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Theoretical Analysis of Segmented Wolter/LSM X-ray Telescope Systems

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Abstract:

The Segmented Wolter I/LSM X-ray Telescope, which consists of a Wolter I telescope with a tilted, off-axis convex spherical Layered Synthetic Microstructure (LSM) optics placed near the primary focus to accommodate multiple off-axis detectors, has been analyzed. The Skylab ATM Experiment S056 Wolter I telescope and the Stanford/MSFC nested Wolter-Schwarzschild x-ray telescope have been considered as the primary optics. A ray trace analysis has been performed to calculate the RMS blur circle radius, point spread function (PSF), the meridional and sagittal line spread functions (LSF), and the full width half maximum (FWHM) of the PSF to study the spatial resolution of the system. The effects on resolution of defocussing the image plane, tilting and decentrating of the multilayer (LSM) optics have also been investigated to give the mounting and alignment tolerances of the LSM optic. Comparison has been made between the performance of the segmented Wolter/LSM optical system and that of the Spectral Slicing X-ray Telescope (SSXRT) systems.

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Introduction:

Glancing incidence x-ray telescopes have been used to obtain high resolution images of solar x-ray sources, while mounted on the sounding rockets and satellites. The Wolter[1] type I x-ray telescope which includes a paraboloid-confocal hyperboloid and the Wolter-Schwarzschild[2,3] telescope have been the most extensively used soft x-ray telescopes. The Skylab Apollo Telescope Mount (ATM) Experiment S056 Wolter I telescope and the Stanford/MSFC nested Wolter-Schwarzschild telescope were flown to study the sun. They produced high resolution images of the sun on photographic films which have high spatial resolution but less sensitivity than CCD detectors.

In most x-ray telescope systems which have been flown, the system spatial resolution has been limited by the detector. The physical length and mass restrictions imposed by the carrier have restricted the telescope focal length to less than 2m. In order to increase the effective focal length of the telescope without increasing its physical length, several designs[4,5,6] have been considered which couple auxiliary x-ray microscope optics to the primary Wolter I x-ray telescope optics so that the telescope plate scale is increased, and thus, better spatial resolution on the detector is obtained.

Using Layered Synthetic Microstructure (LSM) optics[7,8], it is possible to effectively reflect only a narrow range of wavelengths of the incident x-rays by proper choice of the optical properties and thickness of the multilayers. In the study of the "Design and analysis of spectral slicing x-ray telescope systems (SSXRT)[9], a LSM optic has been coupled with the Wolter I x-ray telescopes (ATM S056 and the Stanford/MSFC nested Wolter-Schwarzschild telescopes) to improve the spatial resolution and plate scale where the LSM optics were considered to be a sphere, ellipsoid, hyperboloid, or asphere. The LSM optic is placed near the prime focus with the LSM's center and focal point located on the optical axis.

In another study, Shealy, Hoover and Gabardi[10] investigated the imaging properties of a two mirror multilayer x-ray imaging system. Theoretical ray trace analysis has been performed on a normal incidence Cassegrain x-ray telescope using internally reflecting concave and externally reflecting convex spherical LSM mirrors. Very high spatial resolution for half field view angles less than 30 arc-min are realized. The resolution discerned by the detector is compatible with that of a true Cassegrain telescope using paraboloidal and hyperboloidal mirrors.

In the SSXRT systems, one image is formed on the detector since only one on axis LSM was coupled with the full primary optics. The purpose of this study is to analyze the Segmented Wolter/LSM X-ray Telescope systems, for which, there are several LSM's with different magnifications and detectors associated with each LSM. The LSM is placed off-axis and is tilted to suit the particular position of the associated detector. The Wolter aperture has been segmented such that four LSM's can be mounted in the focal plane of a Wolter telescope such that approximately 60° sectors of the primary optics aperture will reflect x-rays to the corresponding LSM mirror. The configuration is shown in Figure 1. The coordinates (Xm,Zm) and (Xc,Zc) are locations of the LSM mirror and detector, respectively. The tilt angle of the LSM mirror with respect to the optical axis is denoted by GAMA (γ).

A ray trace analysis has been performed for the Segmented Wolter/Spherical LSM telescope system. The ATM Experiment S056 and the Stanford/MSFC nested Wolter-Schwarzschild optics have been considered as the primary optics. The convex spherical LSM, which is placed in the vicinity of the prime focus, is off-axis, tilted and intercepts about 20% of the rays reflected by the primary optics. Ray trace analysis of the systems have established the optical performance of the full, 30° and 60° sectors of the primary mirror apertures, when used in conjunction with convex spherical LSM optics with different magnifications M=2,6,8x. The RMS blur circle radius and point spread function (PSF) have been evaluated as a function of the half field of view angles. The effects of decentration and tilt of the LSM are carried out to determine the mounting and alignment tolerances. The vignetting effects for off-axis field angles have been studied.

Results:

For a four-detector segmented x-ray telescope system, each detector is located at the middle of the side of a square with the optical axis passing through the center of square. The separation between the detector and optical axis ranges from 1.5 to 2 inches. The spherical LSM mirror is tilted to reflect the on-axis x-rays onto the respective detector. A schematic configuration of part of the segmented Wolter-LSM x-ray telescope is shown in Fig. 1. In Figs. 2,3,4 the variation of the average image positions Xc versus the LSM tilt angle Gama (γ) are plotted for field angles α=0 to 16 arc-min.

For the S056 primary optics, the spherical LSM mirror optics parameter have been evaluated using the technique described in Ref. 9 to yield

M (X)	R_3(cm)	Diameter (cm)
2	269.94	3.8
6	69.37	2.0
8	51.38	2.0

The functional dependence of Xc on γ is linear. The distance between Xc for $\alpha=0$ and Xc for $\alpha=16$ arc-min becomes larger when the magnification M is increased. For intermediate field angles, the Xc vs. γ results are located between the results given. The practical values of the tilt angle γ for Xc=5 cm, the coordinates (Xm,Zm), and the image plane shift ΔZ from the Gaussian point for minimum RMS for $\alpha=0$ are presented in Table 1.

Table 1. Full S056-convex spherical LSM system with Gaussian image plane at the back of primary telescope and Xc=5 cm.

M (X)	γ (rad.)	Xm (cm)	Zm (cm)	ΔZ (cm)
2	0.037	3.815	250.1	0.447
6	0.043	1.635	216.	1.738
8	0.044	1.272	210.4	2.487

The plot of Xc as a function of field angle α for the Stanford/MSFC nested Wolter-Schwarzschild and convex spherical LSM is given in Fig. 5 for M=2X (R_3=1.3m, LSM diameter=3.81 cm) and tilt angles γ=0.06, 0.062, 0.064, 0.066, 0.068 rad. The tilt angle γ=0.068 rad. is the practical value for Xm=1.58 in., ZM=12.769 in., ΔZ=0.25 in.

Figures 5a-h, 6a-h, 7a-h present the PSF and the meridional and sagittal LSF for different fields of view for rays reflected from the S056 Wolter I/Spherical LSM segmented telescope. These figures are somewhat irregular, since a restricted number of rays was traced during the period of this contract.

Figures 8a-h and 9a-h present the PSF and LSF's for S056 Wolter I/Spherical LSM (M=2X) when rays were traced through 60° and 30° segmented apertures of the Wolter I telescope. Comparing Figs. 5, 8 and 9 indicates a 30° to 60° aperture of S056 Wolter I telescope could be used with the present LSM mirror size without a significant loss of rays.

The meridional and sagittal FWHM for M=2X as a function of field angle α are given in Figs. 10, 11 for the full aperture, 30° and 60° sectors of the aperture of the S056-convex spherical LSM telescope. The meridional FWHM's have almost the same values for the full, 30° and 60° aperture sectors of the S056. For the full and 60° sector of the S056, the sagittal FWHM's are about the same, but the values for 30° sector of the S056 are about half those for the 60° sector of S056 at α=16 arc-min. Thus, using a 30° sector of S056 gives better spatial resolution. Figures 12, 13 give the meridional and sagittal FWHM as a function of field angle α for M=2,6,8X using a 60° sector of S056. The meridional FWHM values for M=2,6,8X are about the same, but the sagittal FWHM values increase as M increases. Thus, the 60° sector of S056 and full S056 have the same effect on the spherical LSM. The meridional FWHM values for α=16 arc-min for the SSXRT[3] are 1.4, 1.37, 1.2 arc-sec for M=2,6,8X and the corresponding values of the meridional FWHM are 1.35, 1.358, 1.358 arc-sec for 60° sector of S056-decentered spherical LSM. The sagittal FWHM values for 60° sector of S056-spherical LSM are about 10 times smaller than those for SSXRT for α=16 arc-min. Thus, there is no great loss in resolution associated using the segmented x-ray telescope with tilted LSM elements when compared to SSXRT with centered LSM optics.

For the nested Wolter-Schwarzschild/spherical LSM and SSXRT, the sagittal and meridional FWHM behave the same way as the S056-spherical LSM and SSXRT. The PSF and LSF's on the flat focal plane with minimum RMS for on-axis light for the Stanford/MSFC Wolter-Schwarzschild/spherical LSM telescope are given in

Figs. 14a-h. The full aperture has been used in these calculations. The meridional and sagittal FWHM of Wolter-Schwarzschild/spherical LSM for M=2X are given in Fig. 15.

The RMS blur radius is presented in Fig. 16 as a function of field angle α for M=2X and full, 60°, 30° sectors of S056-spherical LSM. For 60° sector and the full aperture of the S056, the RMS values are about the same and are larger than those for 30° sector of S056. The RMS values are about 5 times larger than the FWHM values for α=16 arc-min. Figures 17 and 18 show that the RMS on flat and curved optimum focal surfaces for M=2,6,8X for 60° section of S056-spherical LSM are about the same.

The percent energy loss vs. field angle α for 60° sector of S056-spherical LSM and M=2,6,8X are shown in Figure 19. The percent energy losses due to vignetting for α=16 arc-min are 35%, 54%, 48% for M=2,6,8X, which are larger than the corresponding 28% energy loss for SSXRT. Figure 20 shows the energy loss for M=2X and the Wolter-Schwarzschild/spherical LSM which has 17% energy loss at α=16 arc-min compared with 14% energy loss for SSXRT.

Figures 21 and 22 show the defocussing effects of the RMS radius as a function of field angle α for 60° sector of S056 and WS-spherical LSM. The tilt effects of the spherical LSM for M=2 and 60° sector of S056 and WS-spherical LSM are presented in Figs. 23 and 24. The decentration effects of the S056-spherical LSM are given in Fig. 25. These calculations give the mounting and alignment tolerances for the spherical LSM. That the detector's position shift must be maintained to less than 0.2 cm and 0.04 inches for sub arc-sec RMS blur radius for $\alpha \lesssim 5$ arc-min for S056 and nested Wolter-Schwarzschild/ spherical LSM, respectively. The tilt angle shift of the spherical LSM must be maintained to less than 0.01 rad. from the practical value of tilt angle. The displacement of LSM from its designed position should be less than 0.4 cm.

Conclusion:

The theoretical analysis of segmented Wolter I x-ray telescope coupled with the convex spherical multilayer optics have been performed. The resolution for the segmented optics system is better than that for SSXRT system, but the percent energy losses at large field angles for the segmented system is greater than that for the SSXRT. The advantage of the segmented system is to provide more images at different magnifications without changing the physical dimension of the telescope envelope. It is recommended that a segmented telescope be flown on a rocket flight as part of the Stanford/MSFC nested Wolter-Schwarzschild x-ray telescope.

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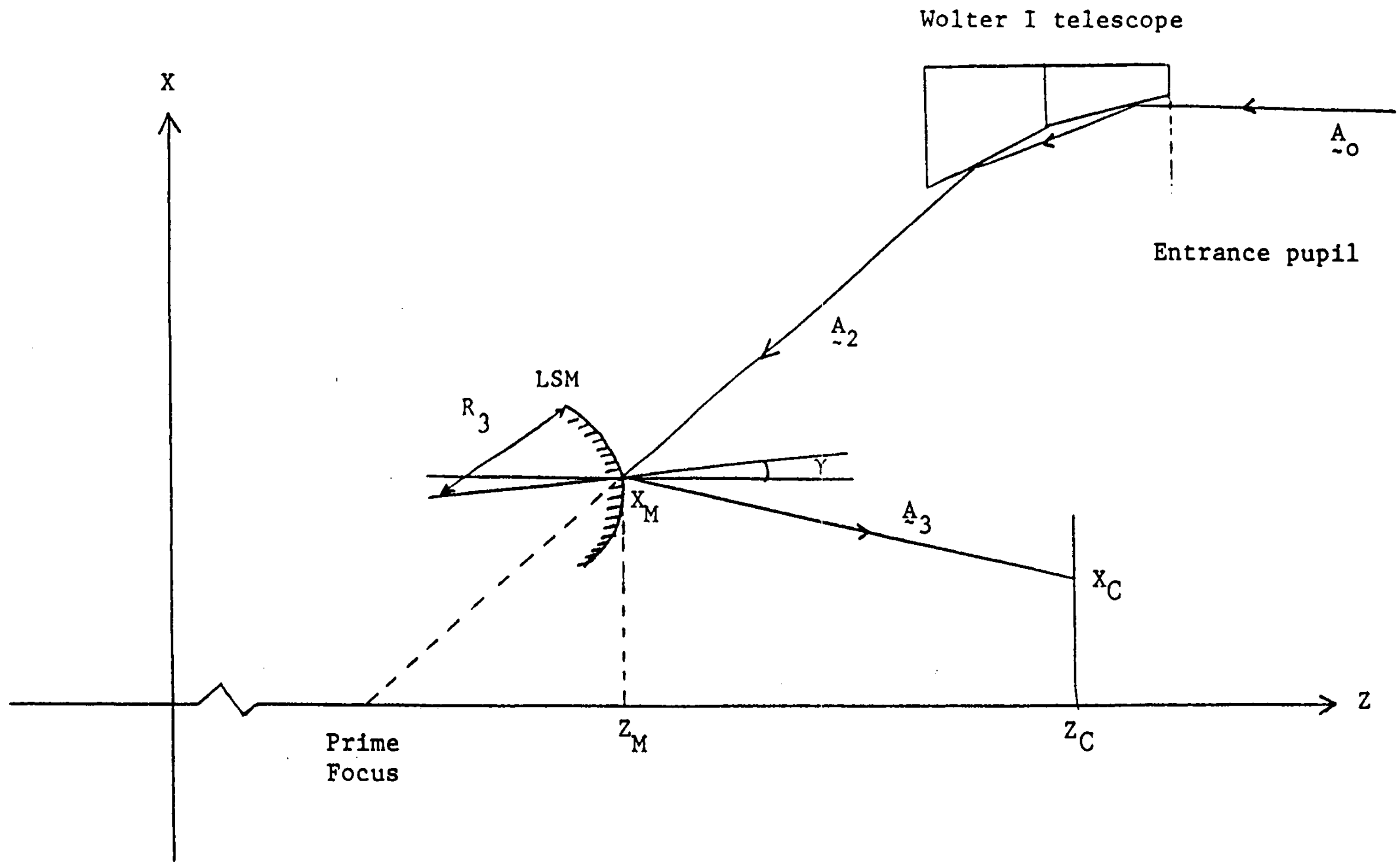


Figure 1. Schematic configuration of segmented Wolter/LSM x-ray telescopes.

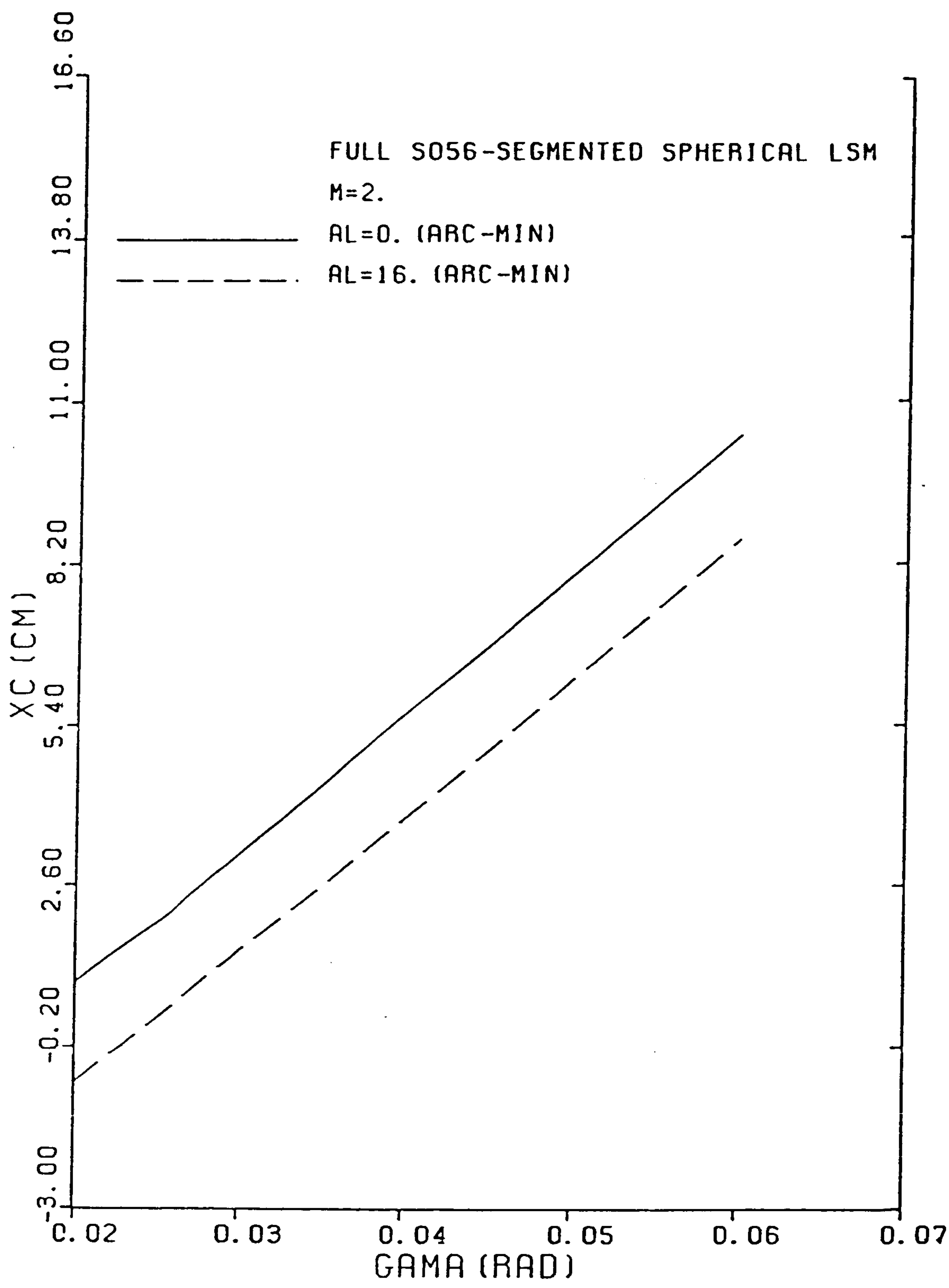


Figure 2. Average image position Xc versus field angle for full S056-segmented spherical LSM and M=2 and Gaussian focal plane.

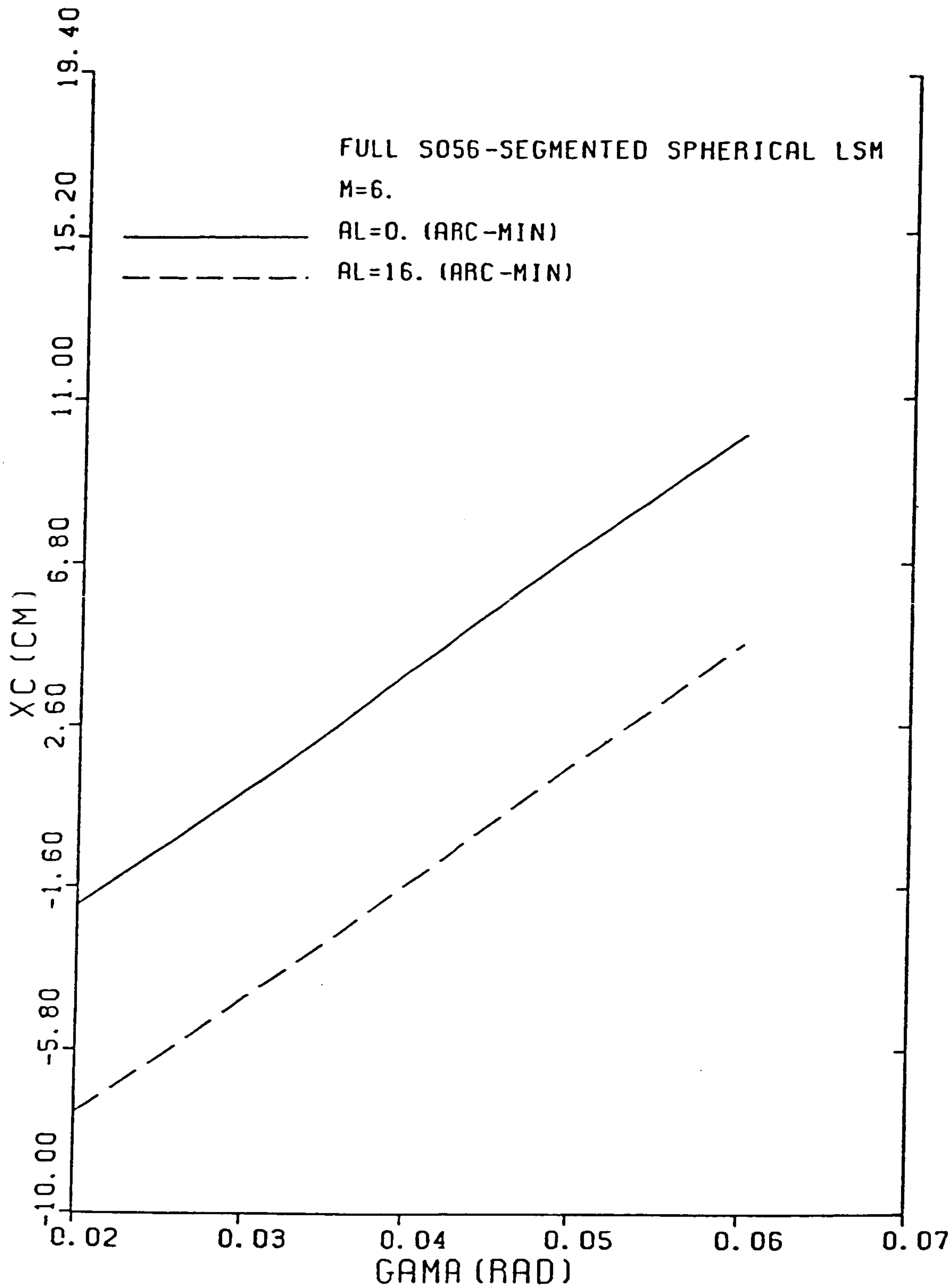


Figure 3. Average image position Xc versus field angle for full S056-segmented spherical LSM and M=6 and Gaussian focal plane.

