FINAL TECHNICAL REPORT

"New High-Resolution Optic for Soft-X-Ray Imaging"

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CREOL/University of Central Florida

Account # 65-03-504

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE

3. REPORT TYPE AND DATES COVERED
FINAL REPORT 1 Jul 93 - 30 Jun 96

4. TITLE AND SUBTITLE
(AASERT-92) Development of a New High-Resolution Optic for Soft X-Ray Imaging

5. FUNDING NUMBERS
61103D
3484/TS

6. AUTHOR(S)
Professor Silfvast

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
University of Central Florida
Orlando, Florida 32816-0150

AFOSR-TR-96
0545

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
AFOSR/NE
110 Duncan Avenue Suite B115
Bolling AFB DC 20332-8080

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
F49620-93-1-0397

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
APPROVED FOR PUBLIC RELEASE: DISTRIBUTION UNLIMITED

12b. DISTRIBUTION CODE

DTIC QUALITY INSPECTED

13. ABSTRACT *(Maximum 200 words)*

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14. SU … **PAGES**

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	

Design of a partial Schwarzschild objective for soft x-ray reflection imaging microscopy

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Abstract

The design of a partial Schwarzschild objective lens is given for a soft x-ray reflection imaging microscope. The system has a magnification of 200x with an object spatial resolution of less than 100nm, and a depth of focus of the system of ±0.5μm. The parameters of the objective lens consisted of two spherical mirrors are evaluated and optimized at a wavelength of 135Å to obtain diffraction-limited imaging over a 25μm field size. The feasibility of using aspheric mirrors to improve the image quality is investigated. The field of view could reach to 40μm if the spherical optic is replaced with aspheric optic. Diffractive optics is also discussed briefly due to the fabrication problems of aspheric mirrors. Either of the optic in this paper will be coated with Mo:Si multilayer reflecting surfaces to obtain high optical efficiency.

I. INTRODUCTION

In the field of microscopy, attempts are continuously made to develop new methods and techniques in order to improve the quality of images (in term of resolution and contrast), and to extract more information from smaller features. Conventional microscopes, including optical microscopes and electron microscopes, have been developed to reach that goal. However, there are some limitations associated with these microscopes. For example, the amount of detail (resolution) that has been studied in the conventional optical microscope is limited by the wavelength of light and aberrations introduced in the off-axis image field. Electron microscopes, though they have improved resolution, have the disadvantages of a fairly small depth of focus (since electrons can not penetrate thick object wall) and long sample preparation time. Therefore, more quantitative information about mass distribution in the specimen is difficult to obtain.

X-ray microscopy is attempting to solve these problems. It is advancing as a prospective technology due to the recent improvement of x-ray optics and high brightness x-ray sources[1-4]. An X-ray microscope would offer an advantage over a conventional microscope by providing both ultra-high resolution and good depth of focus combined with an extremely short exposure time, which is approximately the laser pulse duration. The development of a soft-x-ray microscope can have important applications in biological and material sciences, ranging from observations of various types of organic specimens including living cells, to the high-resolution examination and inspection of surfaces including those associated with microchips and other materials having fine-featured patterns.

Our objectives are to eventually develop a soft-x-ray reflection imaging microscope using a compact soft x-ray source and a normal incidence multilayer-coated Schwarzschild optic, and to use the microscope to obtain ultra-high resolution images at high magnification with good fidelity and high sensitivity. We have already studied a microscope with a 15x Schwarzschild objective working in the region of 50-60nm wavelength using illumination by transmission[5]. The system is essentially free of geometrical aberrations and the ultimate resolution (W) is limited by diffraction effects which are sensitive to wavelength (λ) and numerical aperture according to the relationship $W \sim 0.5\ \lambda / NA$. Practically, the system has been measured with a resolution of a few microns by visible light, and less than one micron using EUV light illumination. Here the resolution is limited by both the design of the 15x Schwarzschild and the wavelength of the light source used for imaging. Resolution can be improved by extending the wavelength from EUV light (50-60nm) to shorter wavelengths. Optimum wavelength will most likely be determined by the illuminating source and reflectivity of the optical system. Molybdenum/silicon multilayer reflective coatings for the mirrors have been demonstrated to yield up to ~70% reflectance at an illumination wavelength of 13-14 nm. A lithium discharge source operating at 13.5nm is being developed that is sufficiently intense for applications of microscopy and lithography[6]. Therefore a suitable combination of the optic and the source for the proposed imaging arrangements is suggested. We also expect a large depth of focus ($DOF \sim 0.5\ \lambda/(NA)^2$) to obtain good image contrast of samples by reducing the numerical aperture of the microscope objective. Therefore there will be a compromise between the resolution and the depth of focus to choose an appropriate numerical aperture..

In this paper, we present a 200x magnification partial Schwarzschild microscope objective working at the wavelength of 13.5nm in order to obtain $\sim 0.05\mu m$ resolution and $\pm\ 0.5\mu m$ depth of field. The magnification was chosen to be able to match the pixel size in the image plane to that of an existing array detector. The definition of a Schwarzschild microscope objective is summarized. We outline the design considerations and the characteristic parameters of the objective. An optical performance analysis of the microscope is also presented.

II. SCHWARZSCHILD OBJECTIVE DESIGN

A single near normal incidence spherical mirror is the simplest focusing or imaging reflective optic. However, for serving as a microscope objective, it cannot obtain good image qualities for specific field size and resolution required nowadays. The use of more than one mirror surface provides larger field size, and even more it can provide an aberration compensation between each separate element. The Schwarzschild objective is a design that has been used for years in ultraviolet and infrared microscopy. After successes in developing multilayer reflective coatings, it was also considered for normal incidence EUV and x-ray microscopy and lithography[7-10] analogous to the well known systems used in the visible region. The Schwarzschild objective configuration is a normal incidence reflecting objective, consisting of two spherical normal incidence mirrors with centers of curvature at the aperture stop (for a finite magnification of the objective, there will be a small deviation from the aperture). The system can be made free of third-order spherical aberration, coma, and astigmatism, and gives more magnification capability, larger field of view and better spatial resolution than a single mirror. A VUV multilayer coated Schwarzschild system was tested in 1980[11] and the first specially designed XUV microscope was tested using bending magnet radiation at Brookhaven National Laboratory[12].

