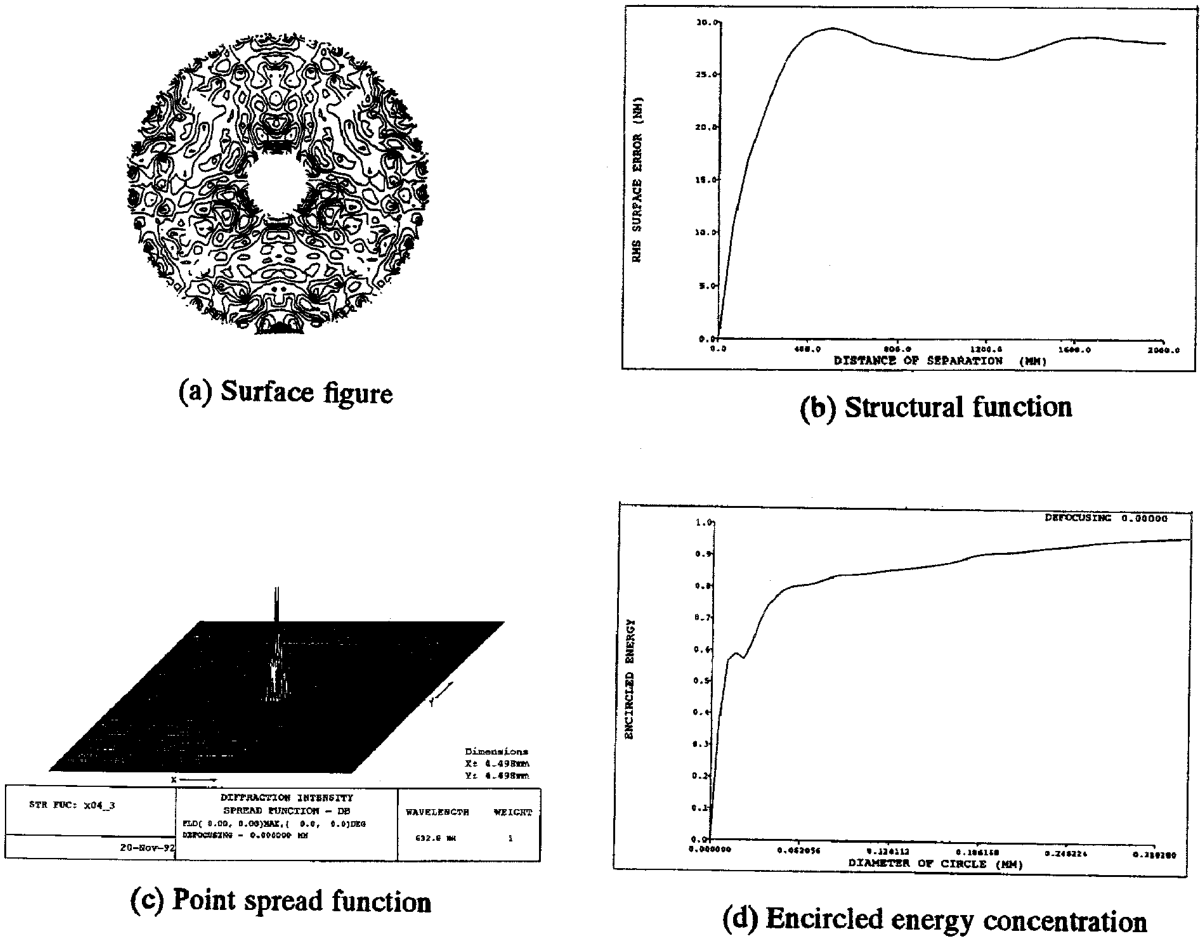
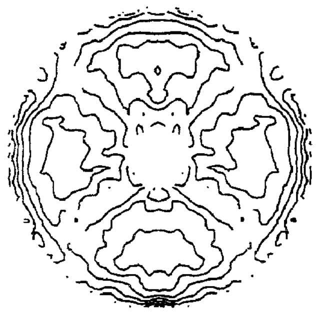
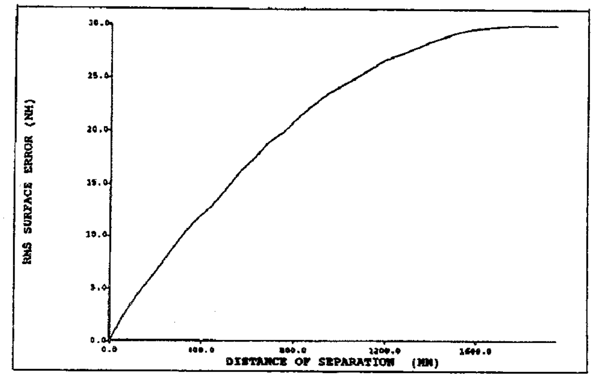


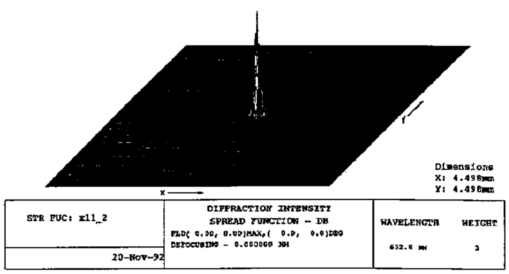
Figure 5. Evaluation of surface figure for model x04_3.