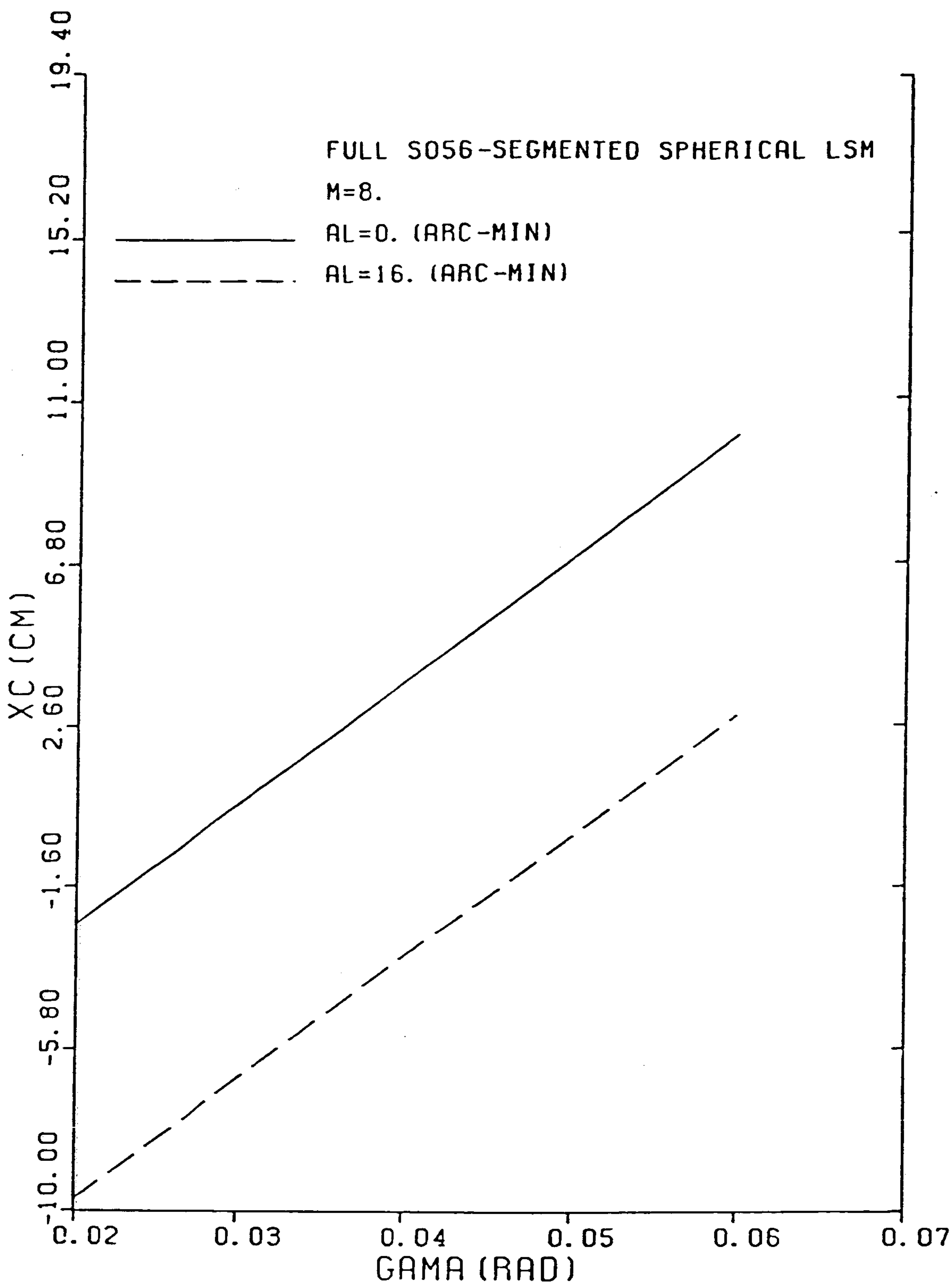


Figure 4. Average image position Xc versus field angle for full S056-segmented spherical LSM and M=8 and Gaussian focal plane.

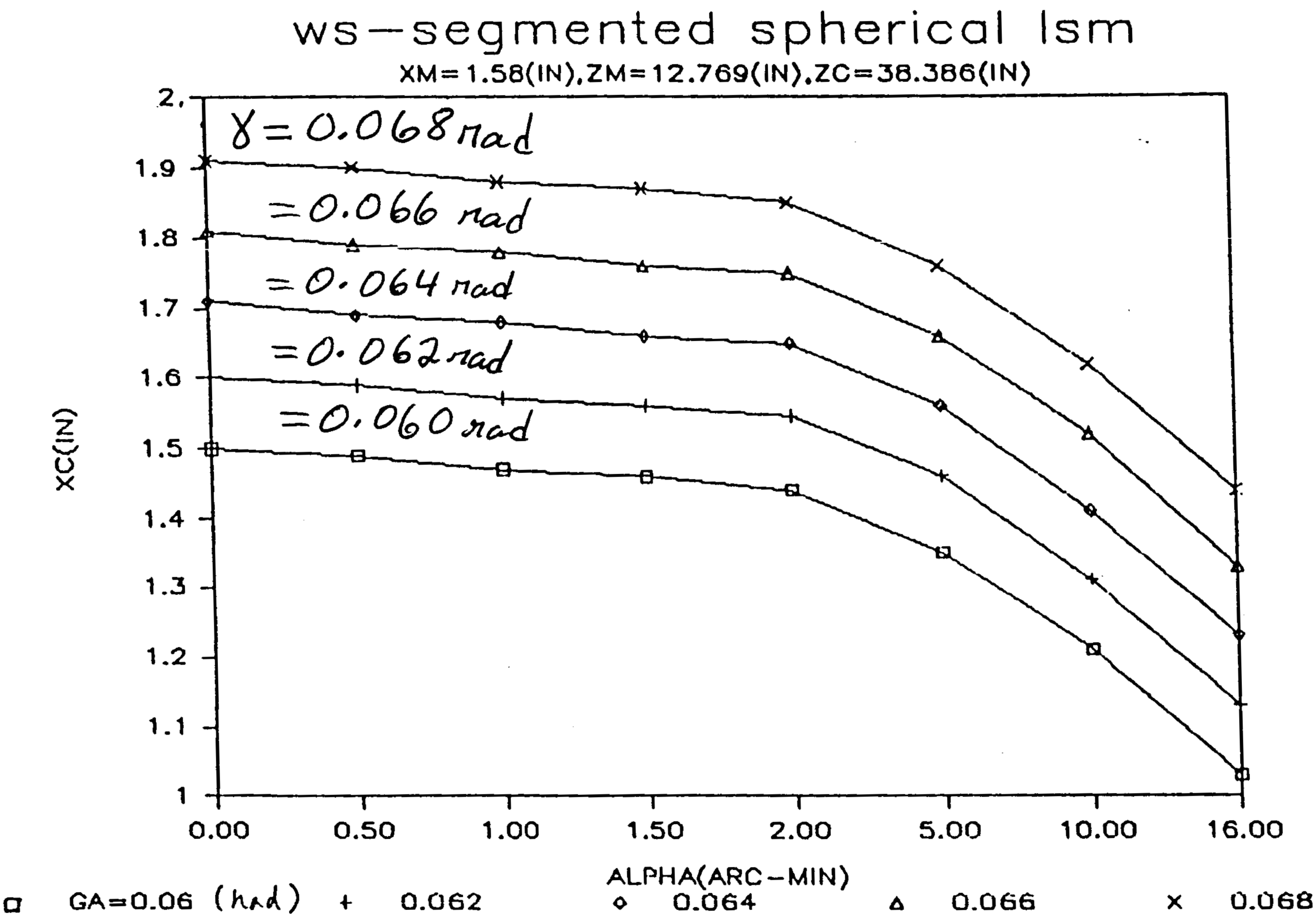


Figure 5. Average image position Xc as a function of field angle α for different tilt angle γ and WS-segmented spherical LSM, M=2.

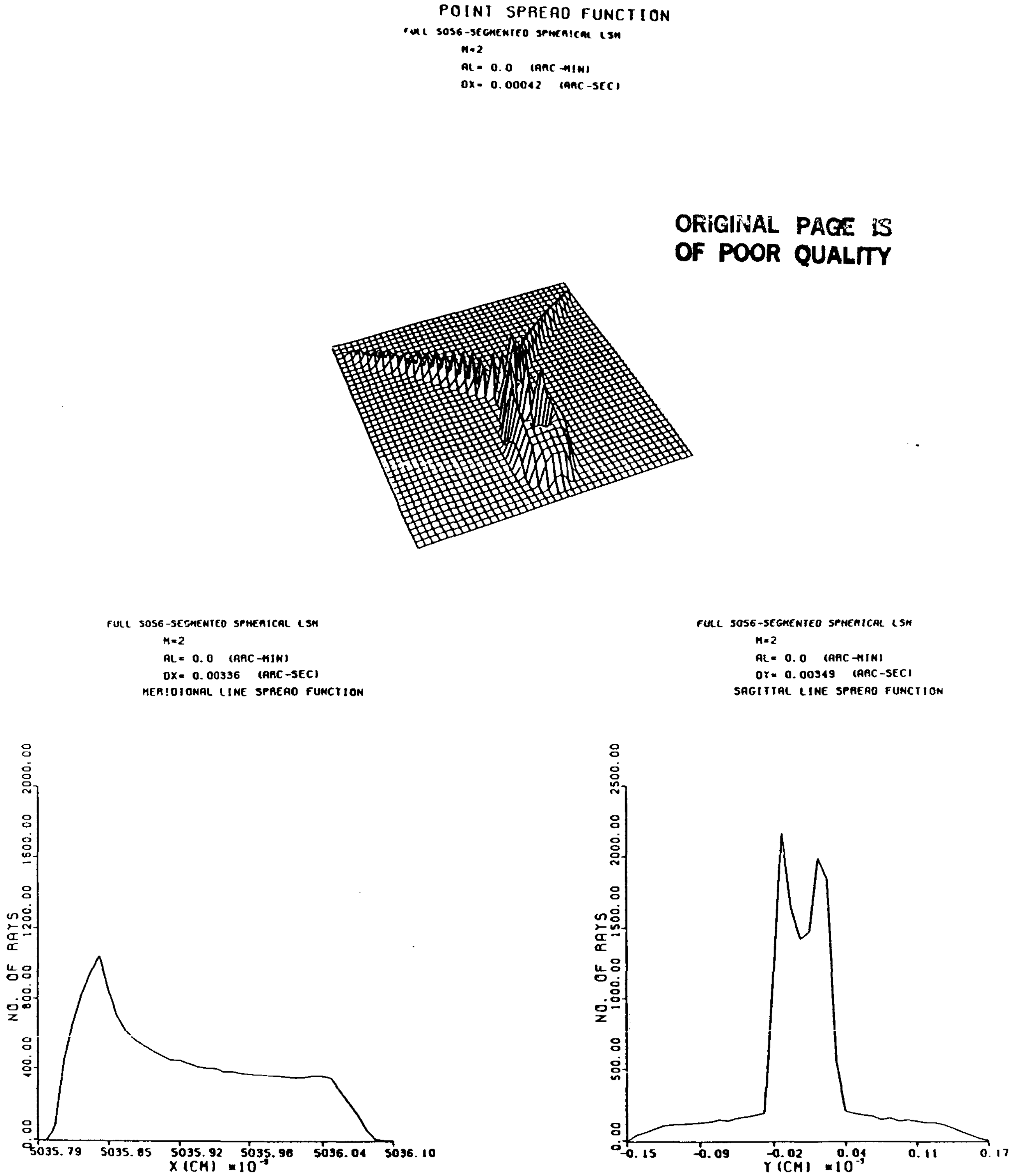
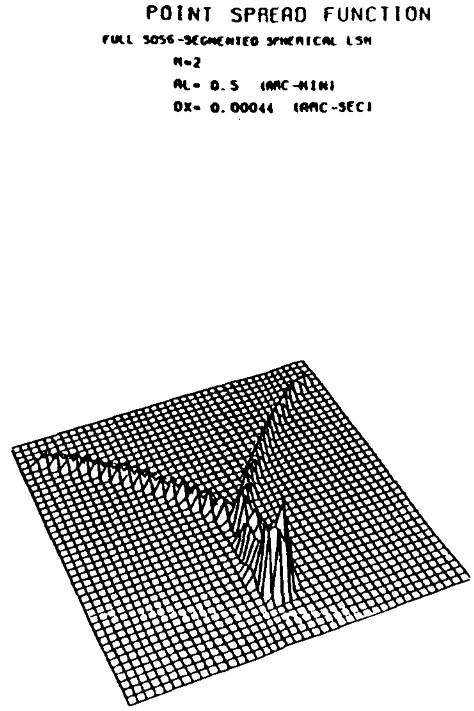
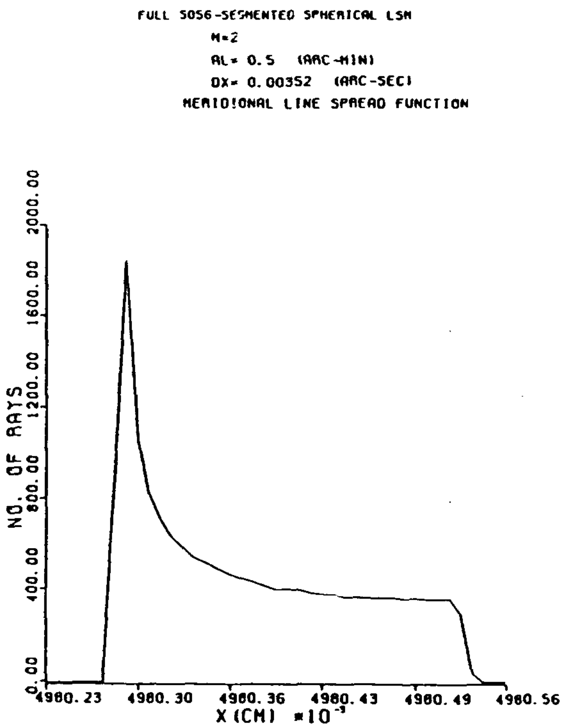


Figure 5a. Upper plot is the point spread function of the S056 Wolter I x-ray telescope (full aperture) and a spherical LSM with M=2X on the flat focal plane with minimum RMS for on axis light. The lower plots are meridional and sagittal line spread functions (LSF) for the same system. For a given value of X, the meridional LSF has been evaluated by summing the number of rays along the Y axis which intercept the image plane. The sagittal LSF has been computed in a similar manner where the role of X and Y axes are reversed. The half field angle is AL = 0 arc-mins.





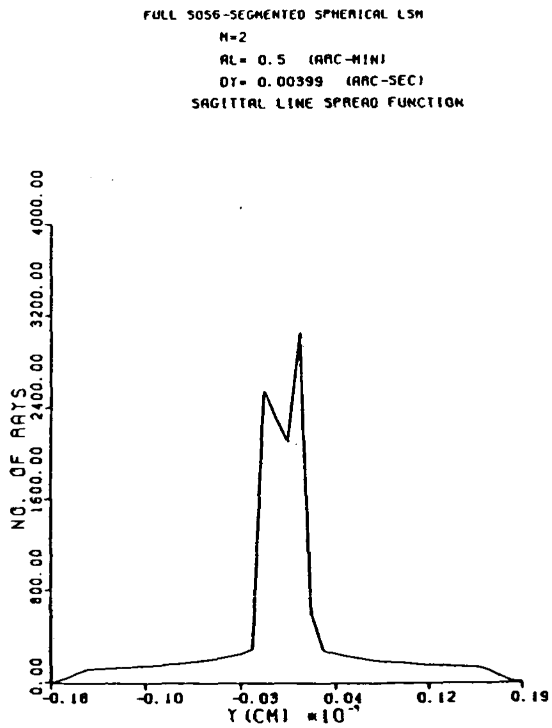


Figure 5b. Upper plot is the point spread function of the S056 Wolter I x-ray telescope (full aperture) and a spherical LSM with M=2X on the flat focal plane with minimum RMS for on axis light. The lower plots are meridional and sagittal line spread functions (LSF) for the same system. For a given value of X, the meridional LSF has been evaluated by summing the number of rays along the Y axis which intercept the image plane. The sagittal LSF has been computed in a similar manner where the role of X and Y axes are reversed. The half field angle is AL = 0.5 arc-mins.

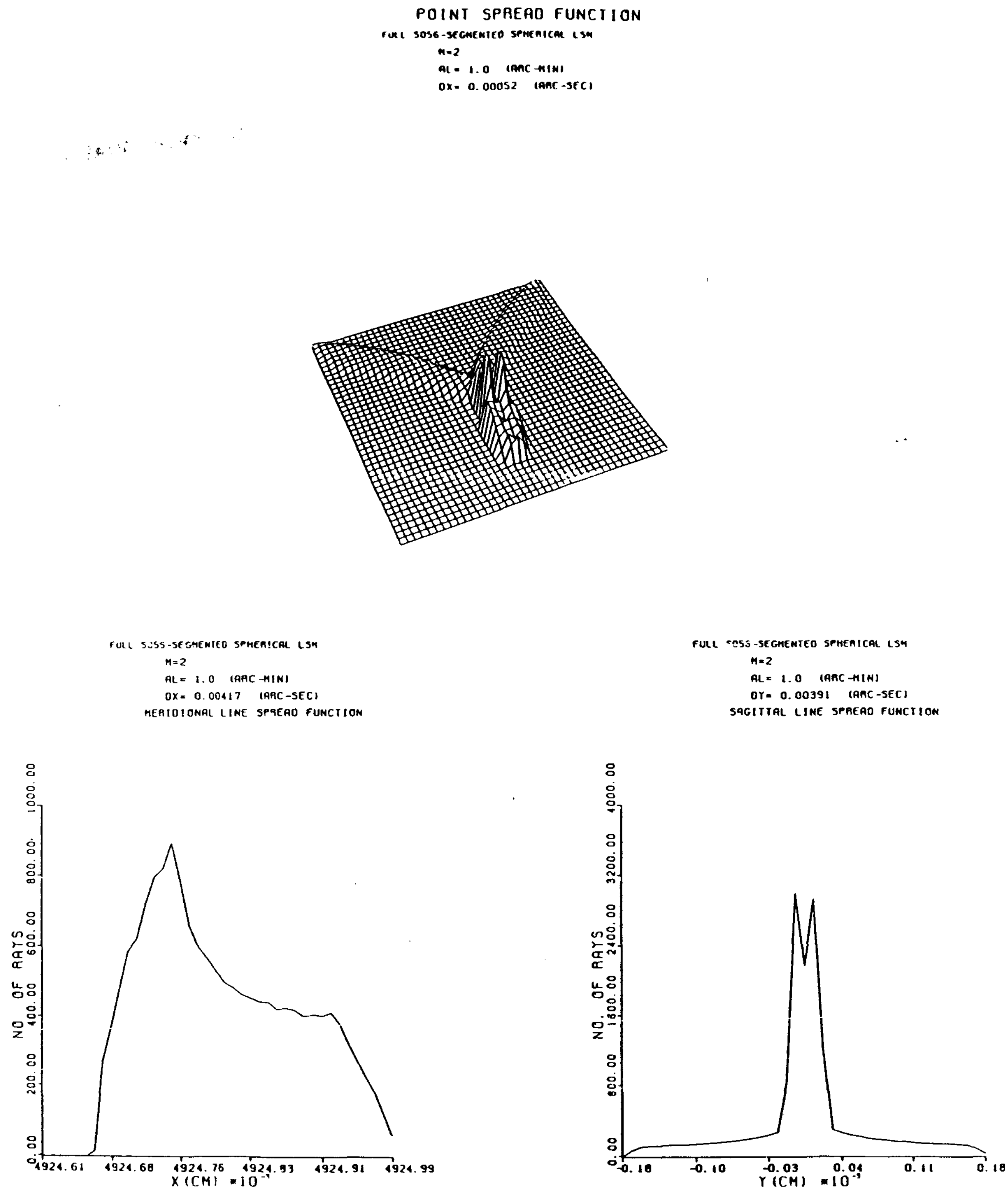


Figure 5c. Upper plot is the point spread function of the S056 Wolter I x-ray telescope (full aperture) and a spherical LSM with M=2X on the flat focal plane with minimum RMS for on axis light. The lower plots are meridional and sagittal line spread functions (LSF) for the same system. For a given value of X, the meridional LSF has been evaluated by summing the number of rays along the Y axis which intercept the image plane. The sagittal LSF has been computed in a similar manner where the role of X and Y axes are reversed. The half field angle is AL = 1.0 arc-mins.

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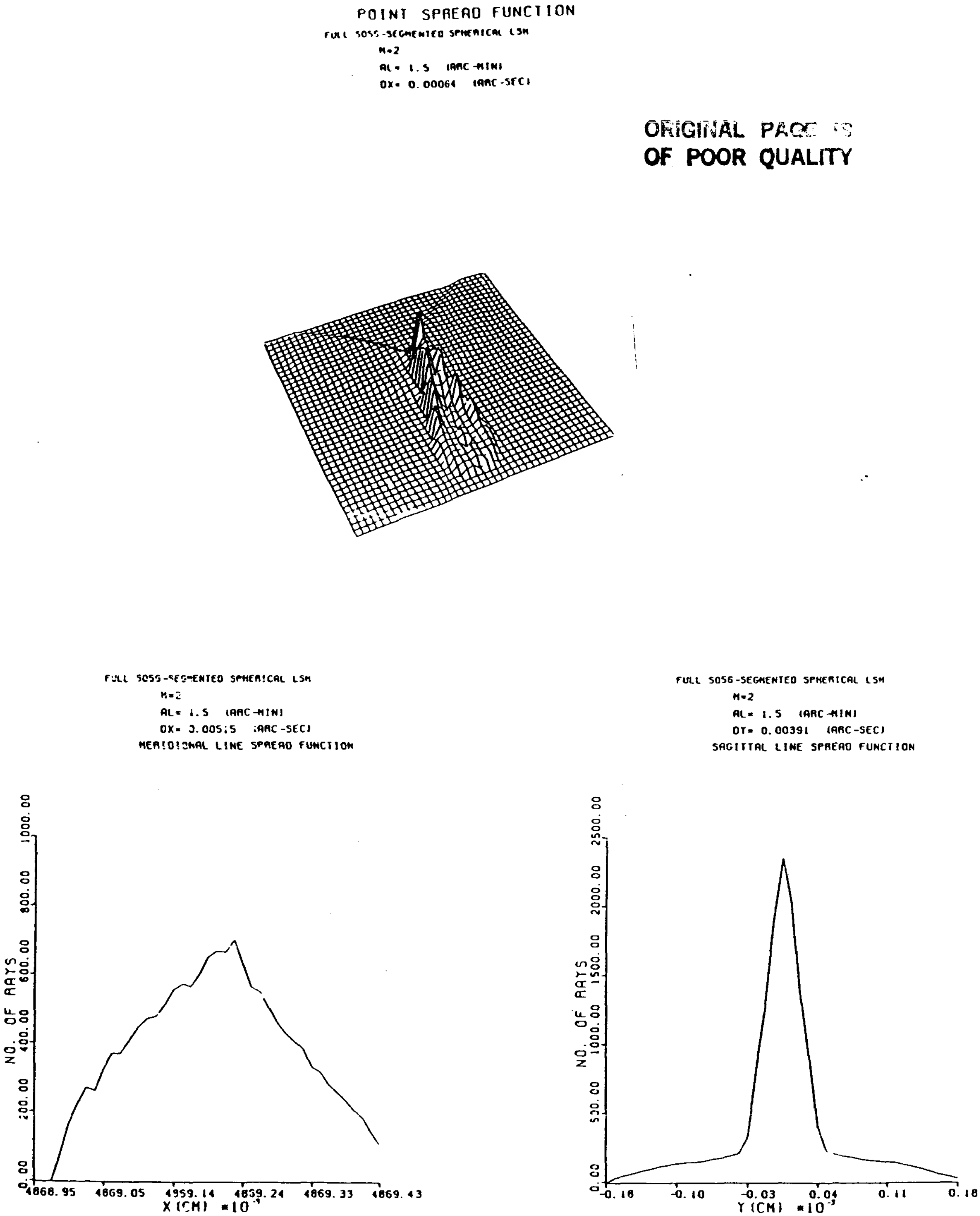


Figure 5d. Upper plot is the point spread function of the S056 Wolter I x-ray telescope (full aperture) and a spherical LSM with M=2X on the flat focal plane with minimum RMS for on axis light. The lower plots are meridional and sagittal line spread functions (LSF) for the same system. For a given value of X, the meridional LSF has been evaluated by summing the number of rays along the Y axis which intercept the image plane. The sagittal LSF has been computed in a similar manner where the role of X and Y axes are reversed. The half field angle is AL = 1.5 arc-mins.