The Schwarzschild objective can also be a powerful microscope objective in the soft-x-ray region when used in conjunction with a high intensity x-ray source[4,7-8]. Compared to an x-ray zone plate, it offers higher numerical aperture and larger field size, however it is presently restricted to wavelengths larger than 44Å[13], the up limit of the "water window".

For a 200x magnification partial Schwarzschild microscope objective working at the wavelength of 13.5nm, we need a numerical aperture of 0.1 in order to obtain ~0.05μm resolution and ± 0.5μm depth of field. The conventional full Schwarzschild has the disadvantages such that the resolution is decreased due to the central obscuration from the secondary mirror of the full objective, and thus the optical performance is reduced according to this criterion;

Compared to the full Schwarzschild, a partial Schwarzschild uses only a portion of the two spherical mirrors which is less than half the diameter of those for the full Schwarzschild. It will also provide the possibility of using a massive and thermally stable mounting arrangement for the mirrors that would provide a long-term stability and eliminate the need of a rather delicate spider mount of the mirrors.

The design we present here is an off-axis partial Schwarzschild objective for soft x-ray reflection imaging microscopy. This optic conceptually involves using only the 0.1NA portion of the full 0.4NA Schwarzschild objective. It will have a magnification of 200x. The magnification was chosen such that the optic could magnify 0.05μm features to an array detector having a pixel size of 10 microns and also have an acceptable optical working distance. The optic uses spherical mirrors, however we also include aspheric mirror designs in order to optimize the diffraction-limited imaging. The optic in both cases will be coated with Mo:Si multilayer reflecting surfaces to obtain high optical efficiency.

III. OBJECTIVE DESIGN PARAMETERS

As shown in the figure 1, the full objective has two concentric spherical mirrors, a large primary concave mirror and a small secondary convex mirror, with the radius of curvature of R_1 and R_2, respectively. d_o is the distance from the object to the aperture stop, which is assumed at the common center of both mirrors. If an objective has a magnification of m, we can find out these parameters with the following equations[8]:

$$R_2 / R_1 = 1.5 - R_2 / d_o + \sqrt{1.25 - R_2 / d_o} \quad (1)$$

$$m = -R_1 R_2 / (2 R_1 d_o - R_1 R_2 - 2 R_2 d_o) \quad (2)$$

To determine the diameter of the primary mirror D_1, we have

$$NA = D_1 / 2\sqrt{(D_1/2)^2 + (d_o + R_1 - d')^2} \quad (3)$$

$$d' = (D_1/2)^2 / (R_1 + \sqrt{R_1^2 - (D_1/2)^2}) \quad (4)$$

where NA is the numerical aperture of the full objective system.

If we choose m =200, and NA=0.40, the radii are computed as R_1 =8.078 mm and R_2 = 3.113 mm. The primary mirror has the diameter of D_1 =8.26 mm, and d_o =2.52 mm. The aperture stop is located on the center of the radius of curvature with a diameter of 2 mm to obtain a full numerical aperture of 0.40.

The partial Schwarzschild uses less than half of the whole objective system in order to increase the depth of focus. The aperture stop is located on the center of the radius of curvature with the diameter of 0.64 mm, which is shifted 0.78mm off the axis of the system, to obtain a partial numerical aperture of 0.1. The partial objective configuration is shown in Figure 2. Table 1 lists the parameters of this objective design.

Table 1. Design Parameters of *Soft X-ray* Schwarzschild Imaging Microscope Objective

		Computation	**Optimization**
D_1	(diameter of primary mirror)	8.26mm	8.26mm
D_2	(diameter of secondary mirror)	2.00mm	2.00mm
R_1	(radius of curvature of primary mirror)	8.078mm	8.0685mm
R_2	(radius of curvature of secondary mirror)	3.113mm	3.1101mm
d	(separation of concentric mirrors)	4.9650mm	4.9588mm
D_{as}	(diameter of aperture stop)	0.64mm	0.64mm
d_o	(object distance from aperture stop)	2.520mm	2.5325mm
d_i	(image distance from aperture stop)	504.00mm	503.9967mm
h	(hole diameter in primary mirror)	3.10mm	3.10mm

IV. DESIGN EVOLUTION AND PERFORMANCE ANALYSIS

i. Spherical optic

Based on the computation described above, we ray traced and optimized the design by choosing the computed parameters in Table 1 as our starting points in order to obtain a large field diffraction-limited imaging. The optimization is computed over a field of view of 25μm for the 500 x 500 pixels array detector. The modified parameters are also listed in Table 1, noting there are some small differences resulting from the optimized computation. With this optimization, we obtained an RMS radius (on the object side) versus the 25μm field of view as shown in figure 3. We also plot the RMS sizes over a large field 50μm in figure 4, which shows the diffraction limited field size is less than 30μm. Also the figure gives us the feeling that the resolution will drop near quadratically when the field of view gets increased. In figures 3 and 4, we also include the resolution versus the field size using aspheric mirrors for comparison. We will discuss this in next section.

Since the objective presented here is in a very small structure, there might be mounting and aligning concerns associating with the relative position alignment of two mirrors and the mounting arrangement for the mirrors. Here we investigate the alignment by modulating the relative position of the two mirrors by tilting the mirrors around their surface center points, respectively. We have found that the tolerance of the mirror surface tilting is within 0.6 min of arc for both the primary mirror and the secondary mirror, for obtaining a near diffraction-limited image. Figure 5 shows the results of this analysis as a function of the field size. Over a 50μm field size, the on-axis image will be worse while the off-axis image gets better with either of the two mirrors tilted. The best field for this case is at around 30μm. When the two mirrors get tilted to the same orientations, for example, both primary tilting and secondary tilting are 0.6 min, the near on-axis image could hardly be diffraction limited. However, they could balance out each other when the two mirrors tilted to different directions. As seen in figure 5, for primary tilting 0.6 min and secondary tilting -0.6 min, the RMS image size could be as close as that of a perfectly fabricated system.

ii. Aspheric optic

According to the previous discussions, the image performance presented by the spherical surfaces is dominated by the third order aberrations (especially spherical, astigmatism, coma and distortion). In order to obtain diffraction-limited imaging and extend the exposure field size, we must investigate the use of non-spherical mirror surfaces.