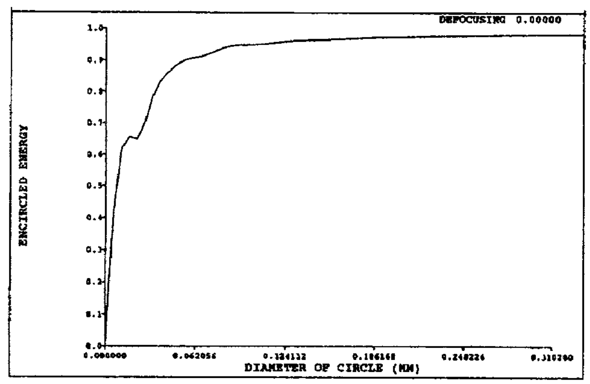
(a) Surface figure



(b) Structural function

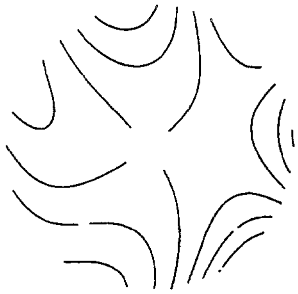


(c) Point spread function

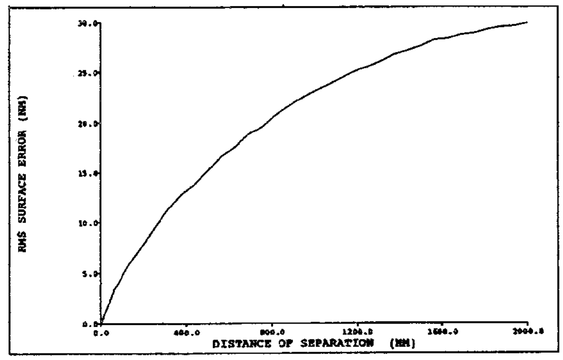


(d) Encircled energy concentration

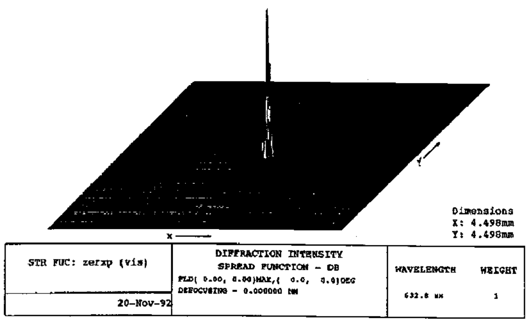
Figure 6. Evaluation of surface figure for model x11_2.



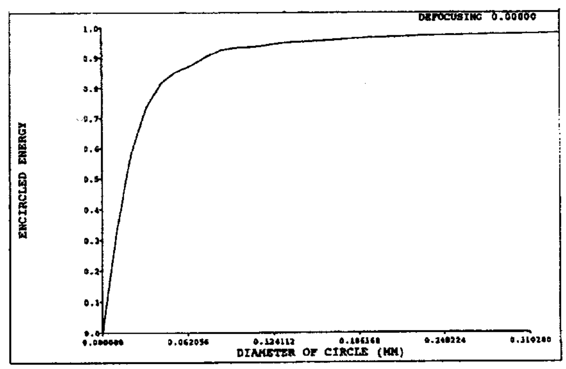
(a) Surface figure



(b) Structural function



(c) Point spread function



(d) Encircled energy concentration

Figure 7. Evaluation of surface figure for model zerxp.

Table 1. Scaling parameters for combined surfaces.

	(scaling parameters)			
	A	B	C	K
model xO4-2	0.50	0.50	0.10	0.88
model xO4-3	3.00	2.00	0.02	1.00
model xll_2	0.50	0.50	0.11	1.00
model zerxp	--	--	--	--

Table 2. Surface RMS surface errors for various grid sizes (CASE 3)
(reference surface RMS = 20 NM)

	(size of uniform grid: n by n)								
	10	16	26	32	50	64	128	256	500
RMS	20.0	20.2	20.2	20.2	20.1	20.0	20.0	20.0	20.0

Table 3. Surface RMS surface errors for various grid sizes (CASE 1)
(reference surface RMS = 20 NM)

	(size of uniform grid: n by n)								
	10	16	26	32	50	64	128	256	500
RMS	15.9	21.8	16.1	20.8	19.8	19.9	20.0	20.0	20.0

Table 4. Optical quality for combined surfaces at wavelength=633 NM.

model x04_2

PCT (%)	DIAMETER OF CIRCLE (MM)	SEPARATION (MM)	STRUCTURAL FUNCTION (RMS)
50	0.016629	20	0.80
85	0.042855	40	1.60
90	0.062200		
95	0.118033		

model x04_3

PCT (%)	DIAMETER OF CIRCLE (MM)	SEPARATION (MM)	STRUCTURAL FUNCTION (RMS)
50	0.008688	20	3.40
85	0.115945	40	6.90
90	0.179475		
95	0.272757		

model xll_2

PCT (%)	DIAMETER OF CIRCLE (MI4)	SEPARATION (MM)	STRUCTURAL FUNCTION (RMS)
50	0.017673	20	1.10
85	0.055580	40	2.20
90	0.073220		
95	0.133259		

model zerxp

PCT (%)	DIAMETER OF CIRCLE (MM)	SEPARATION (MM)	STRUCTURAL FUNCTION (RMS)
50	0.007693	20	0.70
85	0.041239	40	1.40
90	0.055795		
95	0.107819		