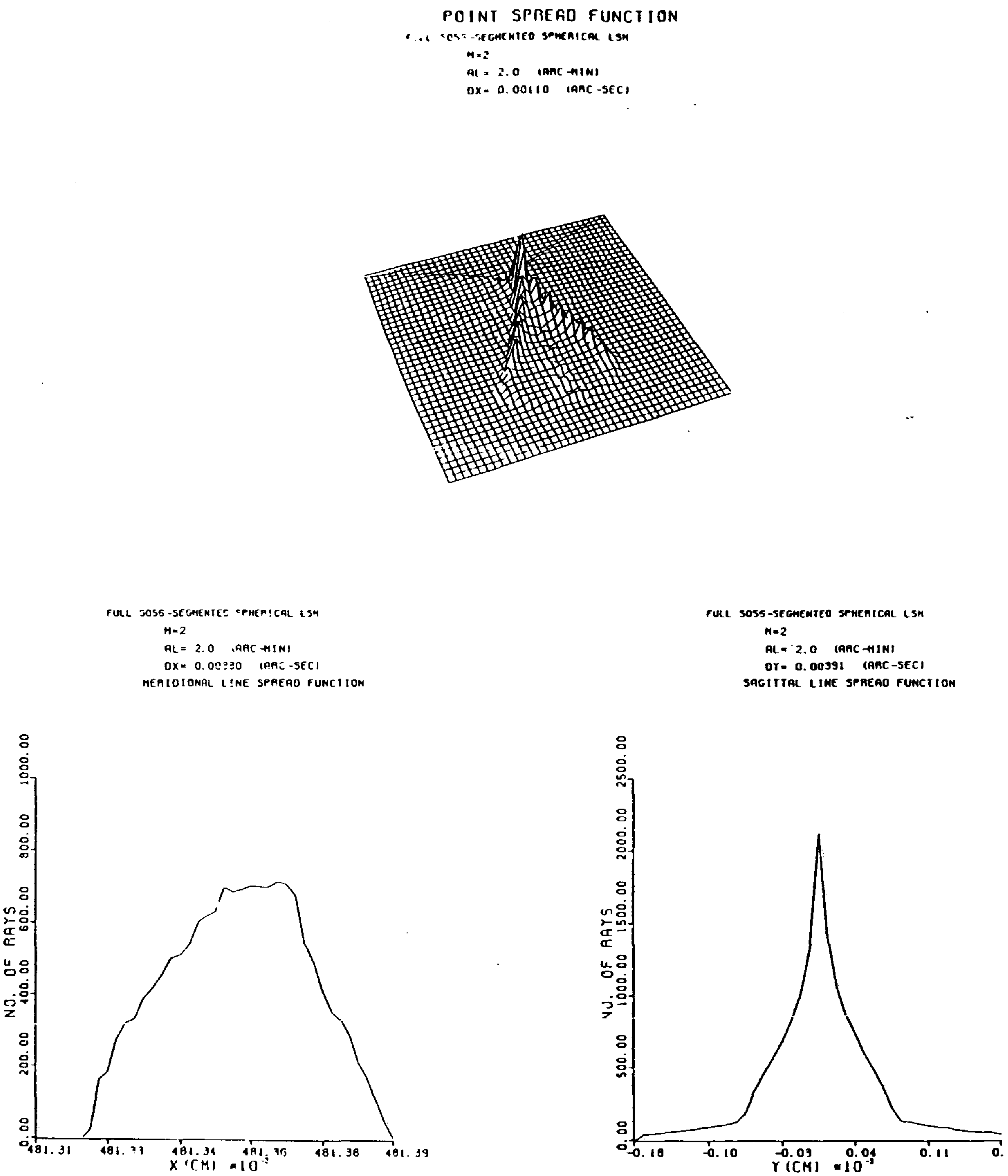


Figure 5e. Upper plot is the point spread function of the S056 Wolter I x-ray telescope (full aperture) and a spherical LSM with M=2X on the flat focal plane with minimum RMS for on axis light. The lower plots are meridional and sagittal line spread functions (LSF) for the same system. For a given value of X, the meridional LSF has been evaluated by summing the number of rays along the Y axis which intercept the image plane. The sagittal LSF has been computed in a similar manner where the role of X and Y axes are reversed. The half field angle is AL = 2 arc-mins.

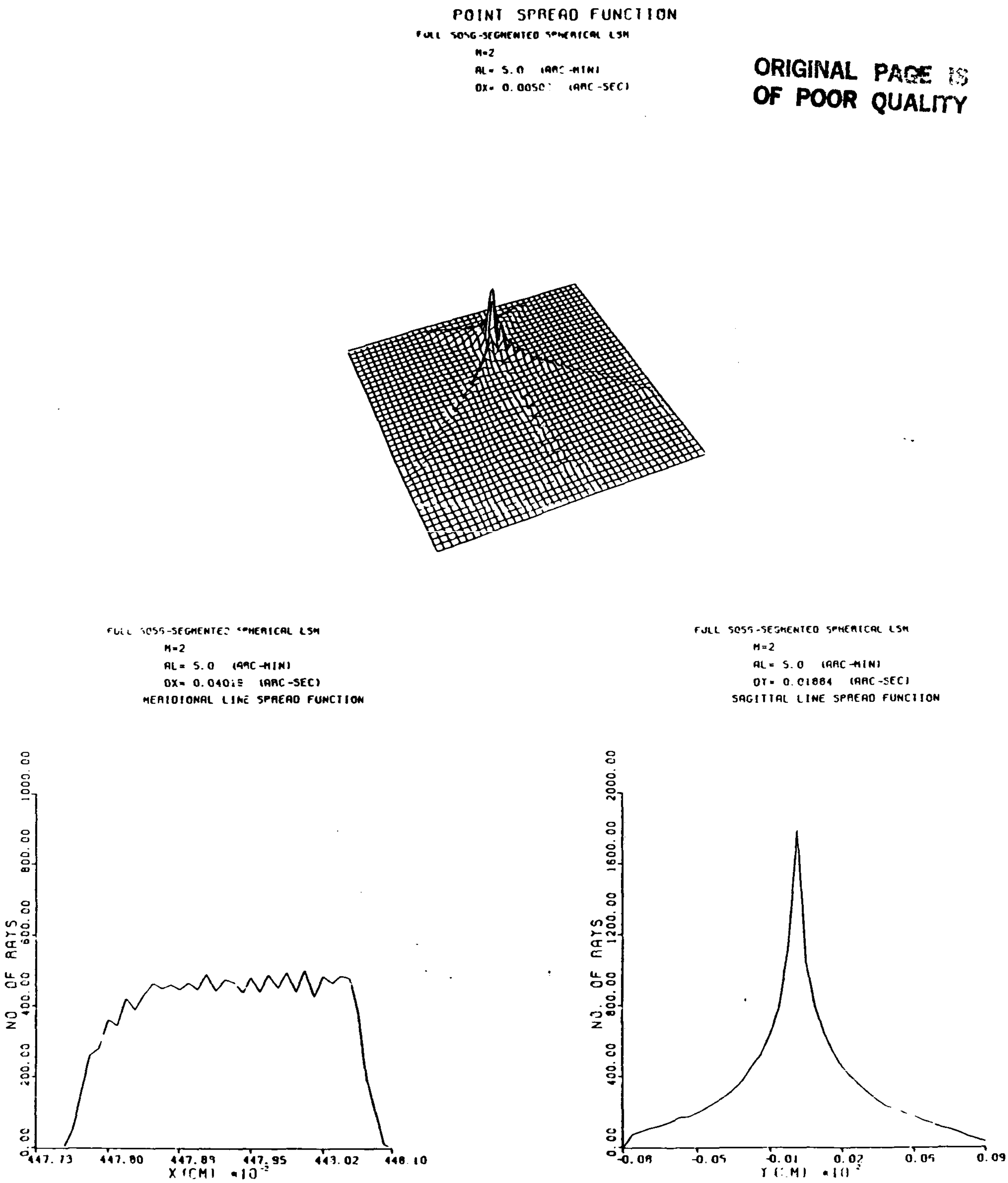


Figure 5f. Upper plot is the point spread function of the S056 Wolter I x-ray telescope (full aperture) and a spherical LSM with M=2X on the flat focal plane with minimum RMS for on axis light. The lower plots are meridional and sagittal line spread functions (LSF) for the same system. For a given value of X, the meridional LSF has been evaluated by summing the number of rays along the Y axis which intercept the image plane. The sagittal LSF has been computed in a similar manner where the role of X and Y axes are reversed. The half field angle is AL = 5 arc-mins.

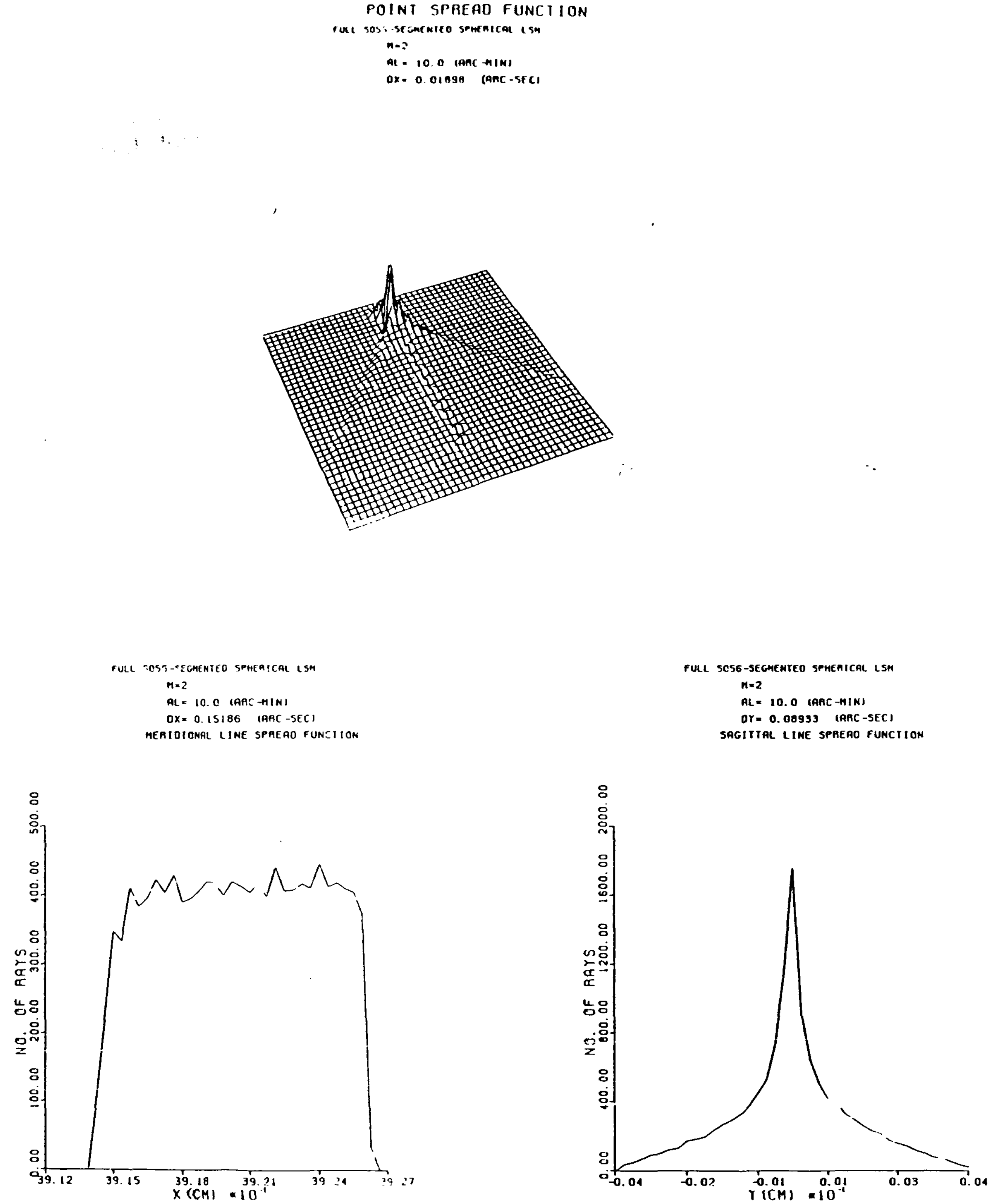


Figure 5g. Upper plot is the point spread function of the S056 Wolter I x-ray telescope (full aperture) and a spherical LSM with M=2X on the flat focal plane with minimum RMS for on axis light. The lower plots are meridional and sagittal line spread functions (LSF) for the same system. For a given value of X, the meridional LSF has been evaluated by summing the number of rays along the Y axis which intercept the image plane. The sagittal LSF has been computed in a similar manner where the role of X and Y axes are reversed. The half field angle is AL = 10 arc-mins.

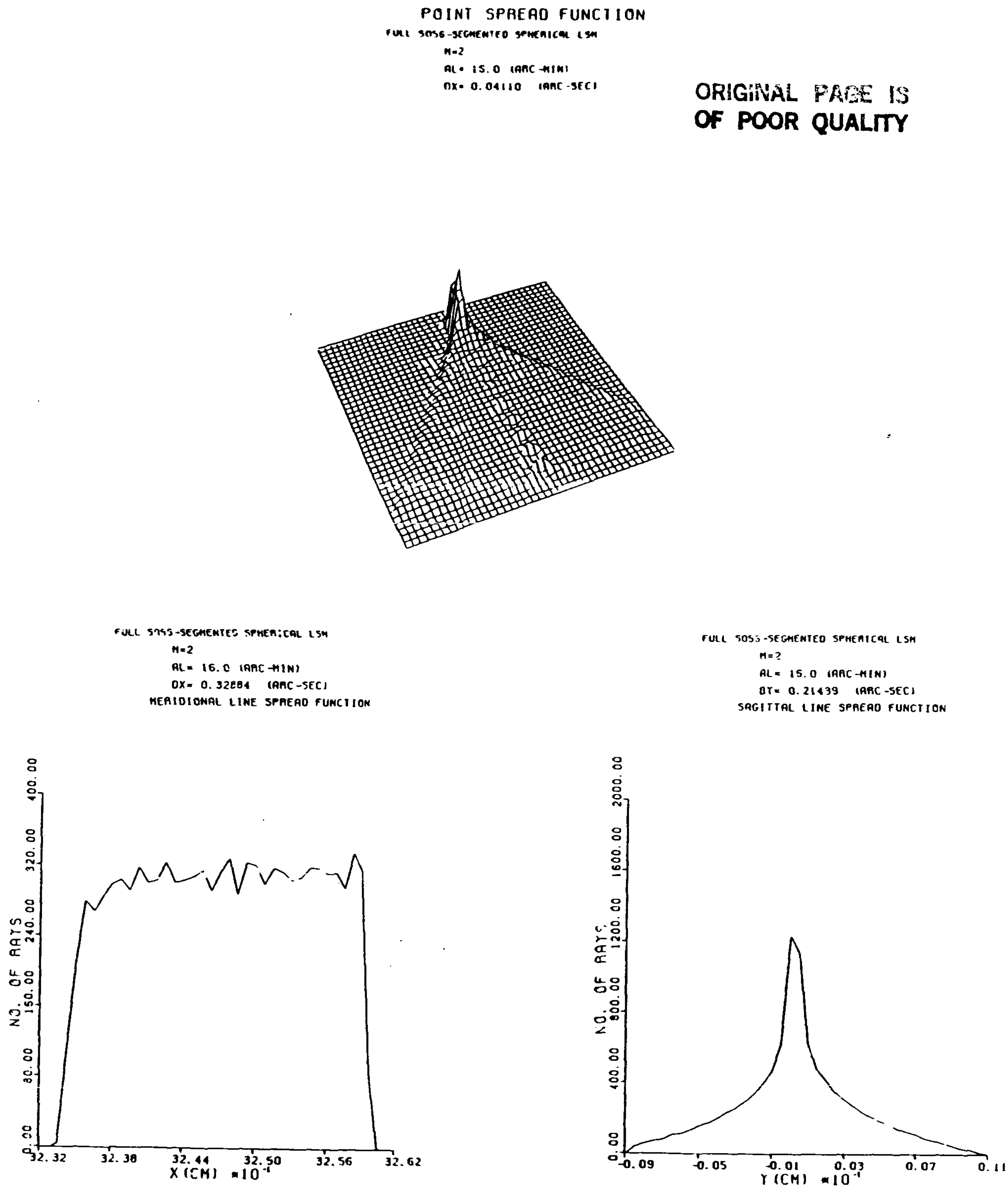


Figure 5h. Upper plot is the point spread function of the S056 Wolter I x-ray telescope (full aperture) and a spherical LSM with M=2X on the flat focal plane with minimum RMS for on axis light. The lower plots are meridional and sagittal line spread functions (LSF) for the same system. For a given value of X, the meridional LSF has been evaluated by summing the number of rays along the Y axis which intercept the image plane. The sagittal LSF has been computed in a similar manner where the role of X and Y axes are reversed. The half field angle is AL = 16 arc-mins.

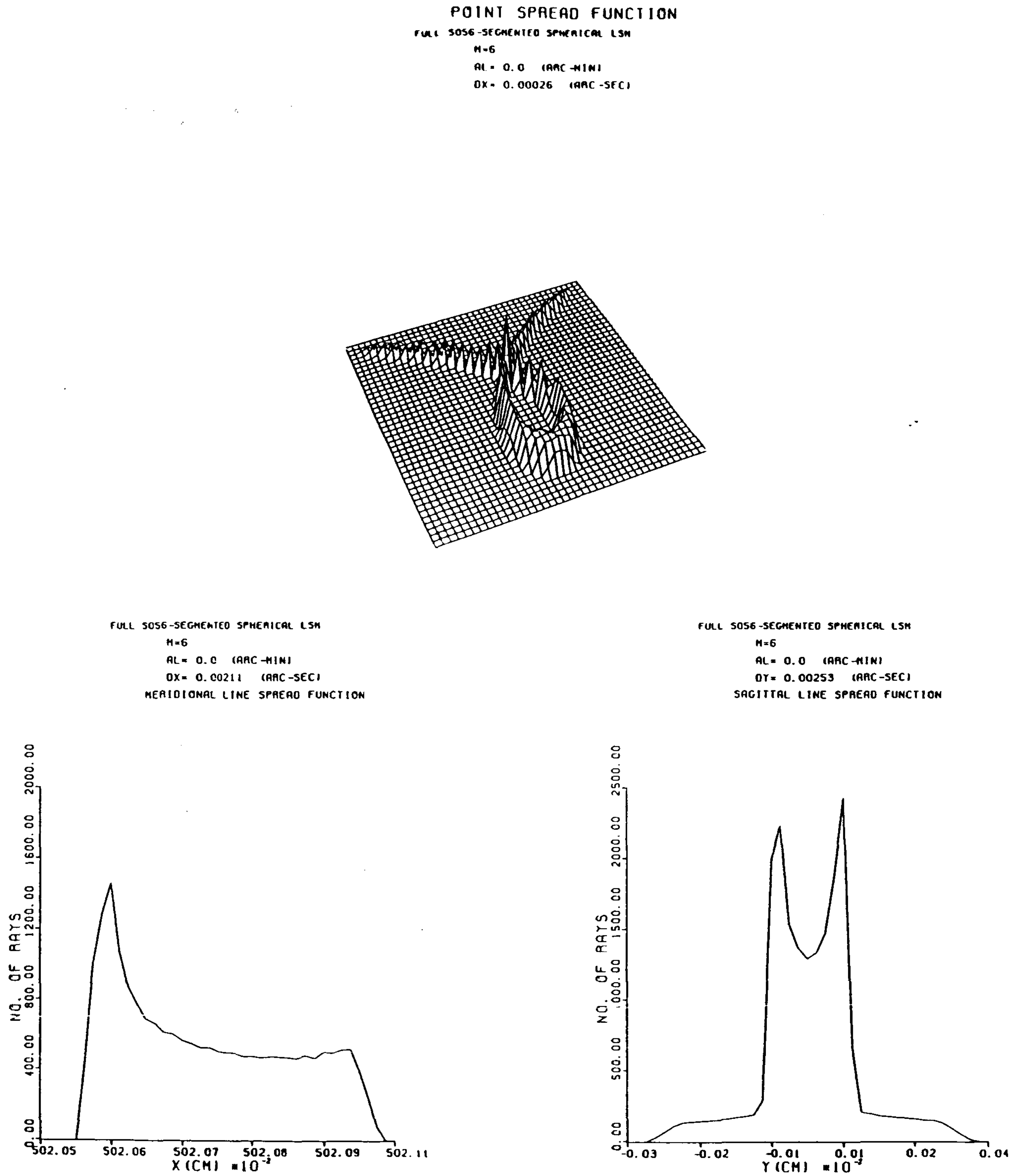
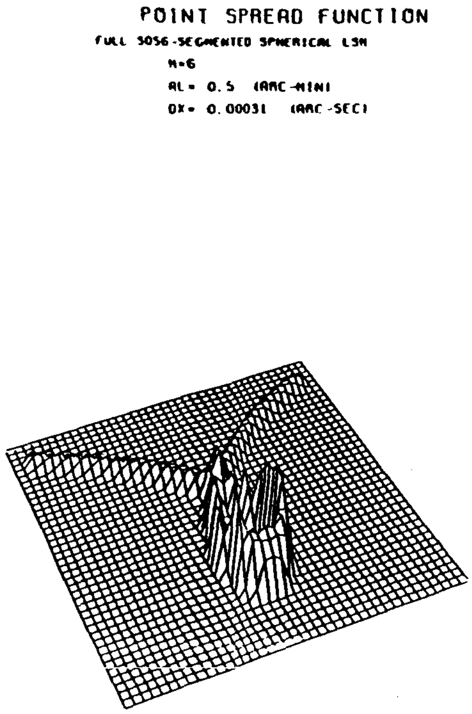


Figure 6a. Upper plot is the point spread function of the S056 Wolter I x-ray telescope (full aperture) and a spherical LSM with M=6X on the flat focal plane with minimum RMS for on axis light. The lower plots are meridional and sagittal line spread functions (LSF) for the same system. For a given value of X, the meridional LSF has been evaluated by summing the number of rays along the Y axis which intercept the image plane. The sagittal LSF has been computed in a similar manner where the role of X and Y axes are reversed. The half field angle is AL = 0 arc-mins.