Z-coordinate of the aspheric surface can be written as

$$Z = \frac{cr^2}{1+\sqrt{1-(1+k)c^2r^2}} + a_1 r + b_1 r^2 + a_2 r^3 + b_2 r^4 + a_3 r^5 + b_3 r^6 + \cdots$$

where c is the reciprocal of the radius of curvature, k conic constant. And a_1, a_2, a_3, ...are odd aspheric polynomial coefficients, b_1, b_2, b_3, ... even aspheric polynomial coefficients, and r the radial coordinate. Here we choose three different cases shown in Table 2 which gives the optimized conic constants and even aspheric polynomial coefficients. A perfectly fabricated objective will exhibit diffraction-limited performance for a wavelength of 135Å when used with the optimum object position on axis. Figure 6 shows the RMS radius versus the field size given by these three cases. Obviously, the near diffraction-limited field of view could be improved with the help of the polynomial aspheric surfaces.

Table 2. Three different cases for the aspheric mirror surfaces.

	Case 1	Case 2	Case 3
Primary mirror	$k_1 = 0.002$	$k_1 = -0.0028$ $b_1 = -1.502 \times 10^{-6}$ $b_2 = -4.553 \times 10^{-7}$ $b3 = -2.469 \times 10^{-8}$	$k_1 = -0.0025$ $b_1 = -4.09 \times 10^{-7}$ $b_2 = 8.6702 \times 10^{-7}$ $b_3 = 7.1012 \times 10^{-10}$
Secondary mirror	$k_2 = 0.0327$	$k_2 = 0.0003$	$k_2 = -0.023$ $b_1 = 1.0318 \times 10^{-6}$ $b_2 = 2.0 \times 10^{-4}$ $b_3 = -2.917 \times 10^{-5}$

Again, as in the spherical version mentioned above, we also like to see the alignment by the relative position of the two mirrors. The results of this analysis as a function of the field shown in figure 7 are shifted down by the order of wavelength compared to the spherical surfaces discussed in above section. Also when the two tilting angles of the mirrors are at primary 0.6 min and secondary -0.6 min, the RMS image size are approaching that of the perfectly fabricated aspheric surfaces.

The diffraction modulation transfer function (MTF) over a 25μm field size for this objective is shown in figure 8 at a numerical aperture of 0.1 and a wavelength of 135Å. In this figure, we also include the MTF of the spherical partial objective and a 0.1 NA full objective for comparison. According to the diffraction MTF for a practical system, the spatial resolution of the partial objective is at least ~20μm in the image plane and thus 0.1μm in the object plane. The full objective, as we mentioned earlier in this paper, will be considered inapplicable due to the center obscuration.

The requirement of nanometer-order figure accuracy[14] for the aspheric optic might be a strict fabrication problem of the aspheric surfaces. To avoid or reduce the stringent requirement for optics, another optic approach was emerged for last few years. Interest in the use of corrective diffractive optics has increased in optical system design, and new methods of calculation and manufacture can simplify and optimize their use. The basic idea is that a diffraction grating on a mirror (or lens) surface can be used to change the direction of reflected (or refracted) beams. For a Schwarzschild objective design, the fabrication tolerance of positioning a grating patterns on a spherical mirror is 1-10% of the grating spacing. Now the accuracy requirement is changed to 100 nm -10 μm (for a typical grating of 10 μm - 1 mm) from the 1 nm figure accuracy of aspheric surfaces. A zone-plate-like blazed grating structure will be optimum for larger diffraction efficiency. It will be coated on the spherical mirror substrate in order to simulate the same deviation between the aspheric surface and its reference sphere, and thus achieve the small aspheric correction.

V. CONCLUSIONS

We have designed a partial Schwarzschild objective for soft x-ray reflection imaging microscopy. The system has an effective working distance of about 50 centimeters and a effective focal length of 2.53mm, with a numerical aperture of 0.1 and a 200x magnification working at the wavelength of 13.5nm. The analysis shows it will have a 0.1μm object spatial resolution and ±0.5μm depth of field for the practical system. The field of view of the objective could reach to 40μm if the spherical optic is replaced with an aspheric optic. The parameters of the objective have been computed and optimized to obtain a diffraction-limited performance over a desired working field. We have also discussed the off-axis optical performance of the objective, and quantitative fabrication tolerances of the spherical and aspheric mirrors. The optic will be coated with Mo:Si multilayer reflecting surfaces to obtain high optical efficiency. This system will have the advantages of compact and convenient for laboratory applications.

VI. ACKNOWLEDGMENTS

Authors are gratefully acknowledge Dr. E. Spiller for his helpful discussion. This work was partially supported by the Air Force Office of Scientific research under Contract No. F49620-92-J-0405 .

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Figure Captions

Fig. 1. Schwarzschild objective configuration for soft x-ray reflection imaging microscopy.

Fig. 2. Partial Schwarzschild objective with numerical aperture of 0.1. The aperture stop with the diameter of 0.64 mm is shifted 0.78mm off axis, and located on the center of the radius curvature. (a) 3D objective; (b) objective on scale.

Fig. 3. Spatial object resolution versus the field of view for partial Schwarzschild objective over a 25μm field. Wavelength λ =13.5nm, Numerical Aperture $NA = 0.1$, magnification $m = 200$, and effective focal length $f = 2.53$mm.

Fig. 4. Spatial object resolution versus the field of view for partial Schwarzschild objective over a 50μm field. Two mirrors in the aspheric objective are conic plus even aspheric polynomial surfaces.