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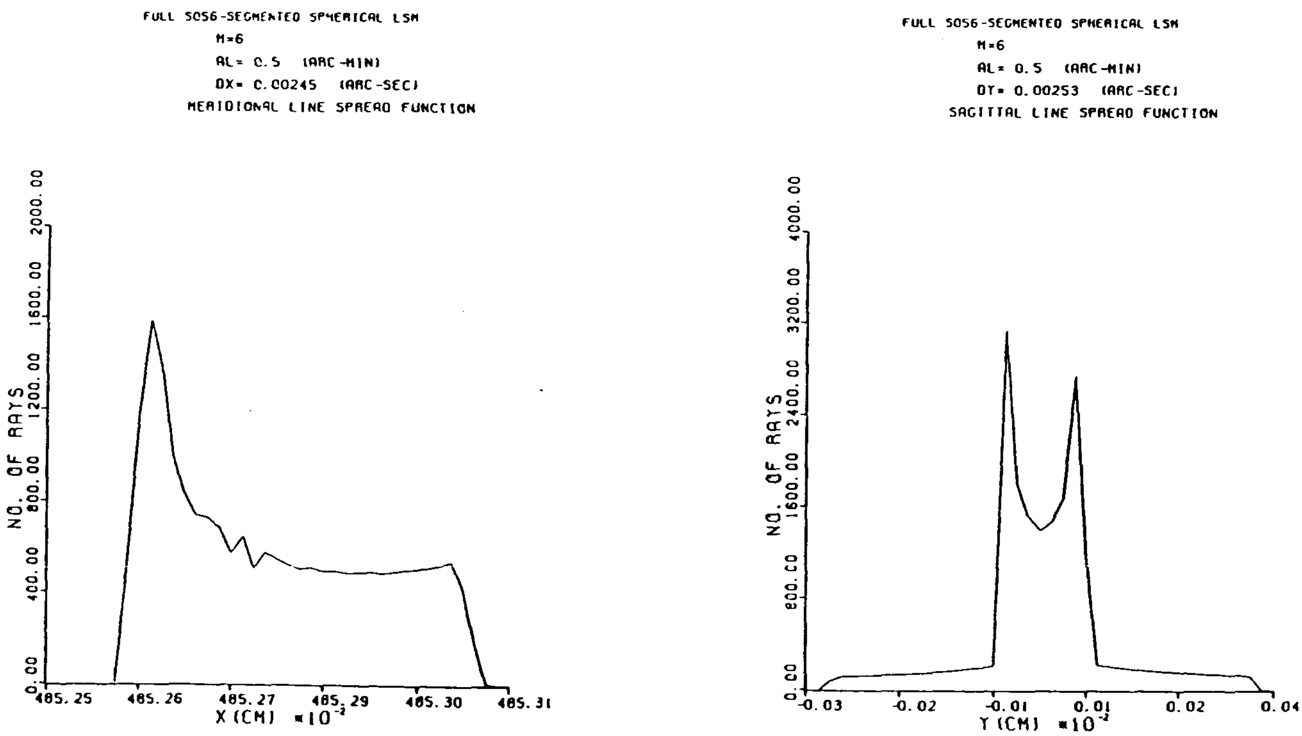


Figure 6b. Upper plot is the point spread function of the S056 Wolter I x-ray telescope (full aperture) and a spherical LSM with M=6X on the flat focal plane with minimum RMS for on axis light. The lower plots are meridional and sagittal line spread functions (LSF) for the same system. For a given value of X, the meridional LSF has been evaluated by summing the number of rays along the Y axis which intercept the image plane. The sagittal LSF has been computed in a similar manner where the role of X and Y axes are reversed. The half field angle is AL = 0.5 arc-mins.

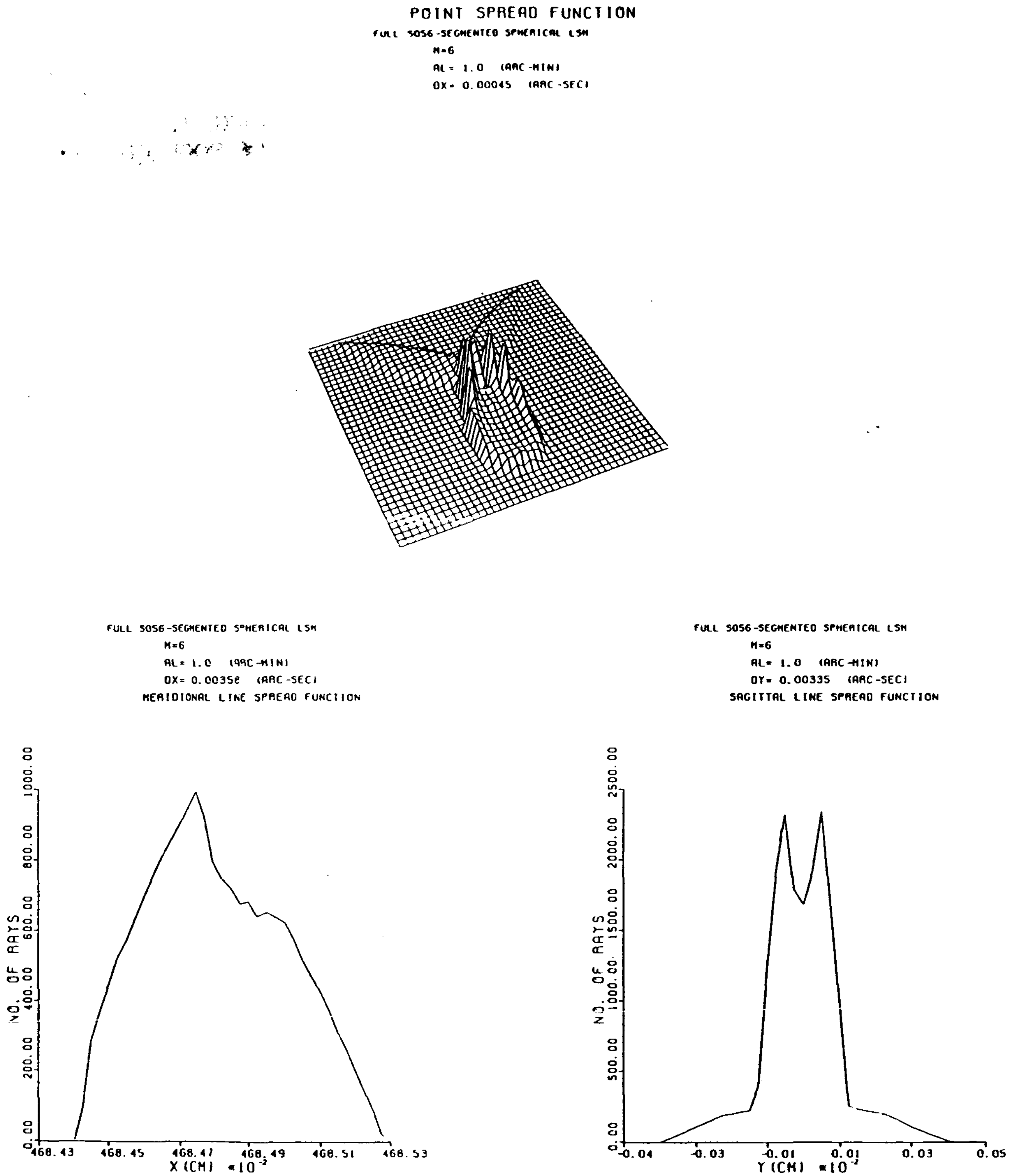


Figure 6c. Upper plot is the point spread function of the S056 Wolter I x-ray telescope (full aperture) and a spherical LSM with M=6X on the flat focal plane with minimum RMS for on axis light. The lower plots are meridional and sagittal line spread functions (LSF) for the same system. For a given value of X, the meridional LSF has been evaluated by summing the number of rays along the Y axis which intercept the image plane. The sagittal LSF has been computed in a similar manner where the role of X and Y axes are reversed. The half field angle is AL = 1.0 arc-mins.

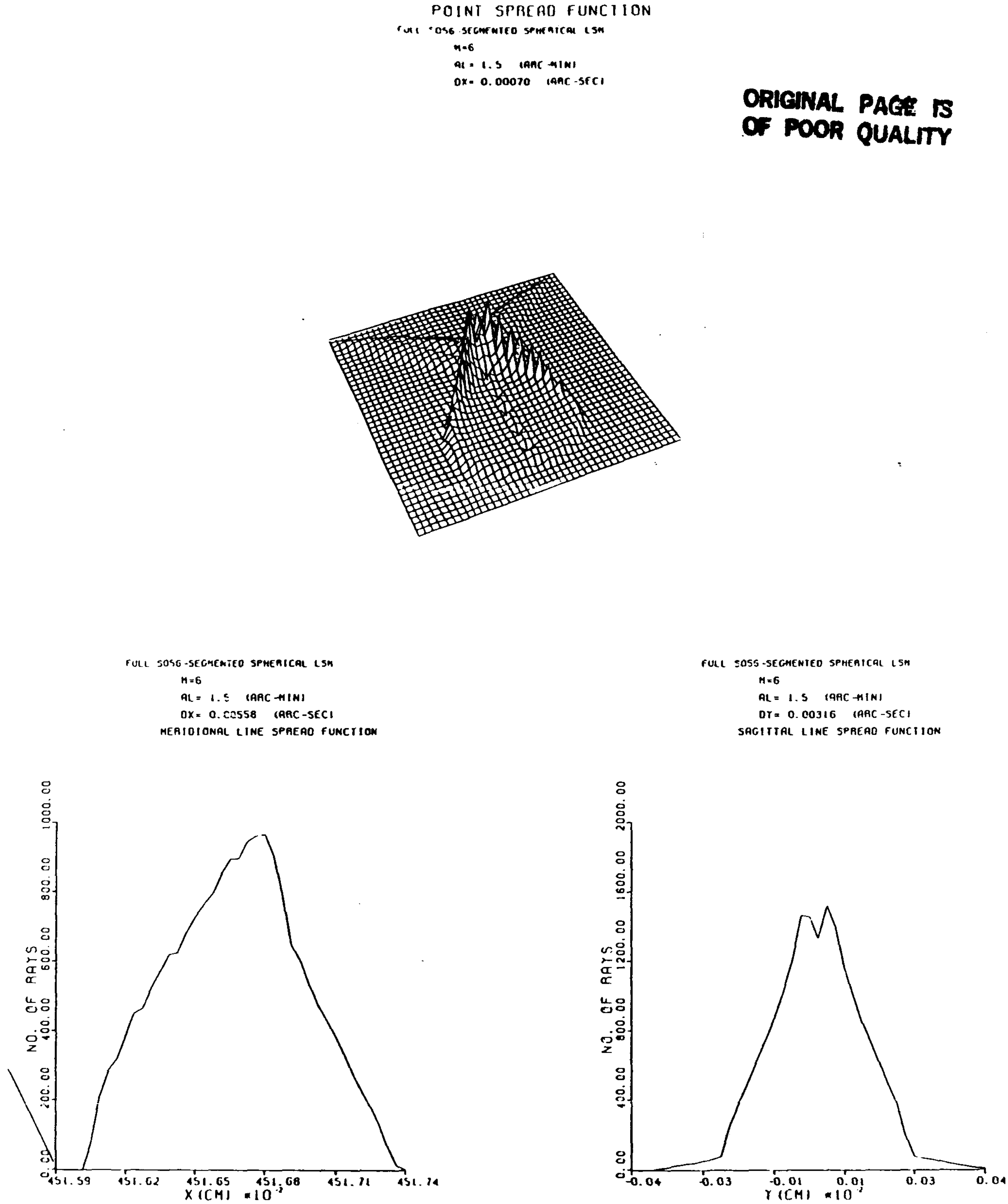


Figure 6d. Upper plot is the point spread function of the S056 Wolter I x-ray telescope (full aperture) and a spherical LSM with M=6X on the flat focal plane with minimum RMS for on axis light. The lower plots are meridional and sagittal line spread functions (LSF) for the same system. For a given value of X, the meridional LSF has been evaluated by summing the number of rays along the Y axis which intercept the image plane. The sagittal LSF has been computed in a similar manner where the role of X and Y axes are reversed. The half field angle is AL = 1.5 arc-mins.

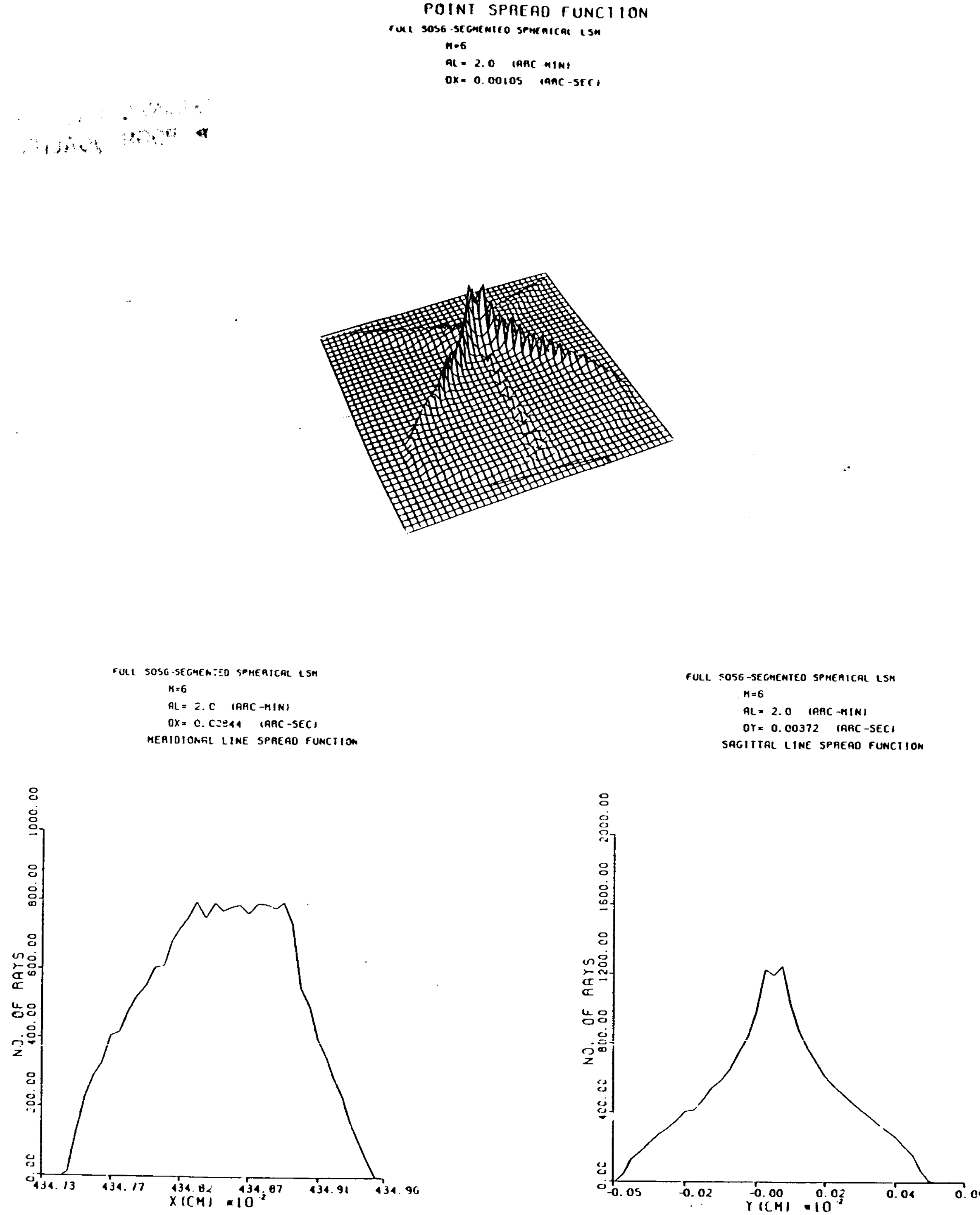


Figure 6e. Upper plot is the point spread function of the S056 Wolter I x-ray telescope (full aperture) and a spherical LSM with M=6X on the flat focal plane with minimum RMS for on axis light. The lower plots are meridional and sagittal line spread functions (LSF) for the same system. For a given value of X, the meridional LSF has been evaluated by summing the number of rays along the Y axis which intercept the image plane. The sagittal LSF has been computed in a similar manner where the role of X and Y axes are reversed. The half field angle is AL = 2 arc-mins.

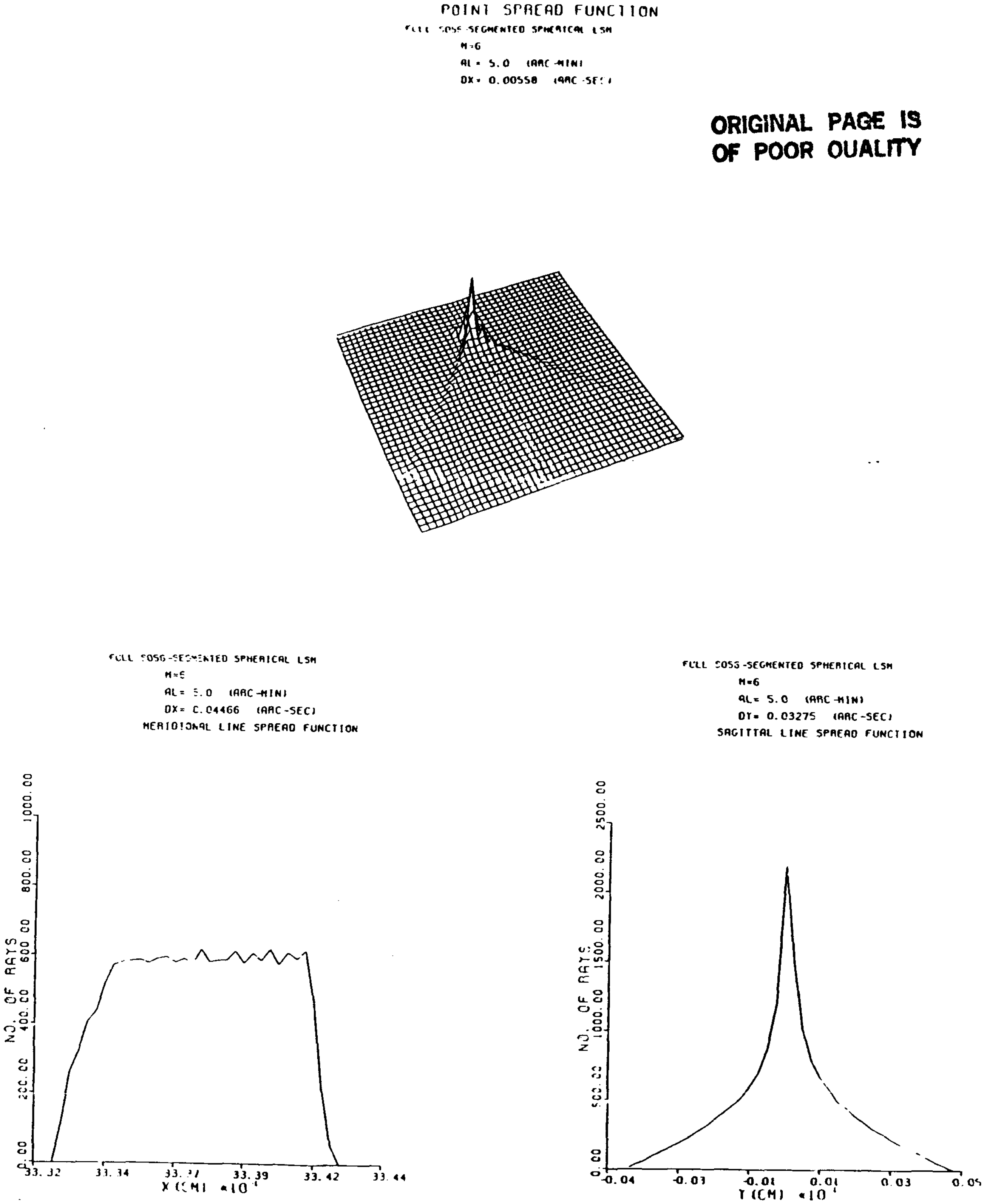


Figure 6f. Upper plot is the point spread function of the S056 Wolter I x-ray telescope (full aperture) and a spherical LSM with M=6X on the flat focal plane with minimum RMS for on axis light. The lower plots are meridional and sagittal line spread functions (LSF) for the same system. For a given value of X, the meridional LSF has been evaluated by summing the number of rays along the Y axis which intercept the image plane. The sagittal LSF has been computed in a similar manner where the role of X and Y axes are reversed. The half field angle is AL = 5 arc-mins.

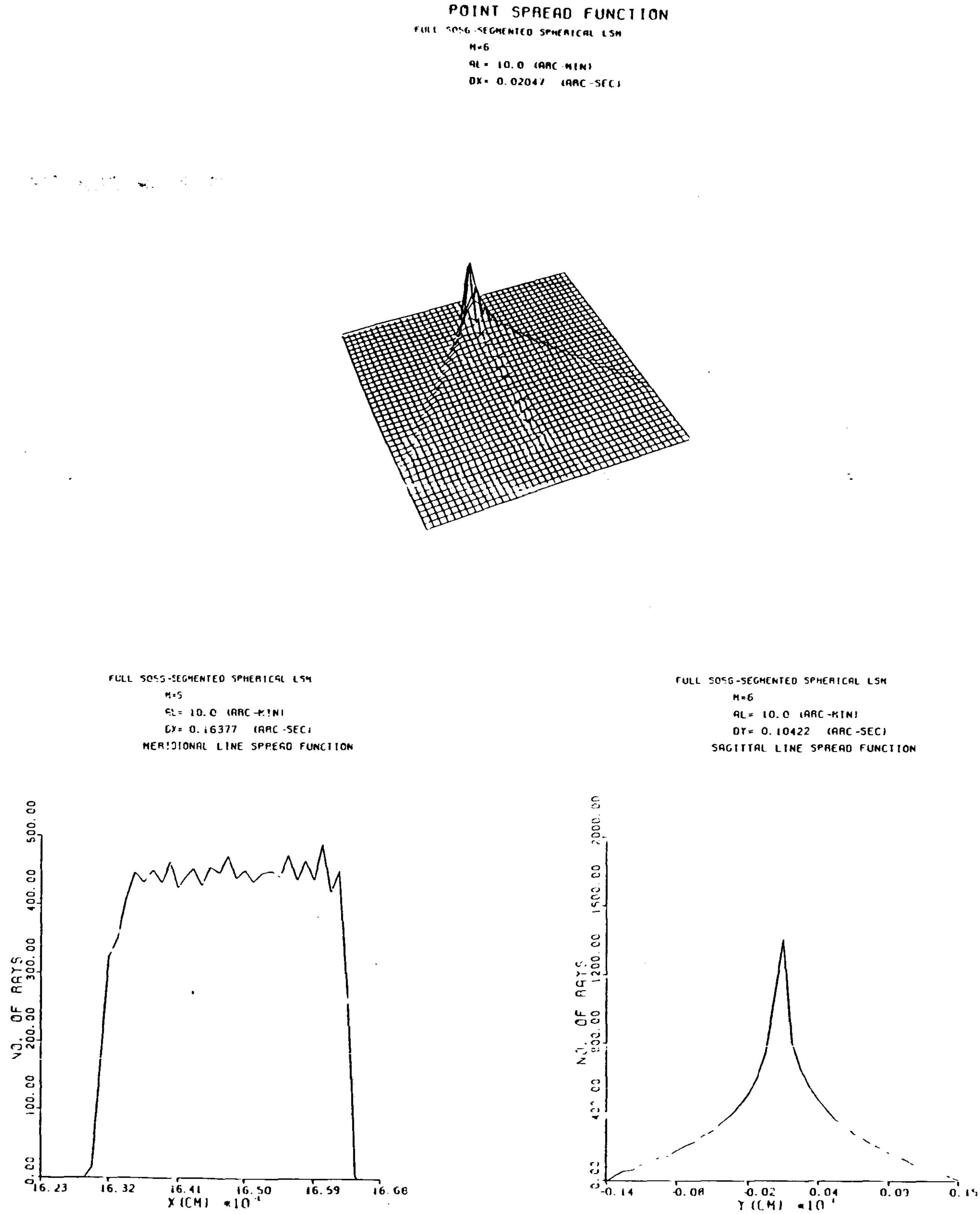
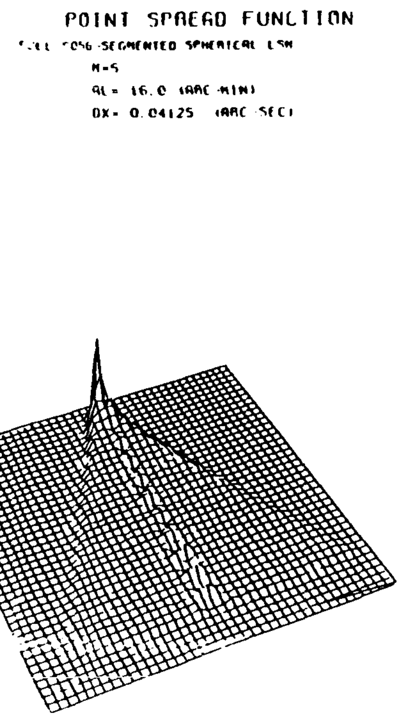
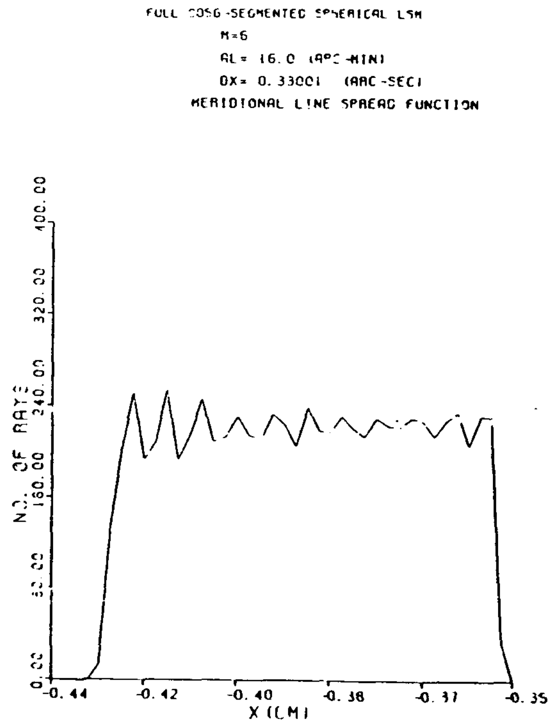


Figure 6g. Upper plot is the point spread function of the S056 Wolter I x-ray telescope (full aperture) and a spherical LSM with M=6X on the flat focal plane with minimum RMS for on axis light. The lower plots are meridional and sagittal line spread functions (LSF) for the same system. For a given value of X, the meridional LSF has been evaluated by summing the number of rays along the Y axis which intercept the image plane. The sagittal LSF has been computed in a similar manner where the role of X and Y axes are reversed. The half field angle is AL = 10 arc-mins.





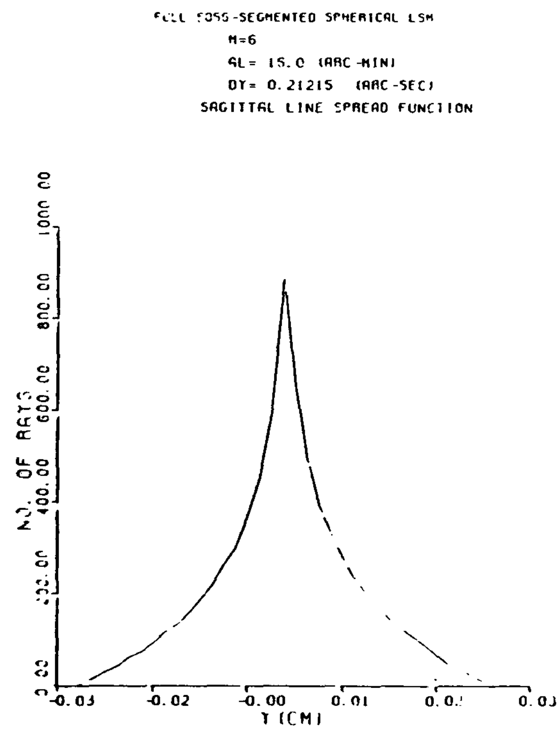


Figure 6h. Upper plot is the point spread function of the S056 Wolter I x-ray telescope (full aperture) and a spherical LSM with M=6X on the flat focal plane with minimum RMS for on axis light. The lower plots are meridional and sagittal line spread functions (LSF) for the same system. For a given value of X, the meridional LSF has been evaluated by summing the number of rays along the Y axis which intercept the image plane. The sagittal LSF has been computed in a similar manner where the role of X and Y axes are reversed. The half field angle is AL = 16 arc-mins.

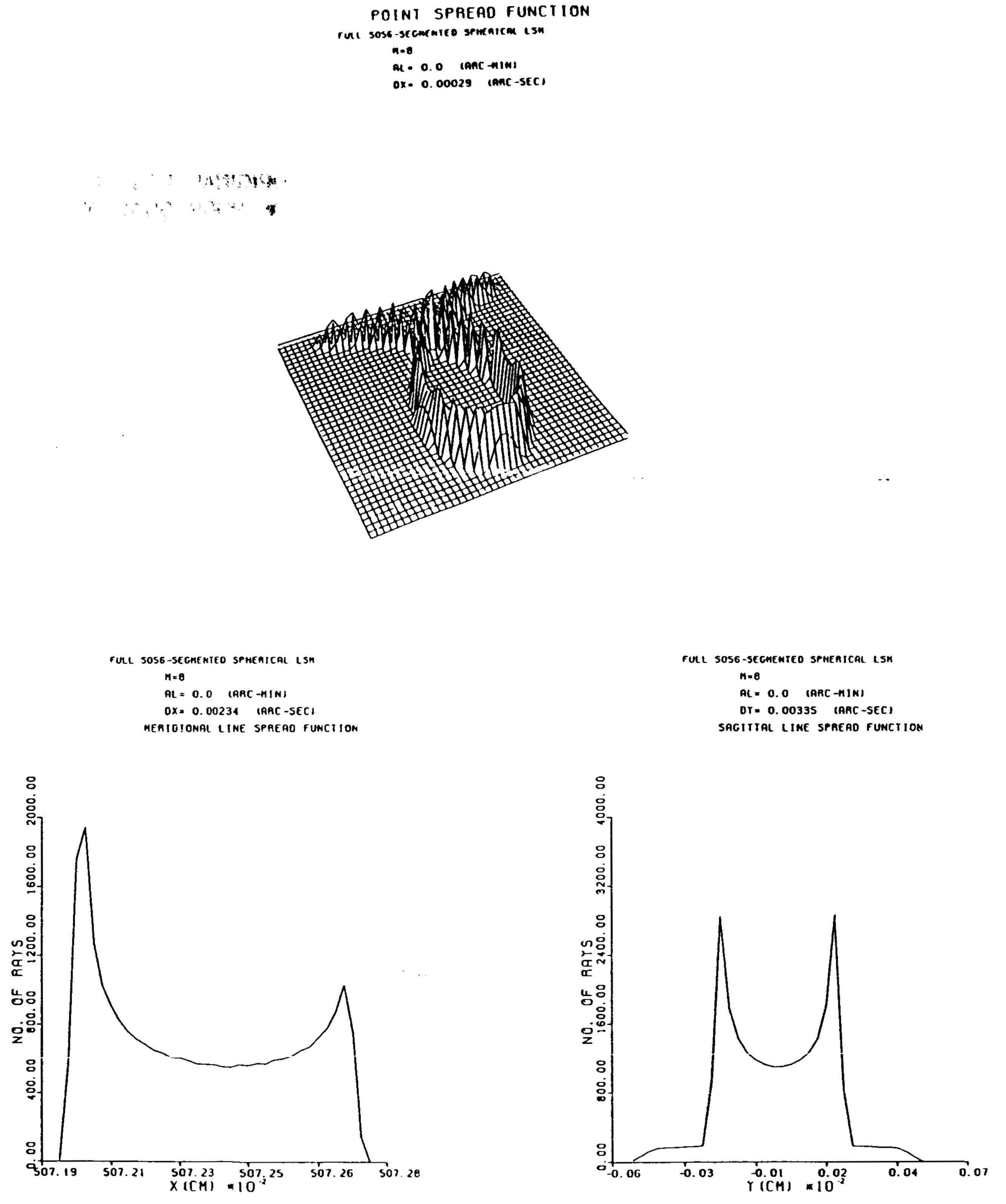


Figure 7a. Upper plot is the point spread function of the S056 Wolter I x-ray telescope (full aperture) and a spherical LSM with M=8X on the flat focal plane with minimum RMS for on axis light. The lower plots are meridional and sagittal line spread functions (LSF) for the same system. For a given value of X, the meridional LSF has been evaluated by summing the number of rays along the Y axis which intercept the image plane. The sagittal LSF has been computed in a similar manner where the role of X and Y axes are reversed. The half field angle is AL = 0 arc-mins.

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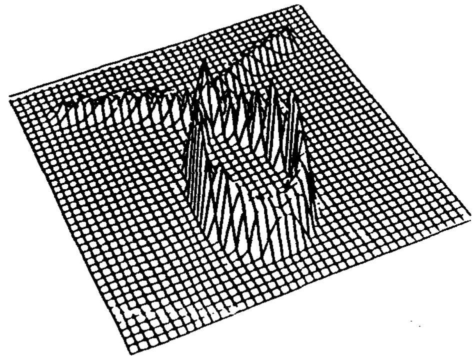
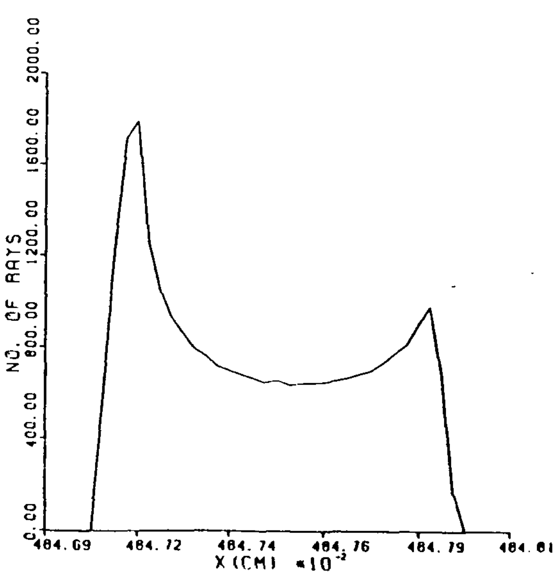




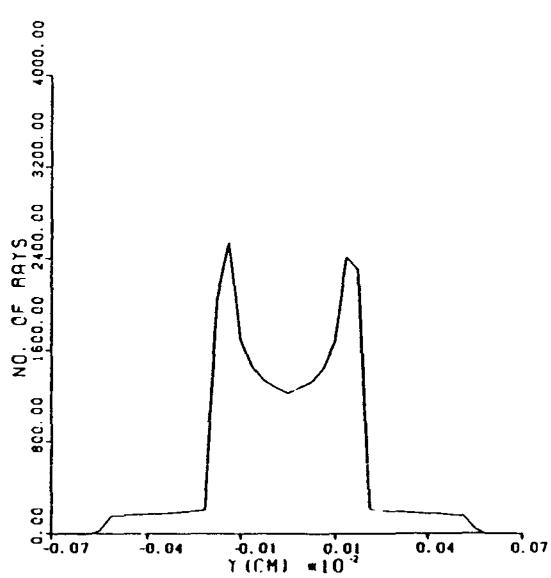


Figure 7b. Upper plot is the point spread function of the S056 Wolter I x-ray telescope (full aperture) and a spherical LSM with M=8X on the flat focal plane with minimum RMS for on axis light. The lower plots are meridional and sagittal line spread functions (LSF) for the same system. For a given value of X, the meridional LSF has been evaluated by summing the number of rays along the Y axis which intercept the image plane. The sagittal LSF has been computed in a similar manner where the role of X and Y axes are reversed. The half field angle is AL = 0.5 arc-mins.

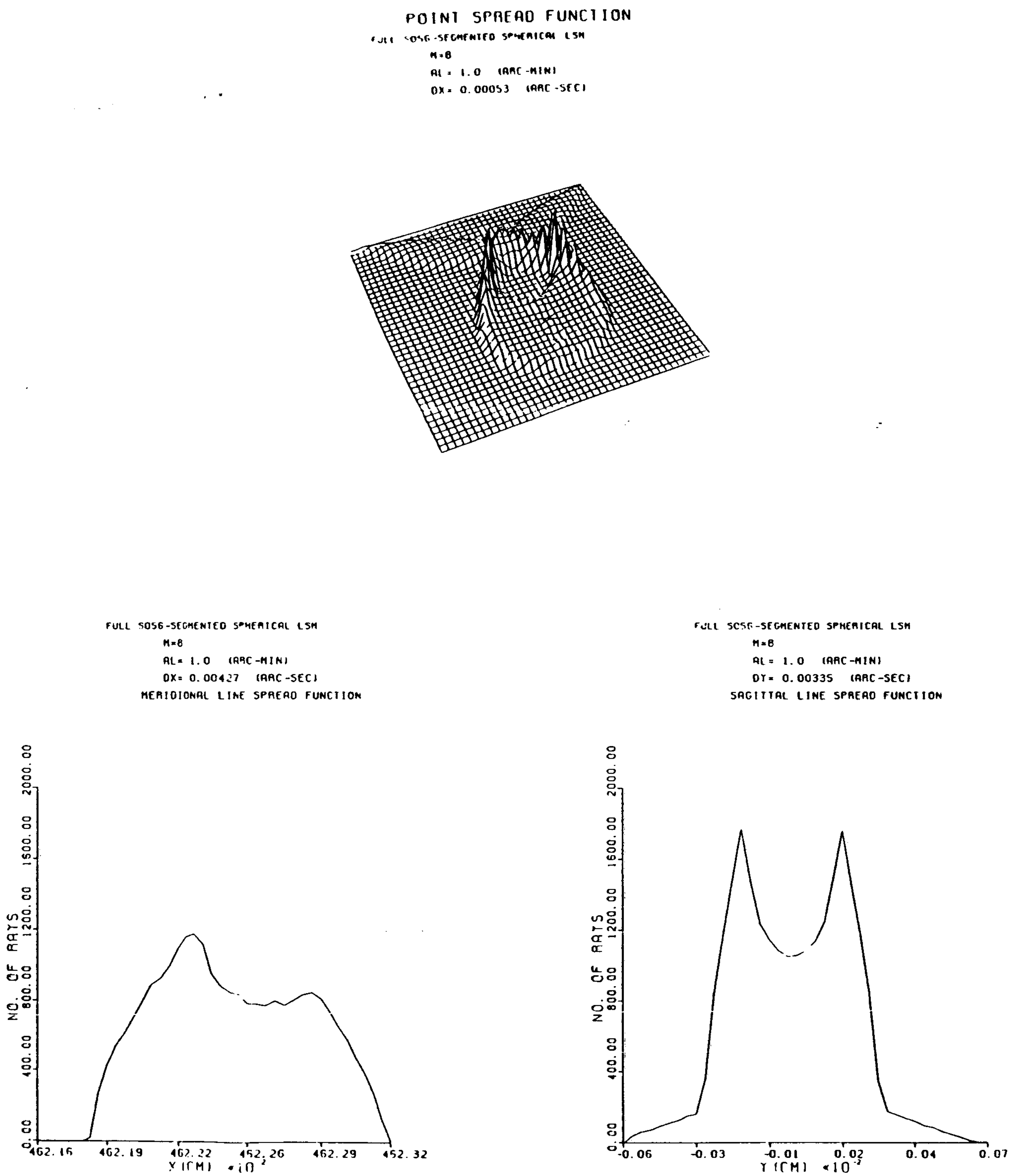


Figure 7c. Upper plot is the point spread function of the S056 Wolter I x-ray telescope (full aperture) and a spherical LSM with M=8X on the flat focal plane with minimum RMS for on axis light. The lower plots are meridional and sagittal line spread functions (LSF) for the same system. For a given value of X, the meridional LSF has been evaluated by summing the number of rays along the Y axis which intercept the image plane. The sagittal LSF has been computed in a similar manner where the role of X and Y axes are reversed. The half field angle is AL = 1.0 arc-mins.

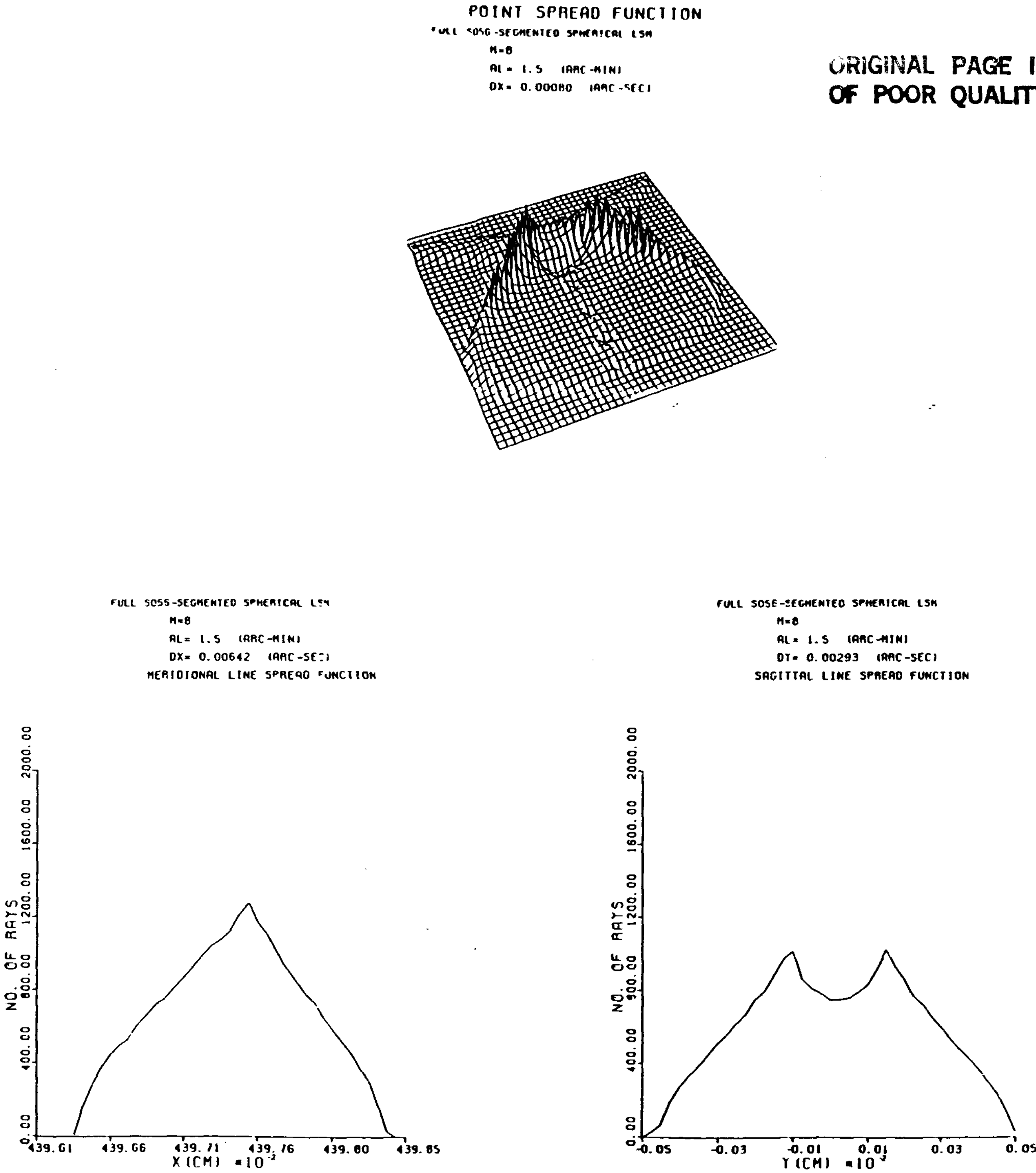


Figure 7d. Upper plot is the point spread function of the S056 Wolter I x-ray telescope (full aperture) and a spherical LSM with M=8X on the flat focal plane with minimum RMS for on axis light. The lower plots are meridional and sagittal line spread functions (LSF) for the same system. For a given value of X, the meridional LSF has been evaluated by summing the number of rays along the Y axis which intercept the image plane. The sagittal LSF has been computed in a similar manner where the role of X and Y axes are reversed. The half field angle is AL = 1.5 arc-mins.

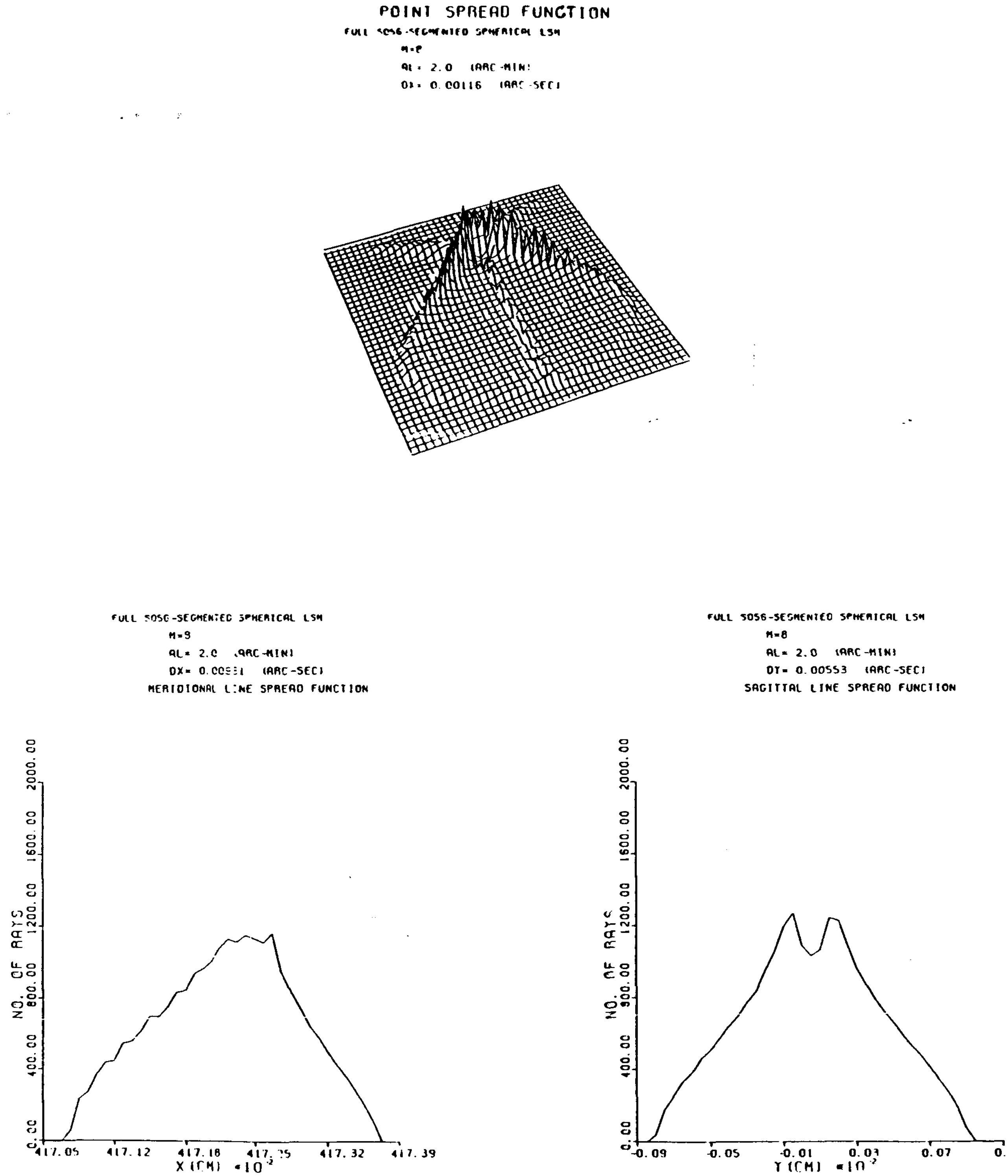
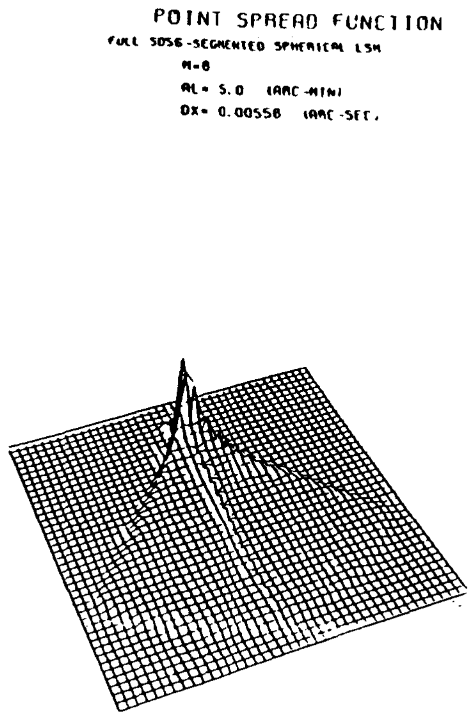
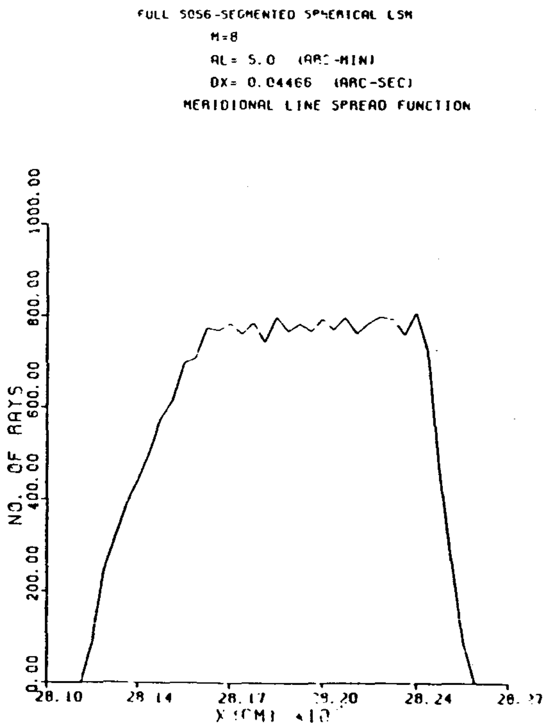


Figure 7e. Upper plot is the point spread function of the S056 Wolter I x-ray telescope (full aperture) and a spherical LSM with M=8X on the flat focal plane with minimum RMS for on axis light. The lower plots are meridional and sagittal line spread functions (LSF) for the same system. For a given value of X, the meridional LSF has been evaluated by summing the number of rays along the Y axis which intercept the image plane. The sagittal LSF has been computed in a similar manner where the role of X and Y axes are reversed. The half field angle is AL = 2 arc-mins.