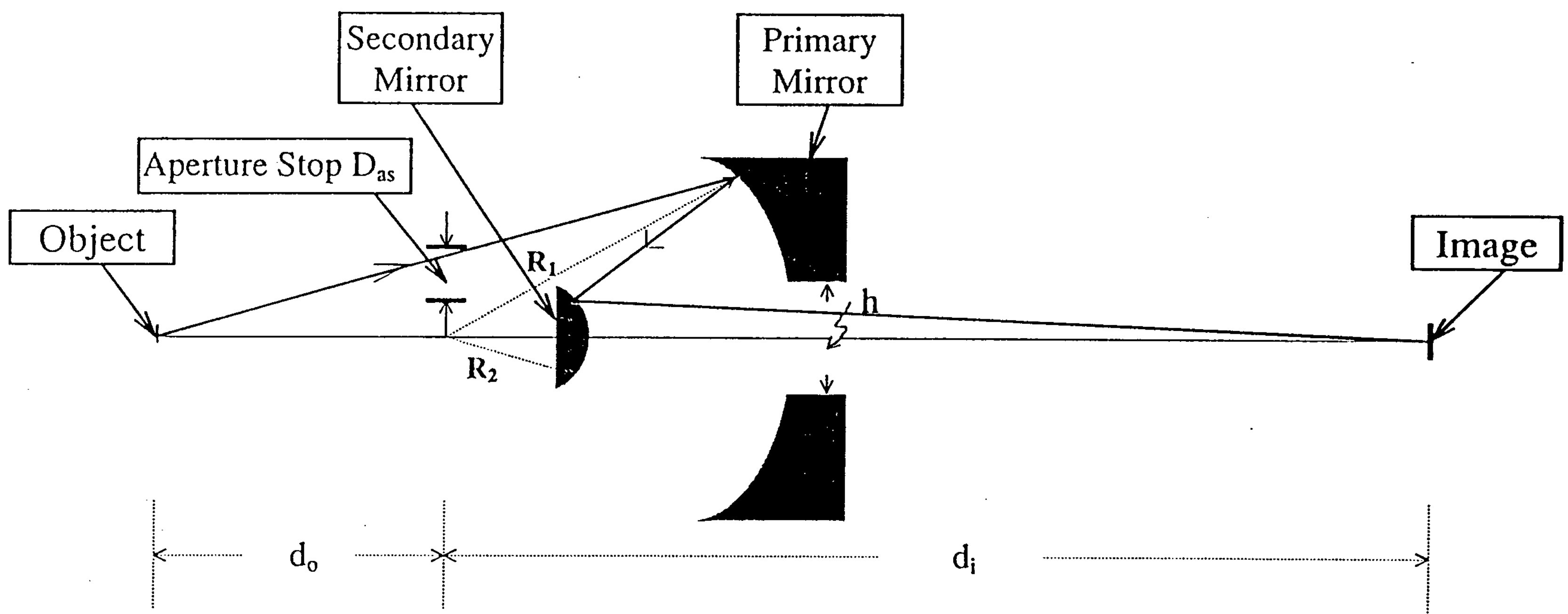
Fig. 5. Optical performance under conditions of (a) either the primary mirror and the secondary mirror tilting, (b) Both mirrors tilting to the same orientation, and (c) both mirrors tilting to different directions, compared with that without tilting for spherical optic.

Fig. 6. Comparison of the three aspheric cases over a 100μm field. First case is conic aspheric where $k_1 = 0.002$ and $k_2 = 0.0327$; Second case is primary mirror with conic plus even aspheric polynomial surface and secondary mirror only conic surface; Third case is both mirrors are conic plus even aspheric polynomial surface.

Fig. 7. Optical performance under conditions of (a) either the primary mirror and the secondary mirror tilting, (b) Both mirrors tilting to the same orientation, and (c) both mirrors tilting to different directions, compared with that without tilting for aspheric optic.

Fig. 8. Calculated diffraction MTF curves for the Schwarzschild objective over a 50μm field size for a full or partial objective. Wavelength λ =13.5nm, Numerical Aperture NA = 0.1, magnification $m = 200$, and effective focal length $f = 2.53$mm.

Figure 1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Primary Mirror
Aperture Stop D_{as}
Object
Image
R_1
R_2
h
d_o
d_i

Figure 2(a)

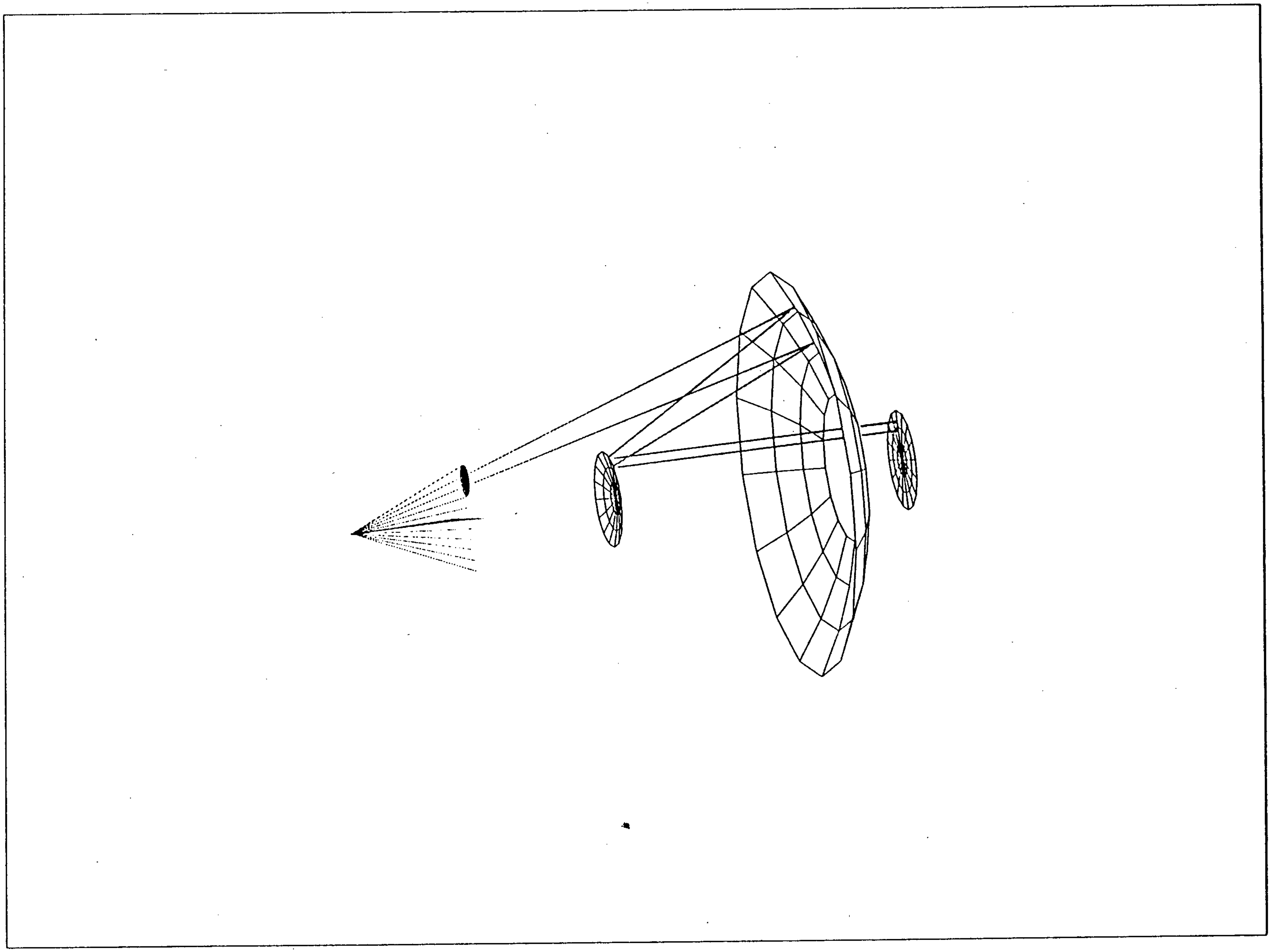


Figure 2

(a)