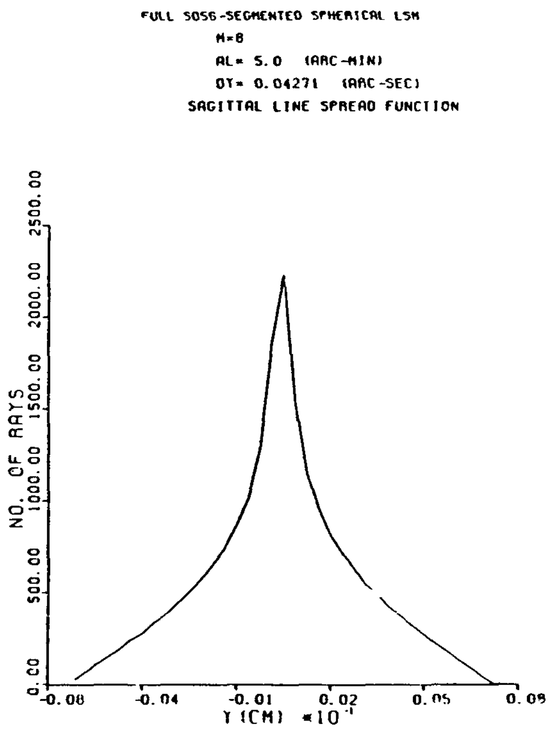
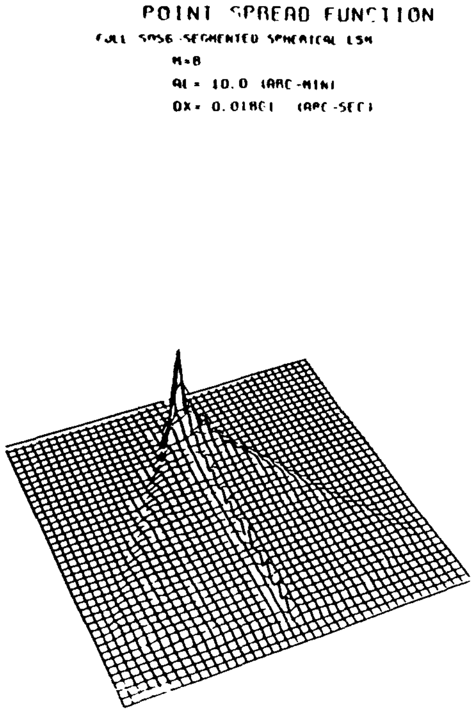
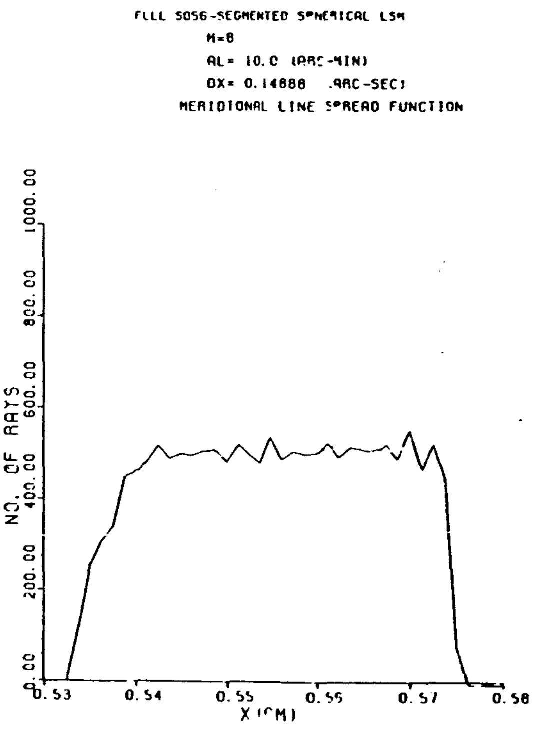


Figure 7f. Upper plot is the point spread function of the S056 Wolter I x-ray telescope (full aperture) and a spherical LSM with M=8X on the flat focal plane with minimum RMS for on axis light. The lower plots are meridional and sagittal line spread functions (LSF) for the same system. For a given value of X, the meridional LSF has been evaluated by summing the number of rays along the Y axis which intercept the image plane. The sagittal LSF has been computed in a similar manner where the role of X and Y axes are reversed. The half field angle is AL = 5 arc-mins.





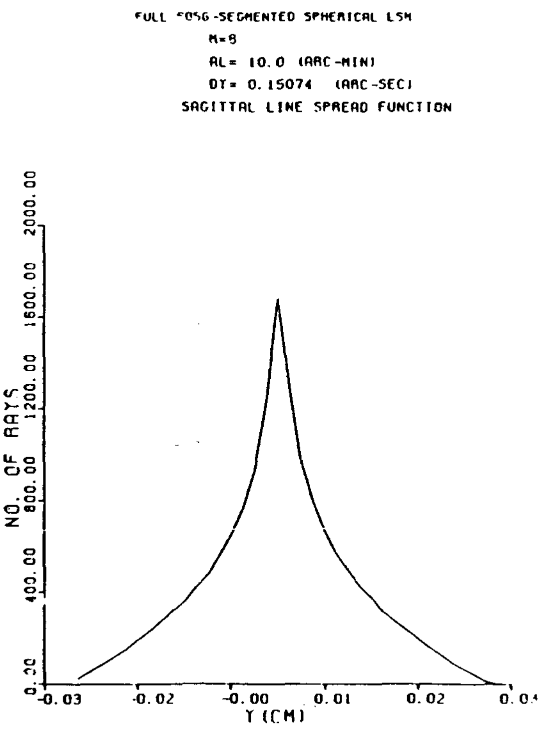


Figure 7g. Upper plot is the point spread function of the S056 Wolter I x-ray telescope (full aperture) and a spherical LSM with M=8X on the flat focal plane with minimum RMS for on axis light. The lower plots are meridional and sagittal line spread functions (LSF) for the same system. For a given value of X, the meridional LSF has been evaluated by summing the number of rays along the Y axis which intercept the image plane. The sagittal LSF has been computed in a similar manner where the role of X and Y axes are reversed. The half field angle is AL = 10 arc-mins.

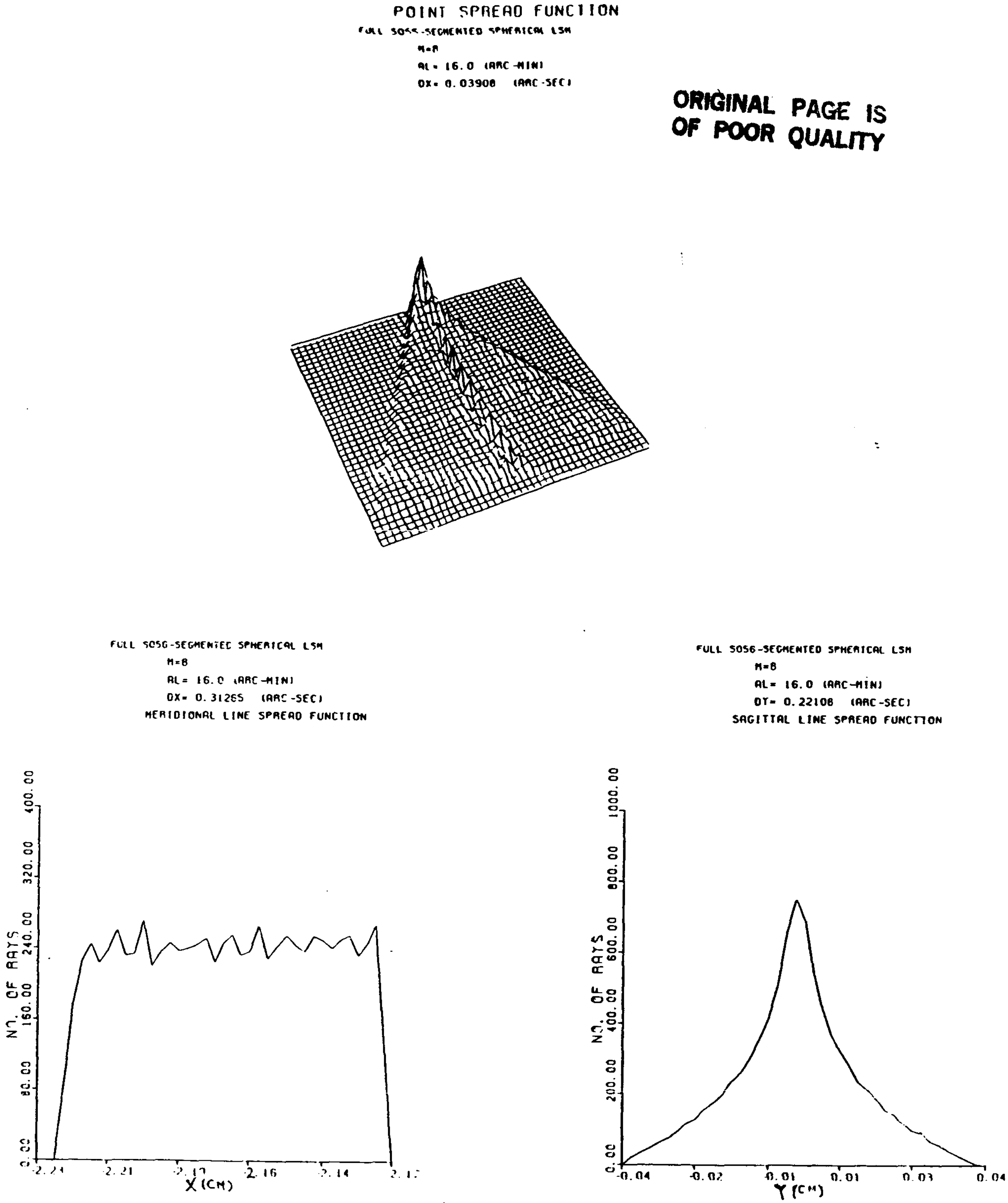


Figure 7h. Upper plot is the point spread function of the S056 Wolter I x-ray telescope (full aperture) and a spherical LSM with M=8X on the flat focal plane with minimum RMS for on axis light. The lower plots are meridional and sagittal line spread functions (LSF) for the same system. For a given value of X, the meridional LSF has been evaluated by summing the number of rays along the Y axis which intercept the image plane. The sagittal LSF has been computed in a similar manner where the role of X and Y axes are reversed. The half field angle is AL = 16 arc-mins.

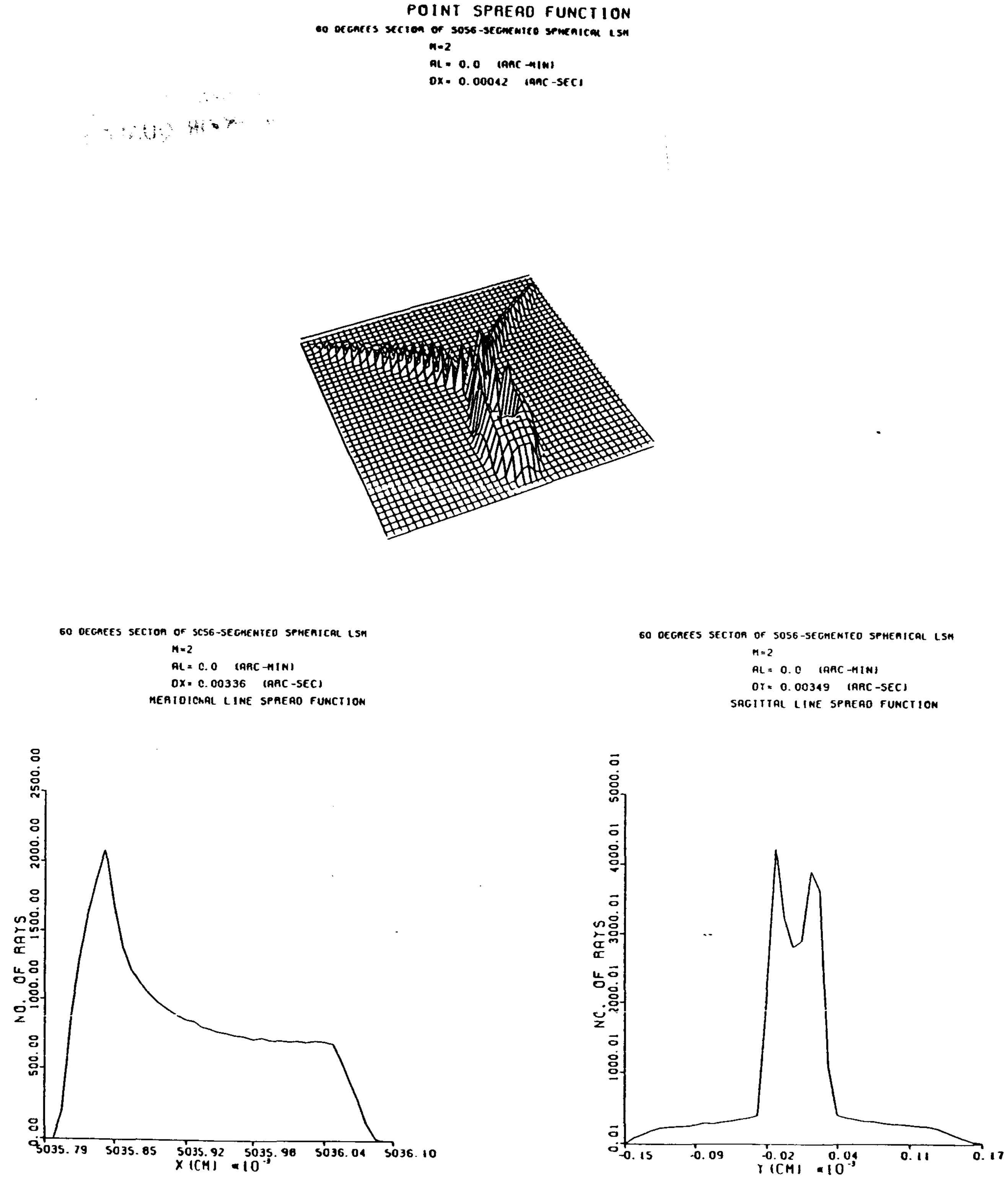
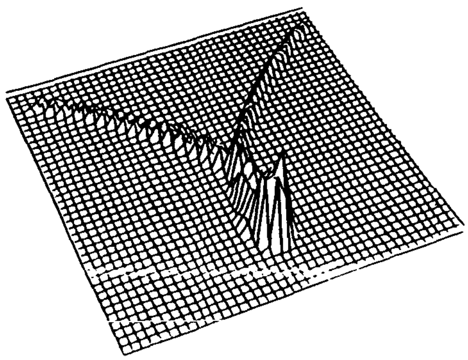
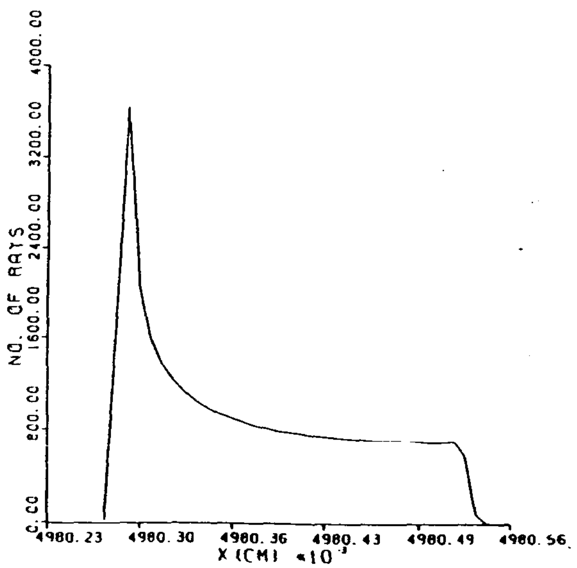


Figure 8a. Upper plot is the point spread function of the S056 Wolter I x-ray telescope (60° segmented aperture) and a spherical LSM with M=2X on the flat focal plane with minimum RMS for on axis light. The lower plots are meridional and sagittal line spread functions (LSF) for the same system. For a given value of X, the meridional LSF has been evaluated by summing the number of rays along the Y axis which intercept the image plane. The sagittal LSF has been computed in a similar manner where the role of X and Y axes are reversed. The half field angle is AL = 0 arc-mins.

POINT SPREAD FUNCTION
60 DEGREES SECTION OF S056-SEGMENTED SPHERICAL LSM
M=2
AL= 0.5 (ARC-MIN)
DX= 0.00044 (ARC-SEC)



60 DEGREES SECTION OF S056-SEGMENTED SPHERICAL LSM
M=2
AL= 0.5 (ARC-MIN)
DX= 0.00252 (ARC-SEC)
MERIDIONAL LINE SPREAD FUNCTION



60 DEGREES SECTION OF S056-SEGMENTED SPHERICAL LSM
M=2
AL= 0.5 (ARC-MIN)
DY= 0.00399 (ARC-SEC)
SAGITTAL LINE SPREAD FUNCTION

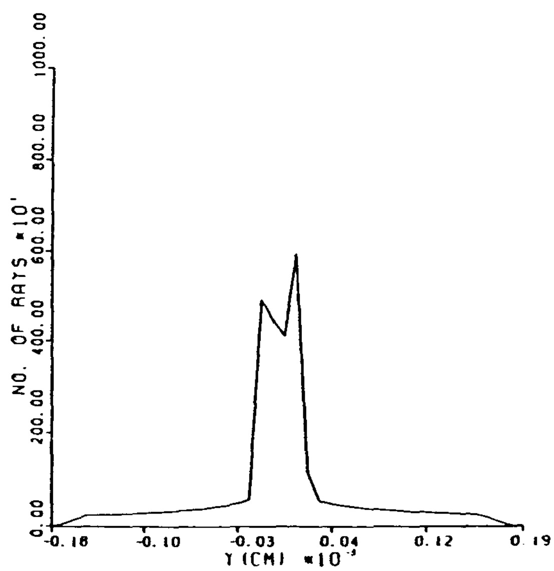
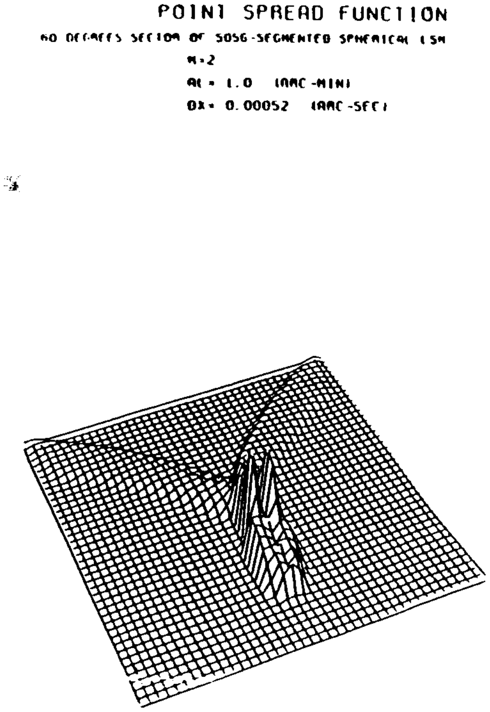
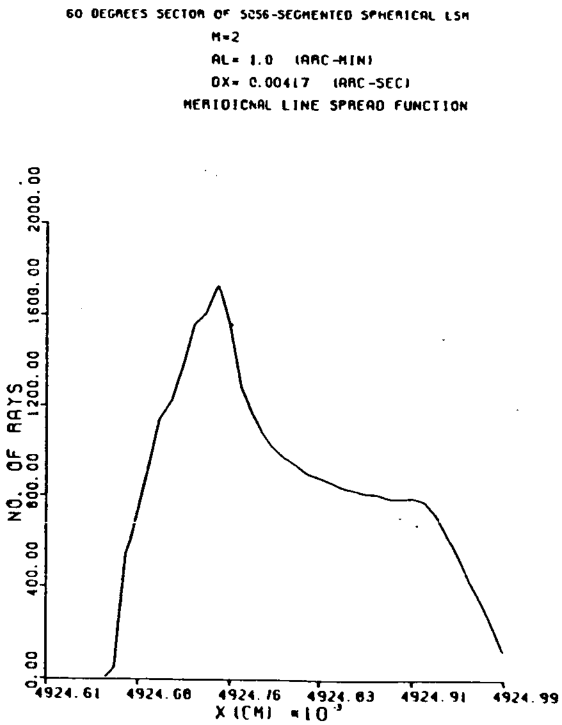


Figure 8b. Upper plot is the point spread function of the S056 Wolter I x-ray telescope (60° segmented aperture) and a spherical LSM with M=2X on the flat focal plane with minimum RMS for on axis light. The lower plots are meridional and sagittal line spread functions (LSF) for the same system. For a given value of X, the meridional LSF has been evaluated by summing the number of rays along the Y axis which intercept the image plane. The sagittal LSF has been computed in a similar manner where the role of X and Y axes are reversed. The half field angle is AL = 0.5 arc-mins.