(b)

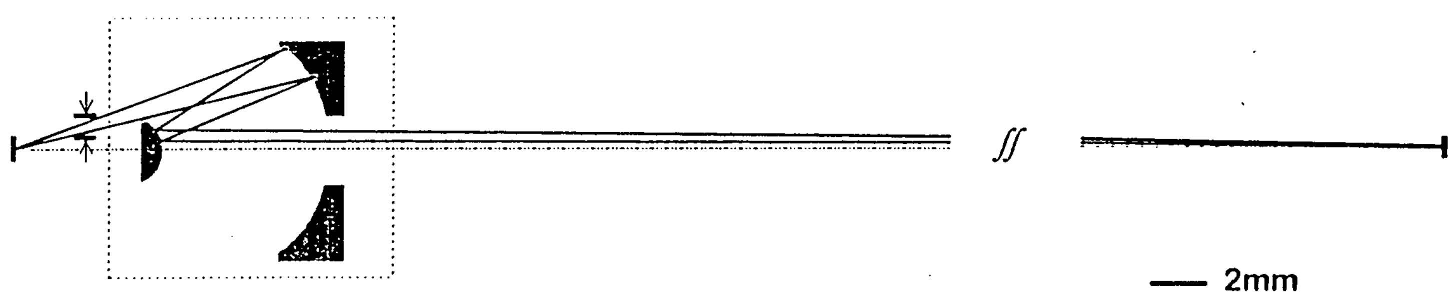


Fig.3 Partial Objective; NA=0.1

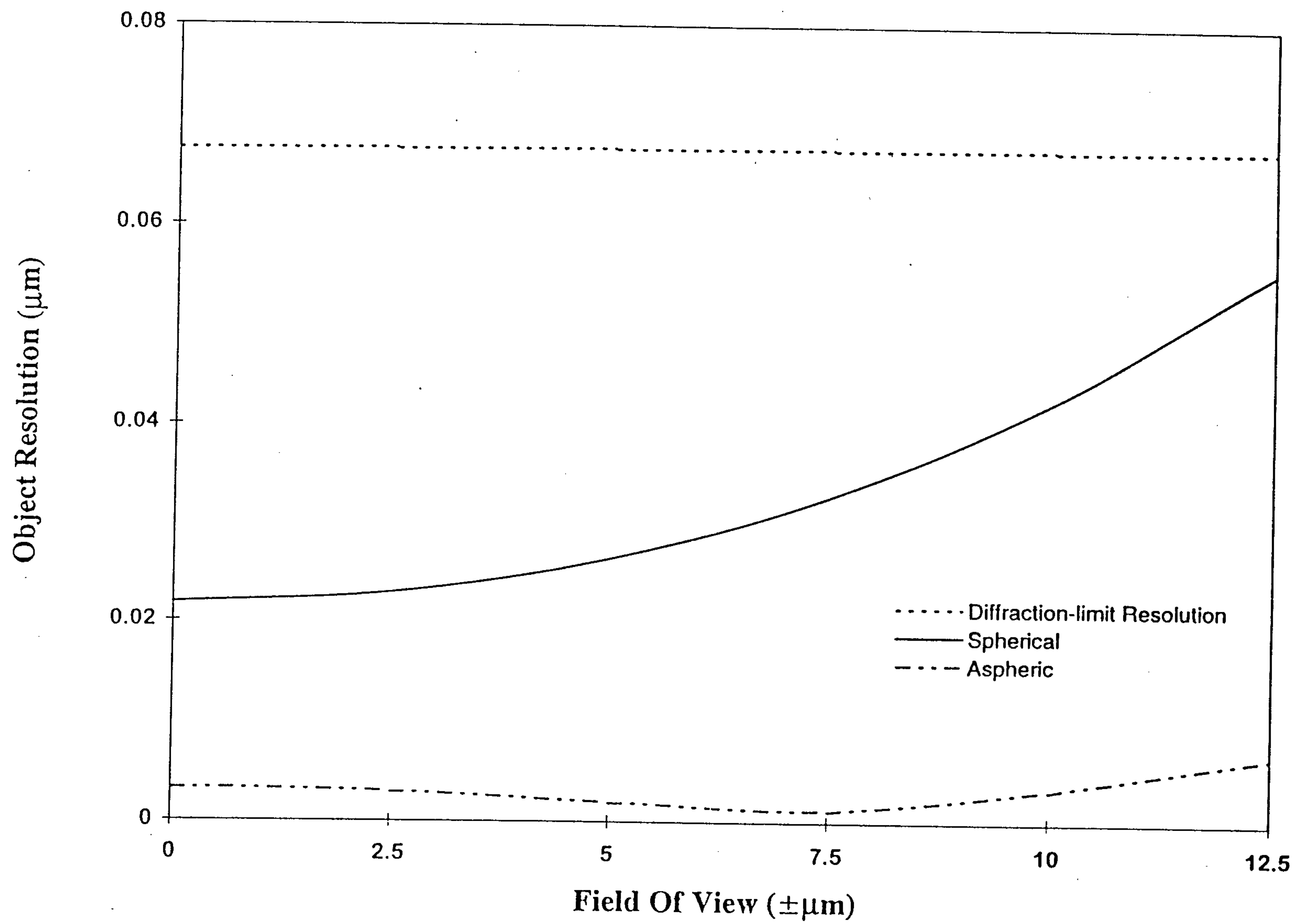
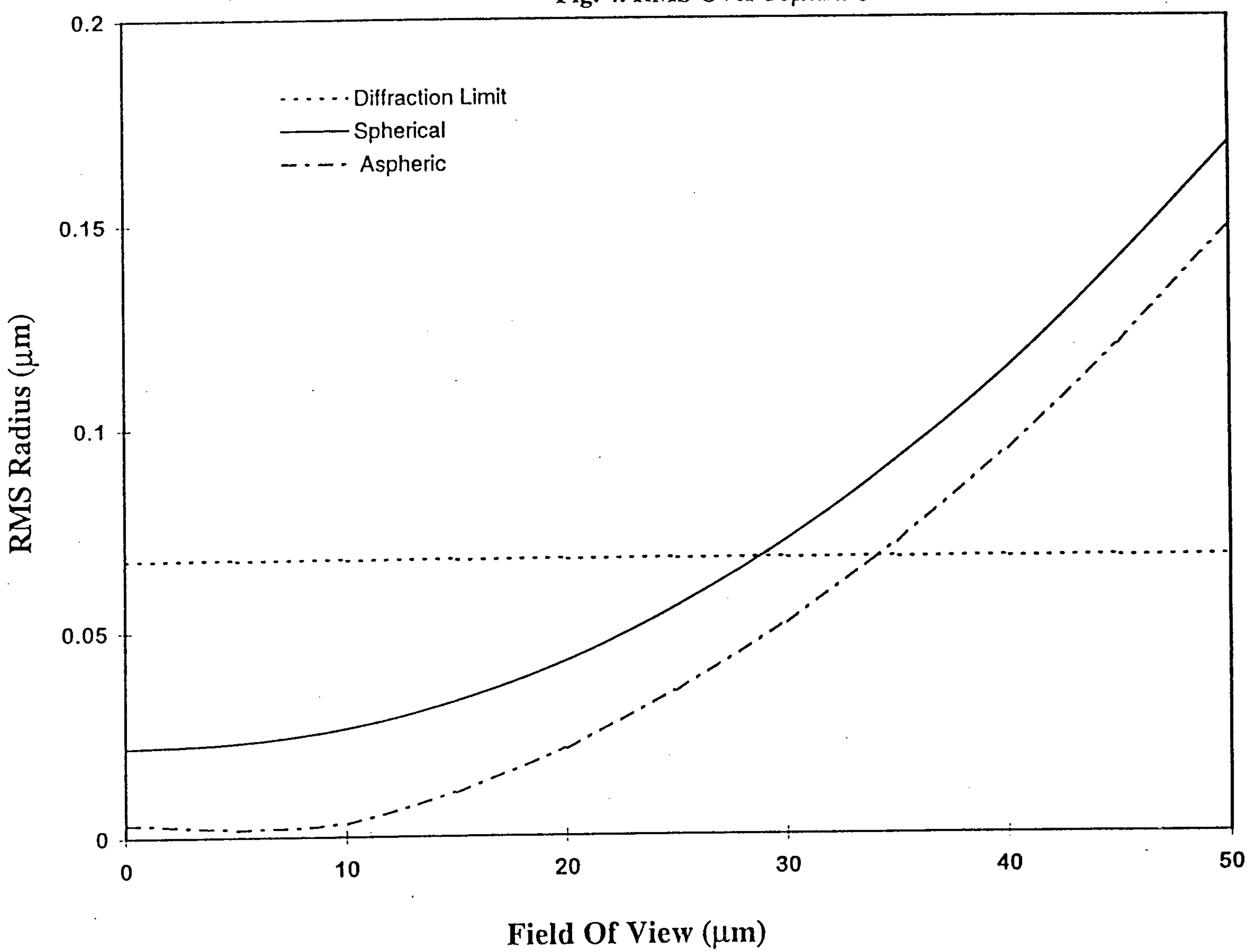


Fig. 4. RMS Over 50μm FOV



Spherical tiltp.xls

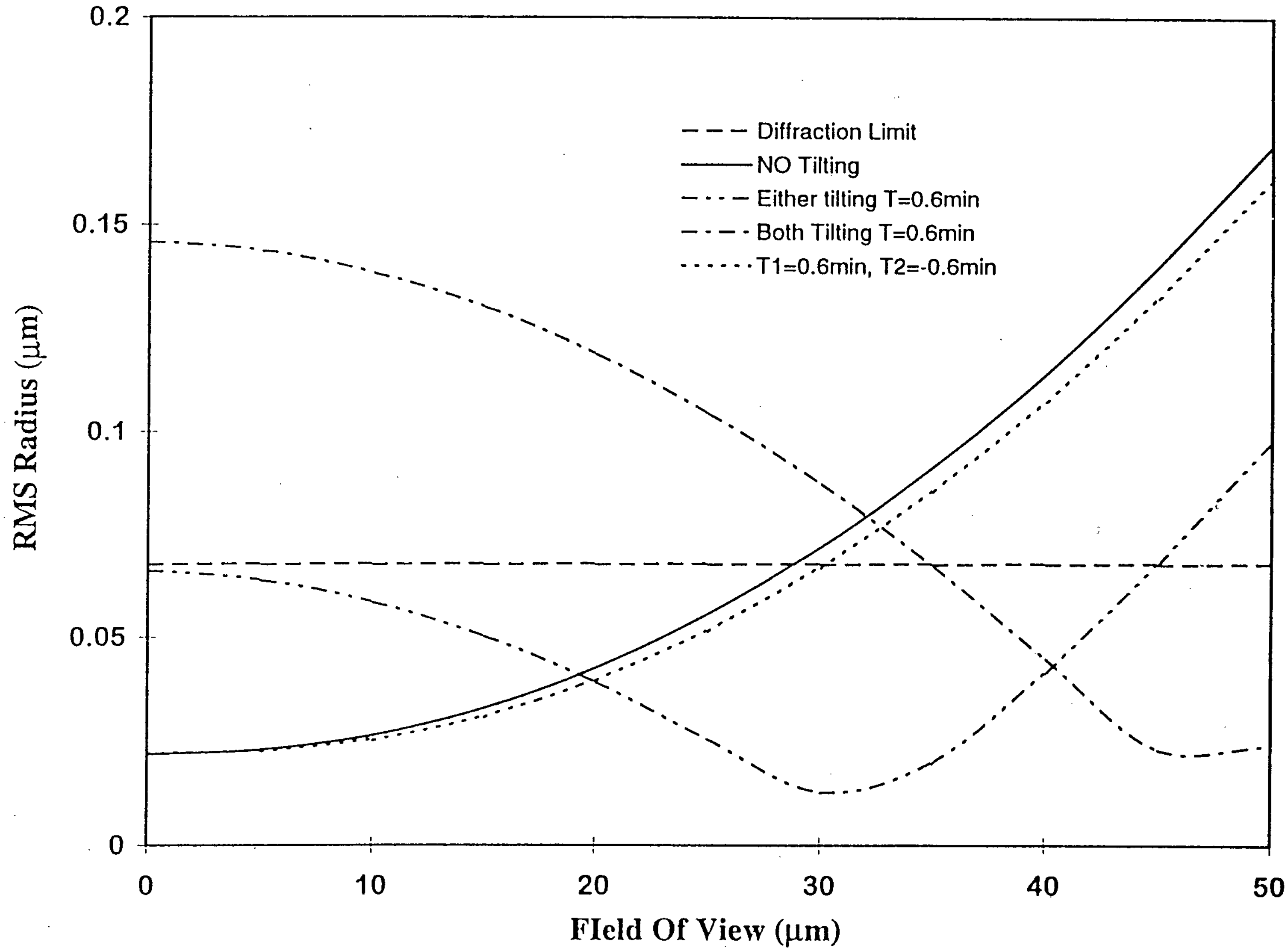


Fig. 5

Aspheric Partial Objective; FOV=50μm; NA=0.1