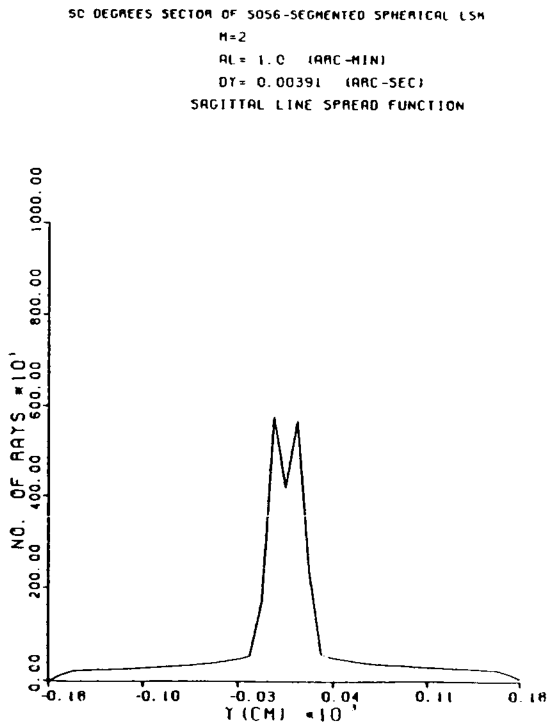
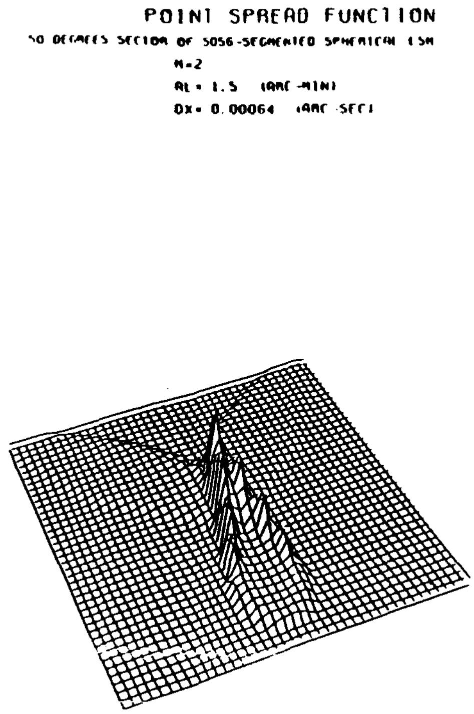
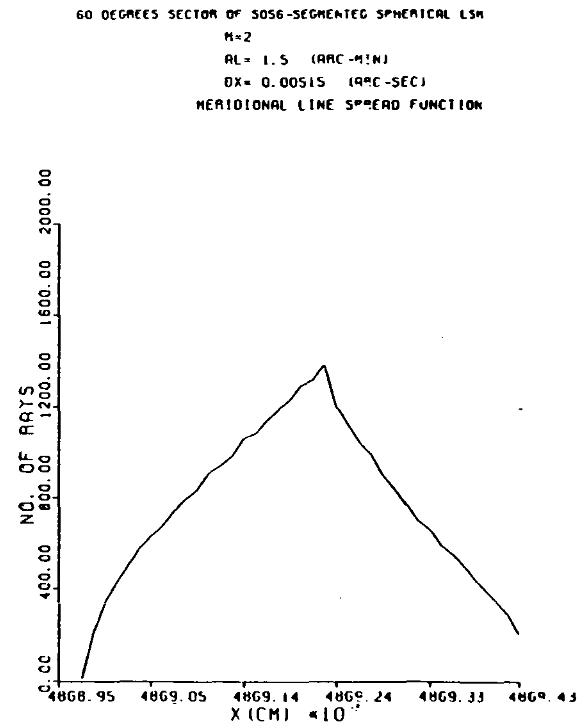


Figure 8c. Upper plot is the point spread function of the S056 Wolter I x-ray telescope (60° segmented aperture) and a spherical LSM with M=2X on the flat focal plane with minimum RMS for on axis light. The lower plots are meridional and sagittal line spread functions (LSF) for the same system. For a given value of X, the meridional LSF has been evaluated by summing the number of rays along the Y axis which intercept the image plane. The sagittal LSF has been computed in a similar manner where the role of X and Y axes are reversed. The half field angle is AL = 1.0 arc-mins.





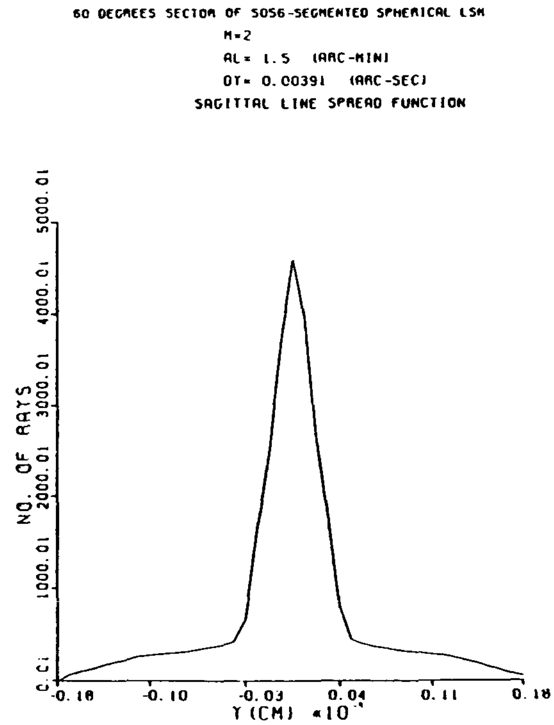
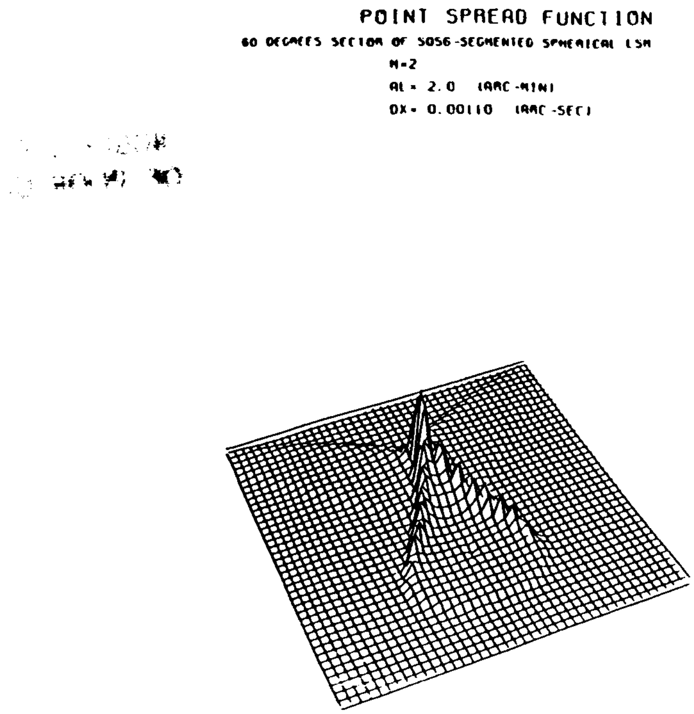
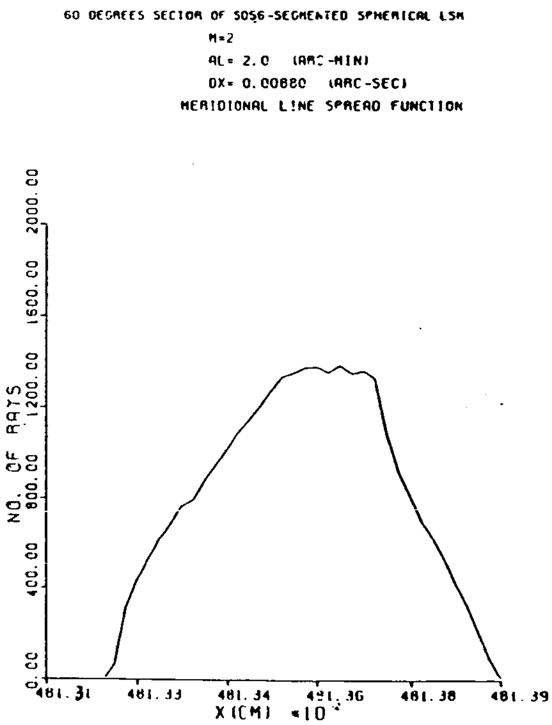


Figure 8d. Upper plot is the point spread function of the S056 Wolter I x-ray telescope (60° segmented aperture) and a spherical LSM with M=2X on the flat focal plane with minimum RMS for on axis light. The lower plots are meridional and sagittal line spread functions (LSF) for the same system. For a given value of X, the meridional LSF has been evaluated by summing the number of rays along the Y axis which intercept the image plane. The sagittal LSF has been computed in a similar manner where the role of X and Y axes are reversed. The half field angle is AL = 1.5 arc-mins.





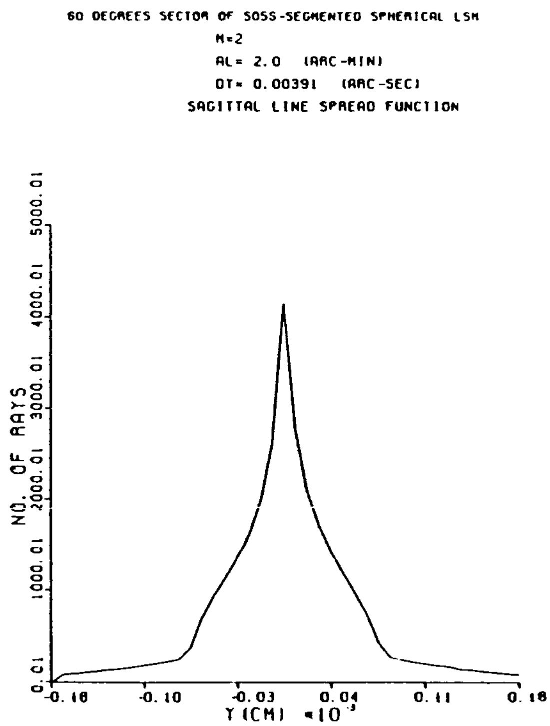
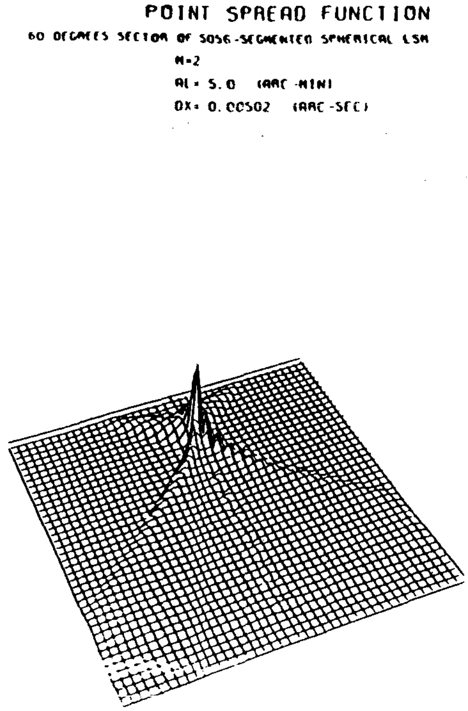
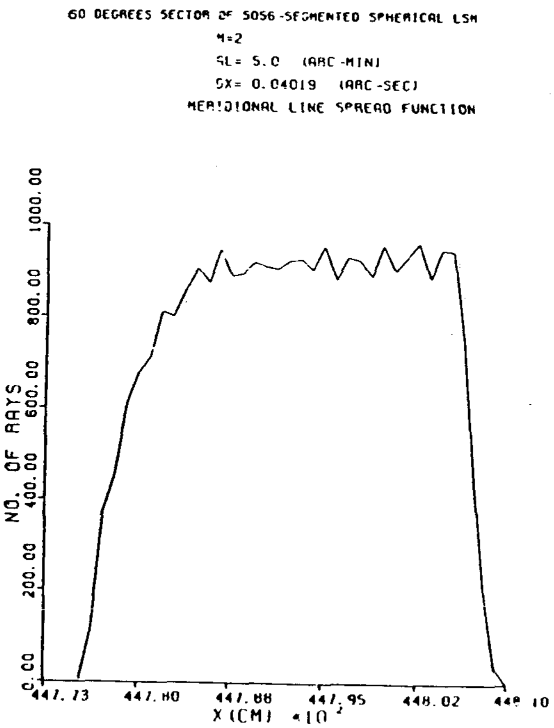


Figure 8e. Upper plot is the point spread function of the S056 Wolter I x-ray telescope (60° segmented aperture) and a spherical LSM with M=2X on the flat focal plane with minimum RMS for on axis light. The lower plots are meridional and sagittal line spread functions (LSF) for the same system. For a given value of X, the meridional LSF has been evaluated by summing the number of rays along the Y axis which intercept the image plane. The sagittal LSF has been computed in a similar manner where the role of X and Y axes are reversed. The half field angle is AL = 2 arc-mins.





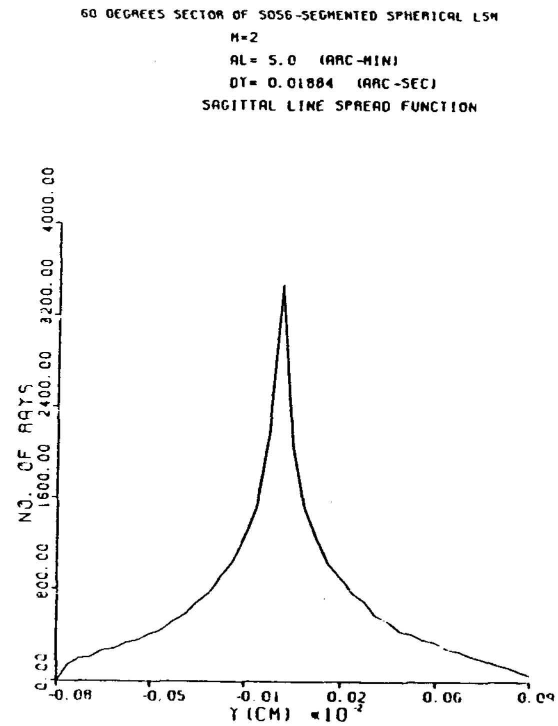


Figure 8f. Upper plot is the point spread function of the S056 Wolter I x-ray telescope (60° segmented aperture) and a spherical LSM with M=2X on the flat focal plane with minimum RMS for on axis light. The lower plots are meridional and sagittal line spread functions (LSF) for the same system. For a given value of X, the meridional LSF has been evaluated by summing the number of rays along the Y axis which intercept the image plane. The sagittal LSF has been computed in a similar manner where the role of X and Y axes are reversed. The half field angle is AL = 5 arc-mins.

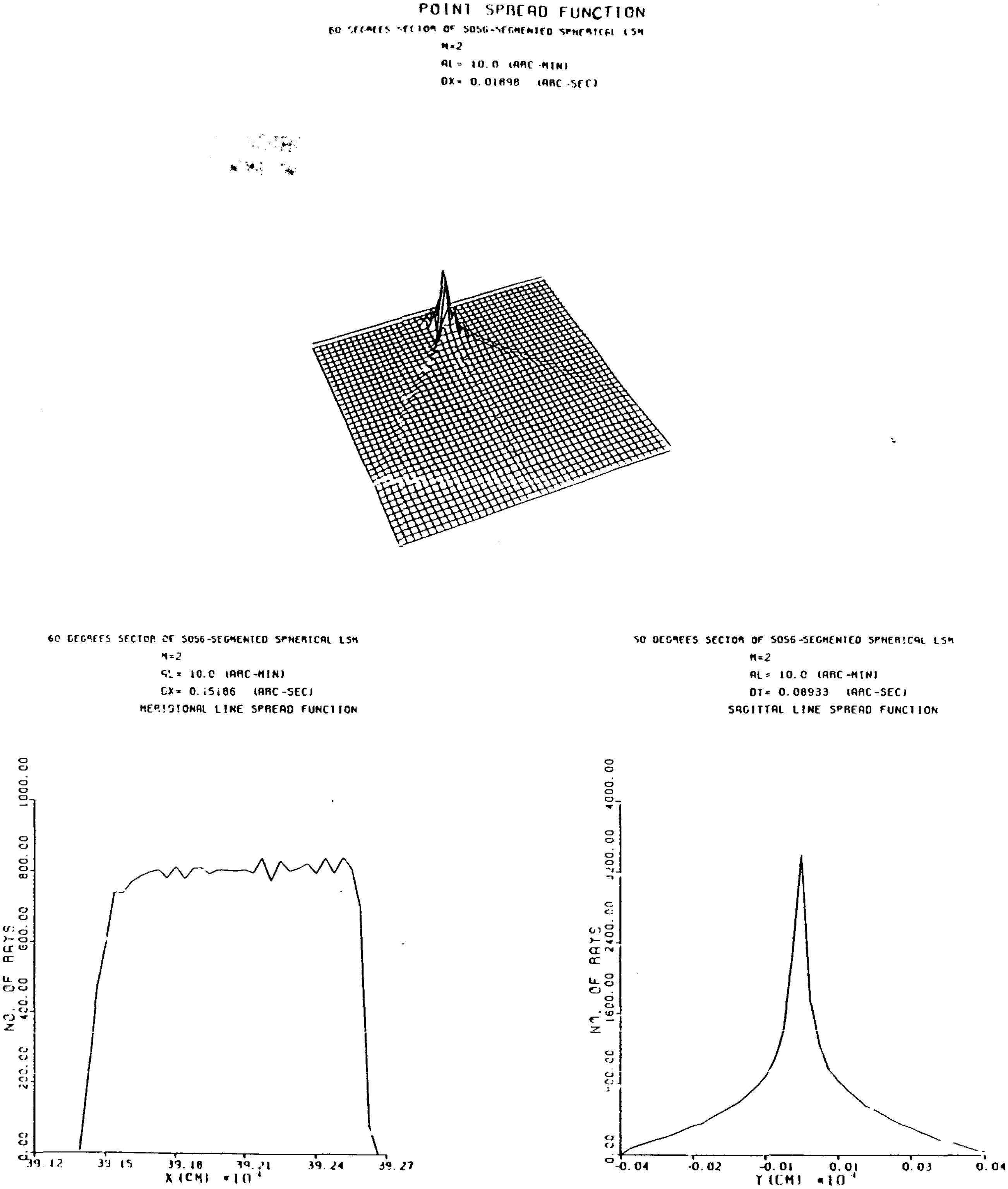


Figure 8g. Upper plot is the point spread function of the S056 Wolter I x-ray telescope (60° segmented aperture) and a spherical LSM with M=2X on the flat focal plane with minimum RMS for on axis light. The lower plots are meridional and sagittal line spread functions (LSF) for the same system. For a given value of X, the meridional LSF has been evaluated by summing the number of rays along the Y axis which intercept the image plane. The sagittal LSF has been computed in a similar manner where the role of X and Y axes are reversed. The half field angle is AL = 10 arc-mins.

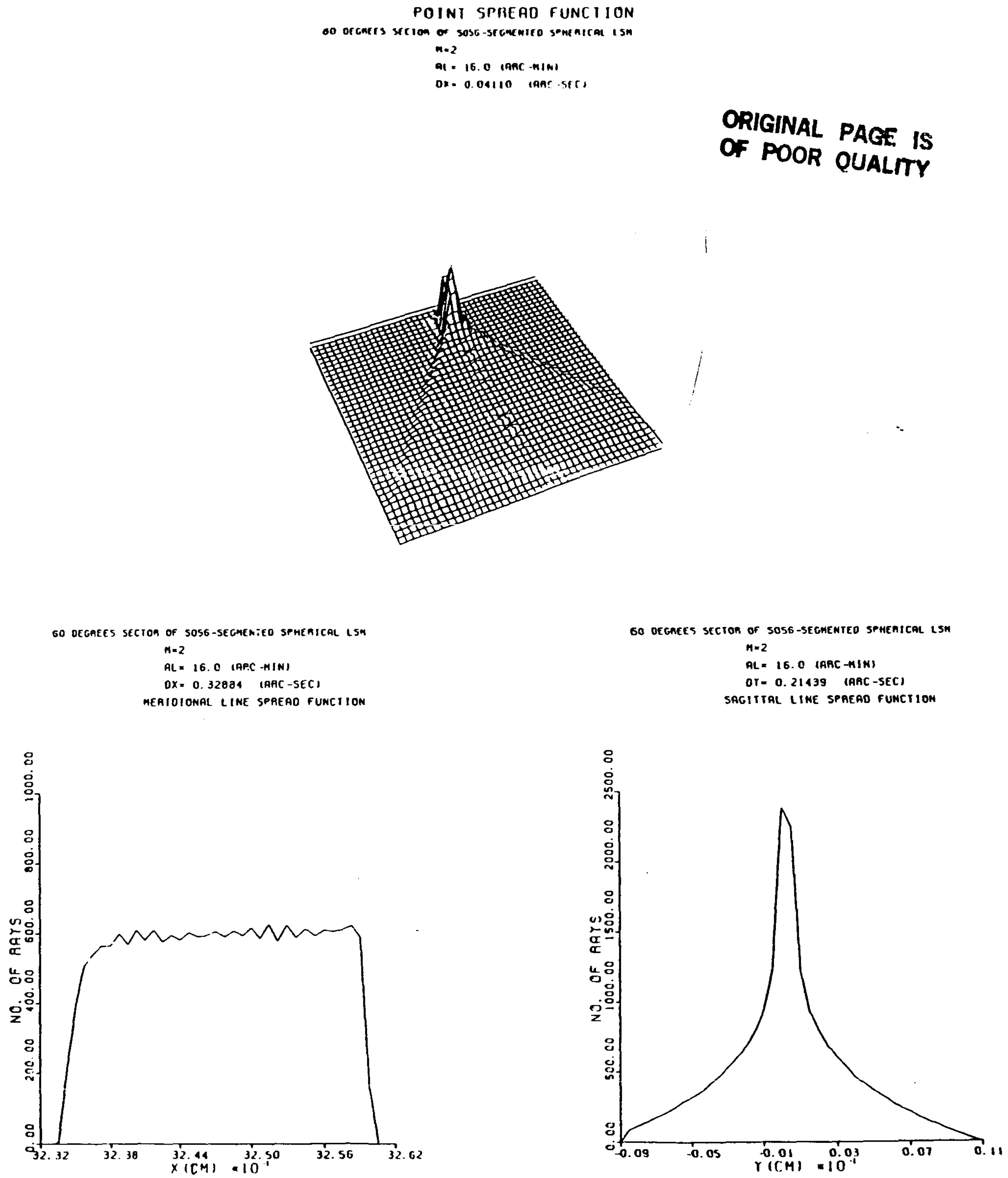
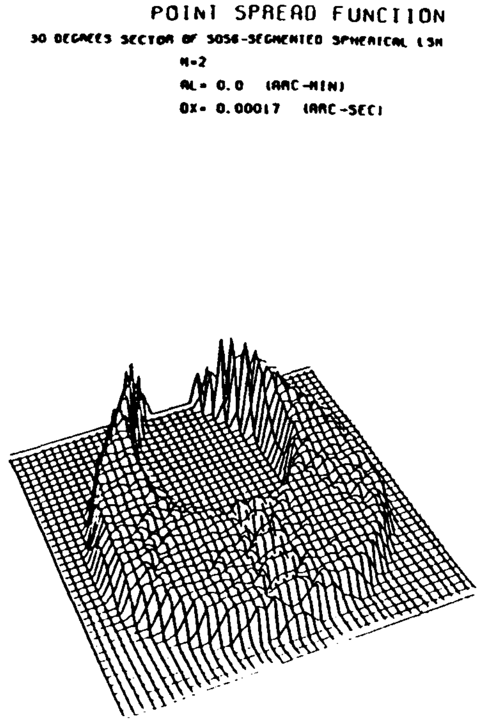
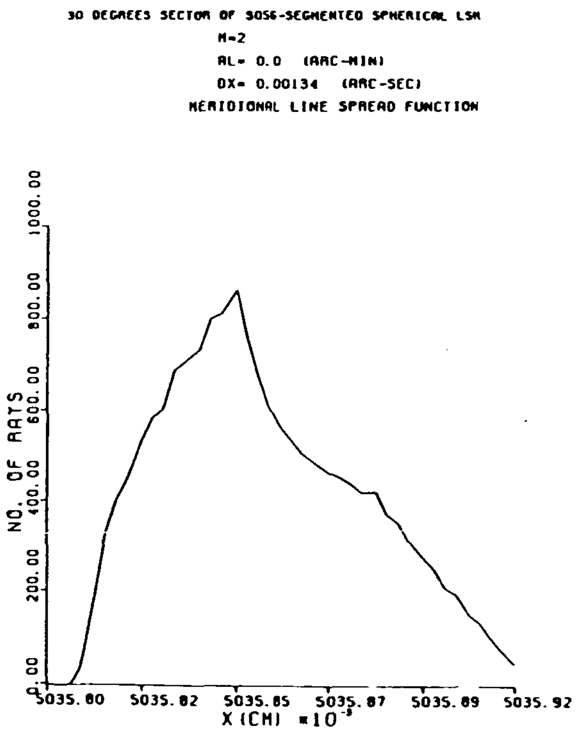


Figure 8h. Upper plot is the point spread function of the S056 Wolter I x-ray telescope (60° segmented aperture) and a spherical LSM with M=2X on the flat focal plane with minimum RMS for on axis light. The lower plots are meridional and sagittal line spread functions (LSF) for the same system. For a given value of X, the meridional LSF has been evaluated by summing the number of rays along the Y axis which intercept the image plane. The sagittal LSF has been computed in a similar manner where the role of X and Y axes are reversed. The half field angle is AL = 1 0 arc-mins.