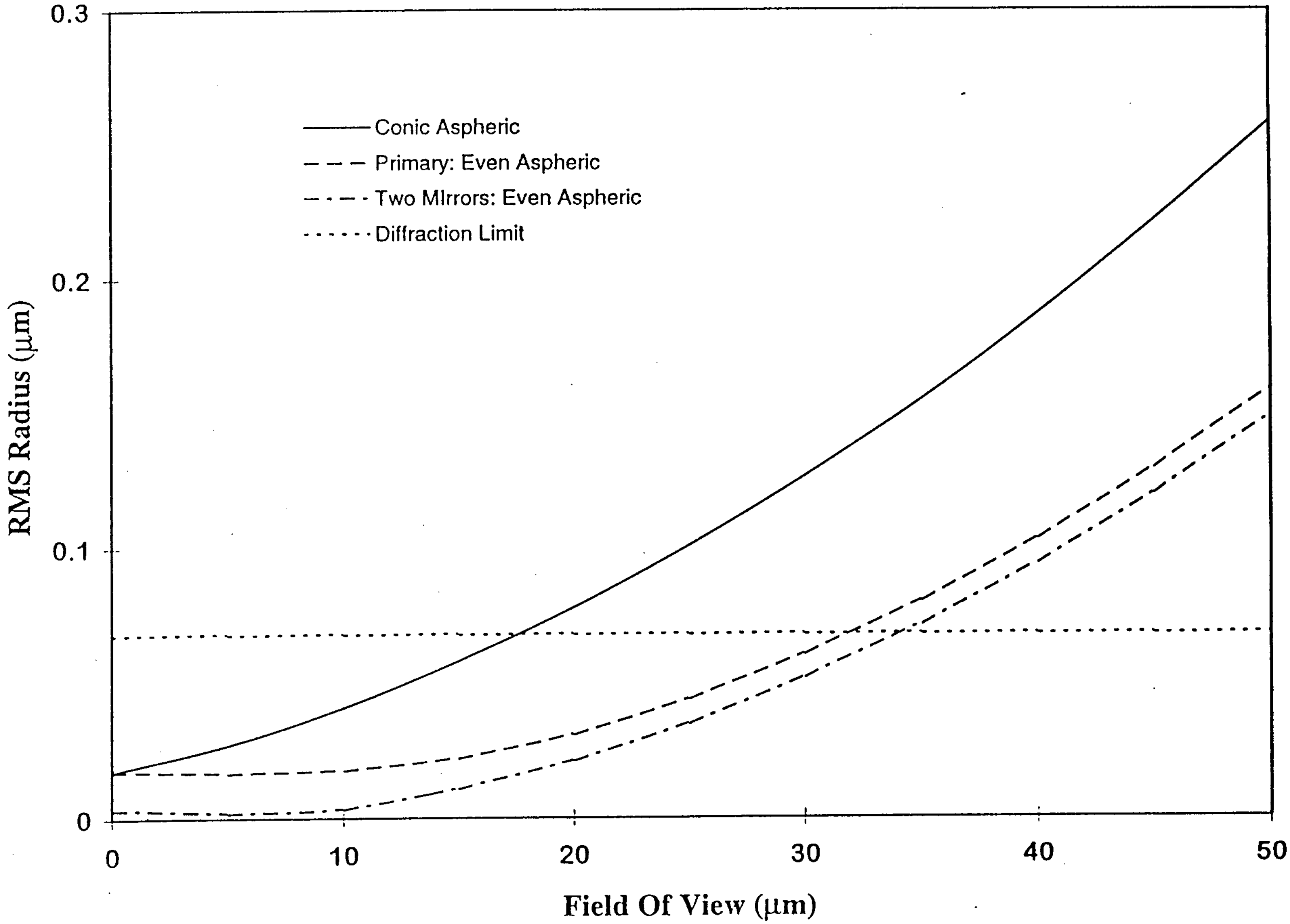


Fig. 6

Aspherical

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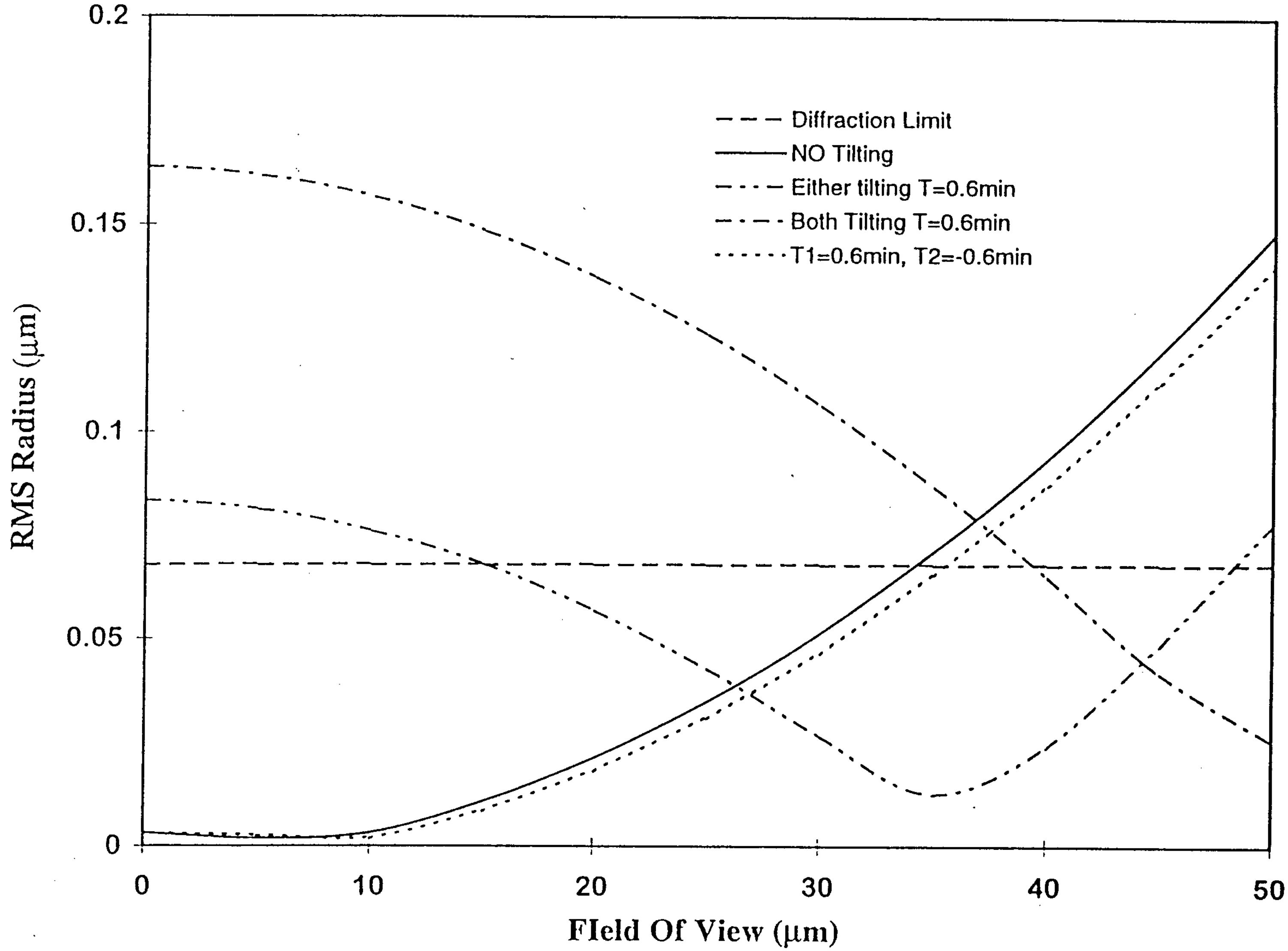
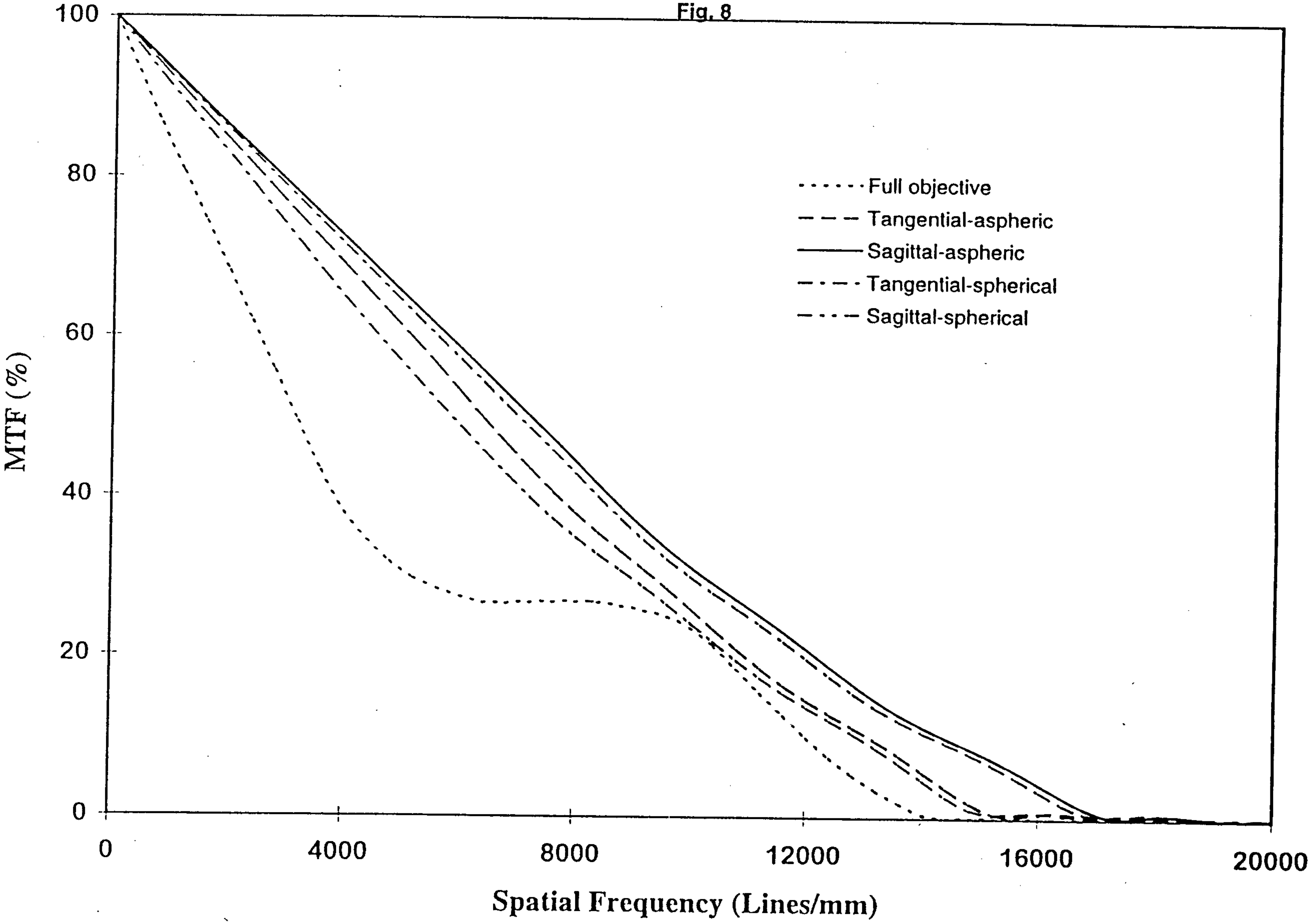


Fig. 7

Fig. 8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Sagittal-aspheric
Tangential-spherical
Sagittal-spherical