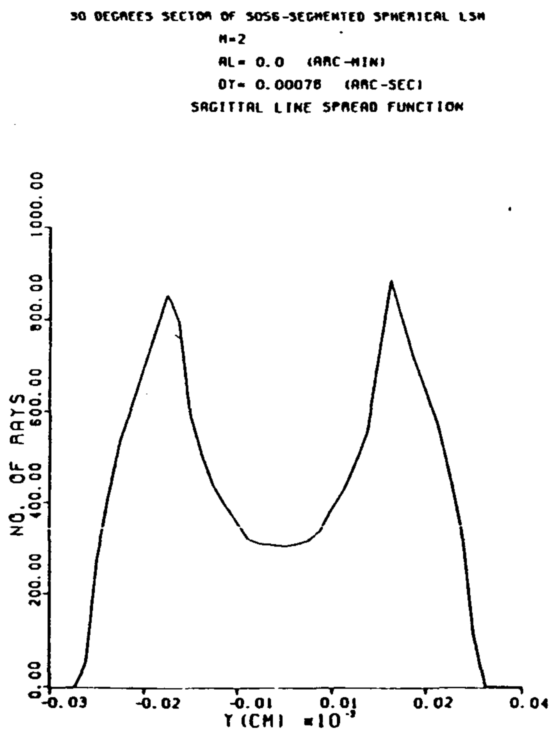
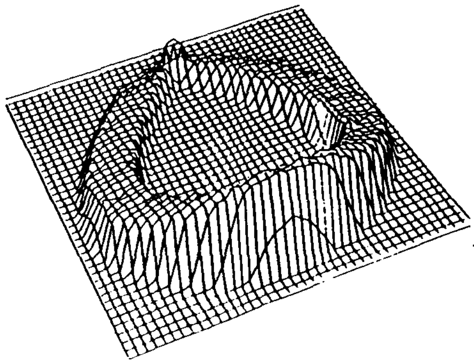
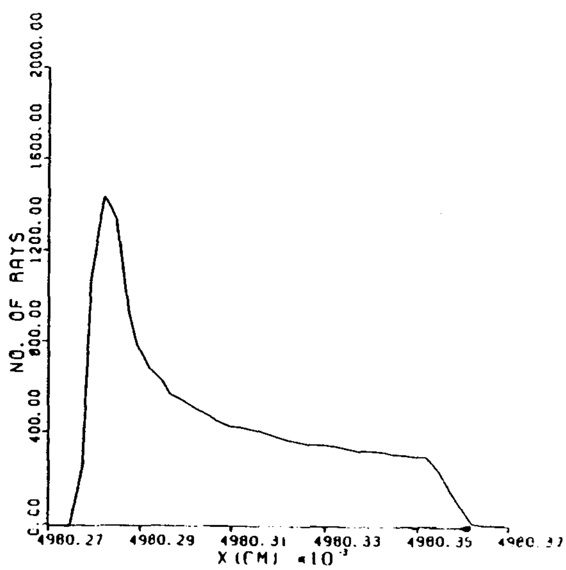


Figure 9a. Upper plot is the point spread function of the S056 Wolter I x-ray telescope (30^{0} segmented aperture) and a spherical LSM with M=2X on the flat focal plane with minimum RMS for on axis light. The lower plots are meridional and sagittal line spread functions (LSF) for the same system. For a given value of X, the meridional LSF has been evaluated by summing the number of rays along the Y axis which intercept the image plane. The sagittal LSF has been computed in a similar manner where the role of X and Y axes are reversed. The half field angle is AL = 0 arc-mins.

POINT SPREAD FUNCTION
30 DEGREES SECTOR OF S056-SEGMENTED SPHERICAL LSM
M=2
AL= 0.5 (ARC-MIN)
DX= 0.00014 (ARC-SEC)



30 DEGREES SECTOR OF S056-SEGMENTED SPHERICAL LSM
M=2
AL= 0.5 (ARC-MIN)
DX= 0.00113 (ARC-SEC)
MERIDIONAL LINE SPREAD FUNCTION



30 DEGREES SECTOR OF S056-SEGMENTED SPHERICAL LSM
M=2
AL= 0.5 (ARC-MIN)
DY= 0.00045 (ARC-SEC)
SAGITTAL LINE SPREAD FUNCTION

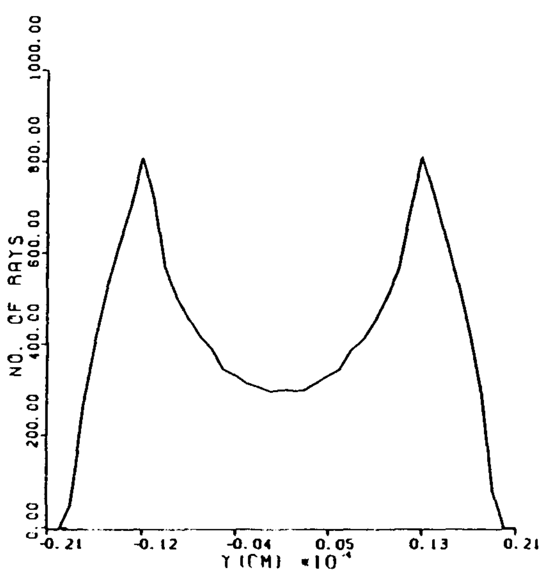


Figure 9b. Upper plot is the point spread function of the S056 Wolter I x-ray telescope (30° segmented aperture) and a spherical LSM with M=2X on the flat focal plane with minimum RMS for on axis light. The lower plots are meridional and sagittal line spread functions (LSF) for the same system. For a given value of X, the meridional LSF has been evaluated by summing the number of rays along the Y axis which intercept the image plane. The sagittal LSF has been computed in a similar manner where the role of X and Y axes are reversed. The half field angle is AL = 0.5 arc-mins.

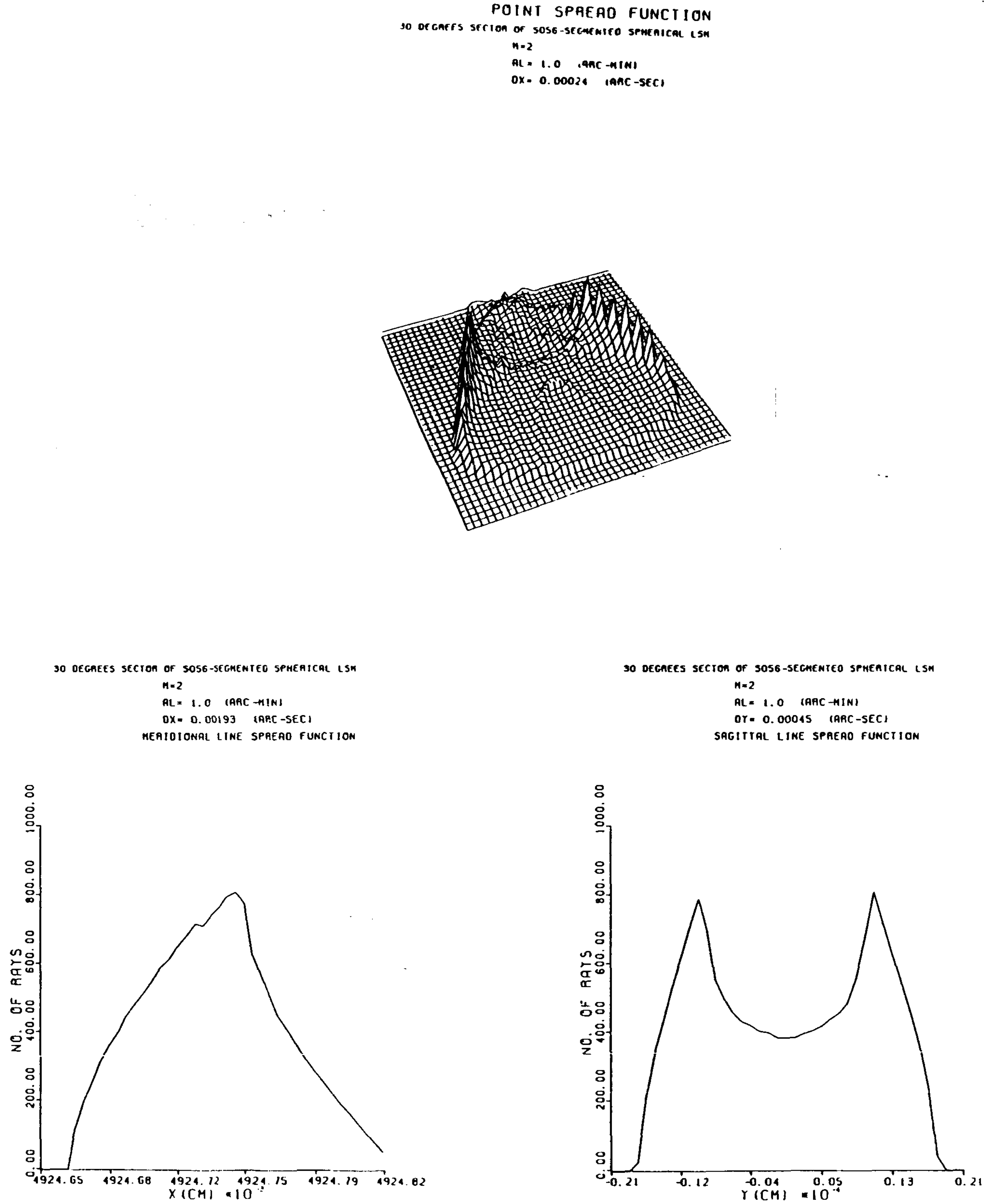
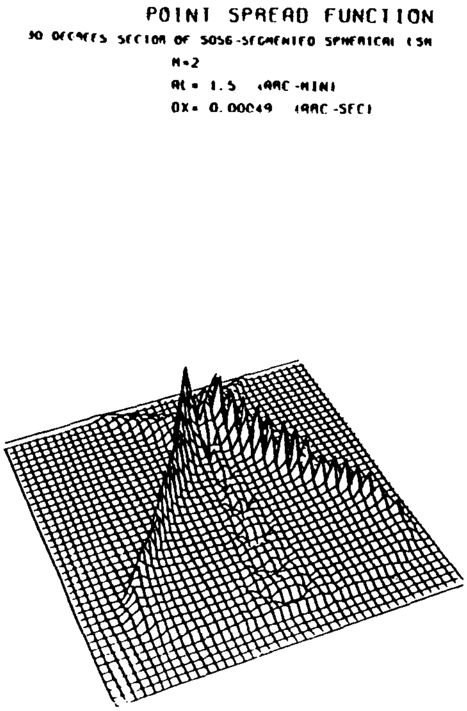
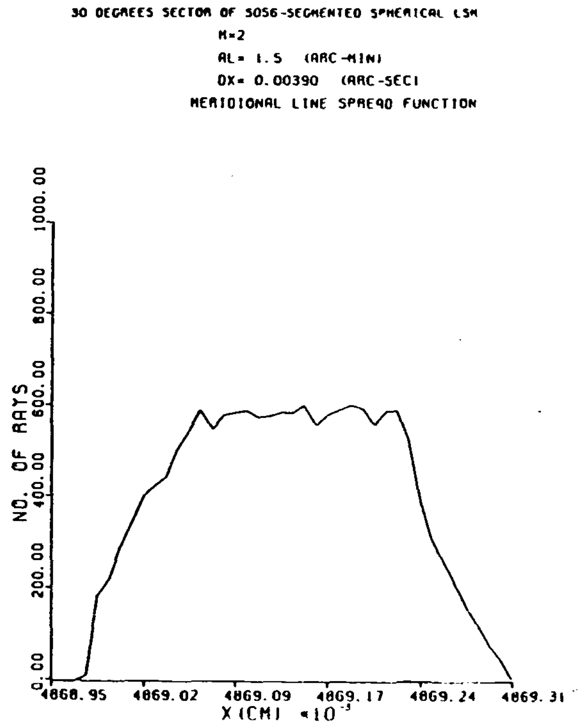


Figure 9c. Upper plot is the point spread function of the S056 Wolter I x-ray telescope (30° segmented aperture) and a spherical LSM with M=2X on the flat focal plane with minimum RMS for on axis light. The lower plots are meridional and sagittal line spread functions (LSF) for the same system. For a given value of X, the meridional LSF has been evaluated by summing the number of rays along the Y axis which intercept the image plane. The sagittal LSF has been computed in a similar manner where the role of X and Y axes are reversed. The half field angle is AL = 1.0 arc-mins.





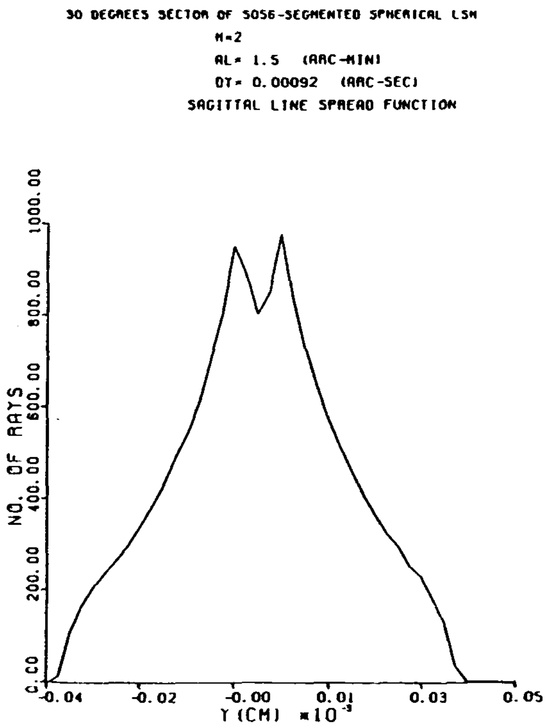


Figure 9d. Upper plot is the point spread function of the S056 Wolter I x-ray telescope (30° segmented aperture) and a spherical LSM with M=2X on the flat focal plane with minimum RMS for on axis light. The lower plots are meridional and sagittal line spread functions (LSF) for the same system. For a given value of X, the meridional LSF has been evaluated by summing the number of rays along the Y axis which intercept the image plane. The sagittal LSF has been computed in a similar manner where the role of X and Y axes are reversed. The half field angle is AL = 1.5 arc-mins.

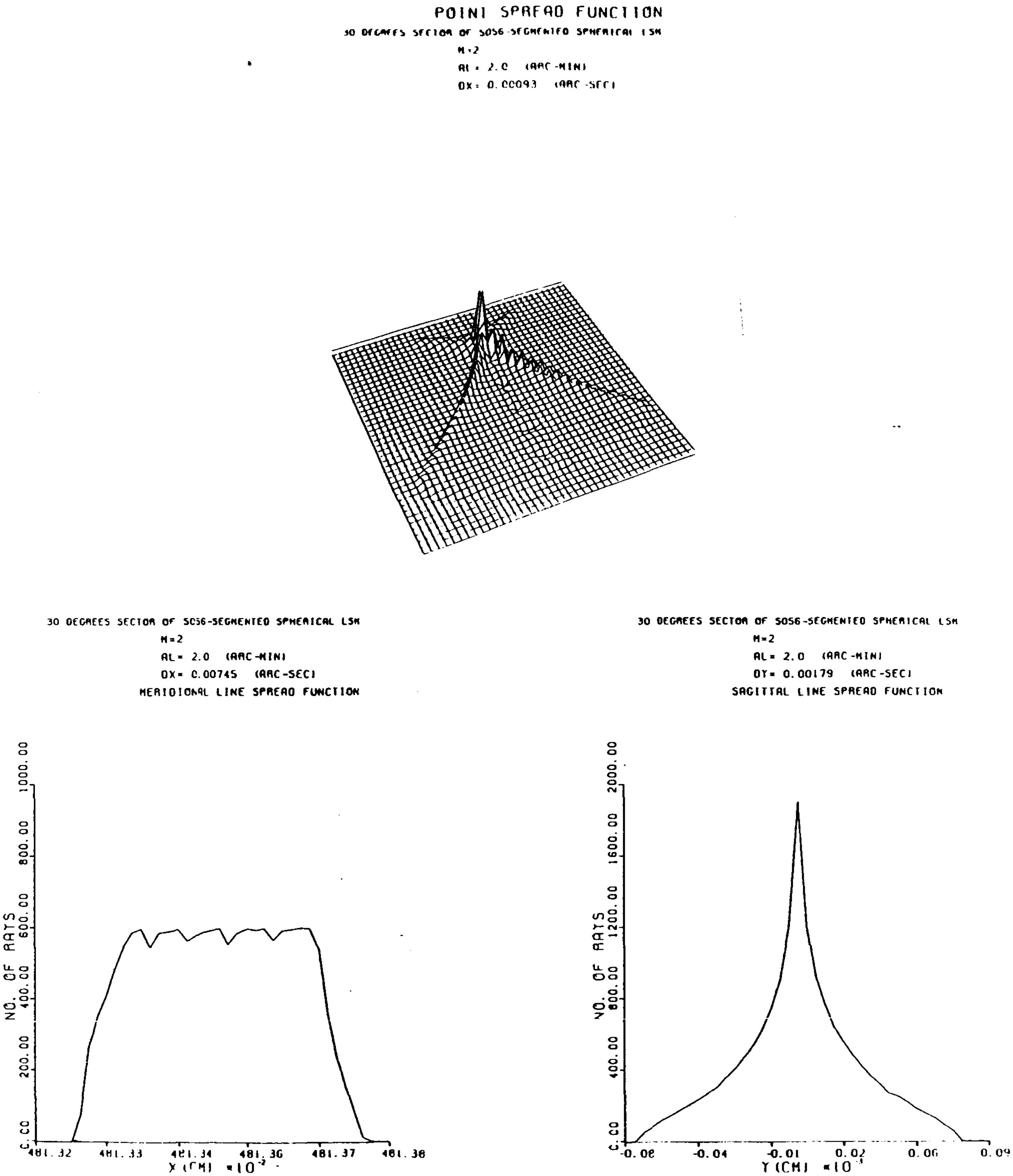
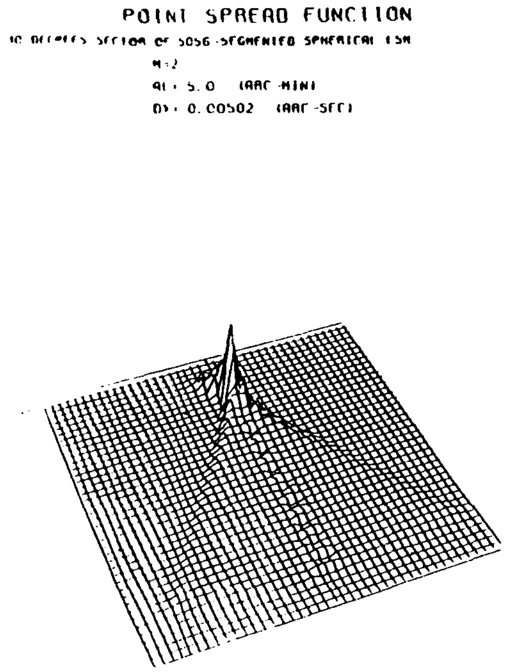


Figure 9e. Upper plot is the point spread function of the S056 Wolter I x-ray telescope (30° segmented aperture) and a spherical LSM with M=2X on the flat focal plane with minimum RMS for on axis light. The lower plots are meridional and sagittal line spread functions (LSF) for the same system. For a given value of X, the meridional LSF has been evaluated by summing the number of rays along the Y axis which intercept the image plane. The sagittal LSF has been computed in a similar manner where the role of X and Y axes are reversed. The half field angle is AL = 2 arc-mins.



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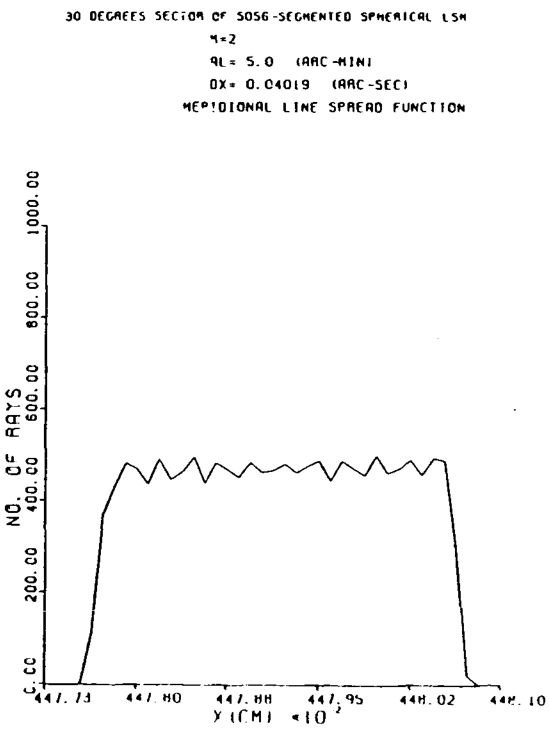


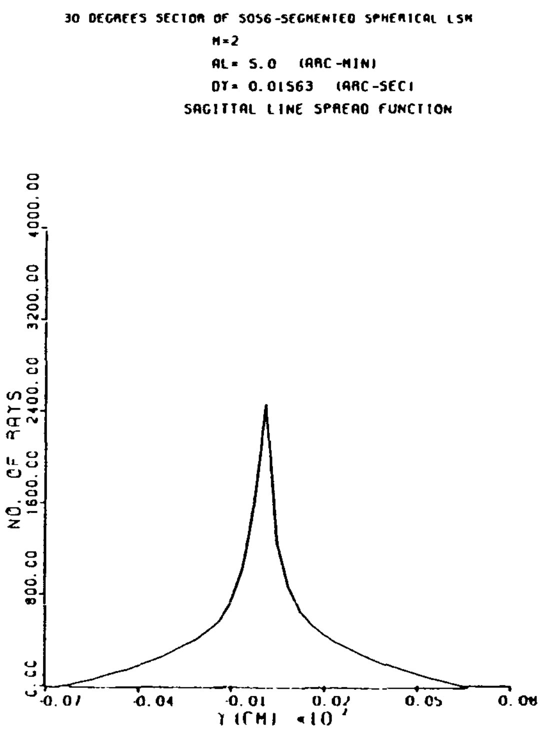


Figure 9f. Upper plot is the point spread function of the S056 Wolter I x-ray telescope (30° segmented aperture) and a spherical LSM with M=2X on the flat focal plane with minimum RMS for on axis light. The lower plots are meridional and sagittal line spread functions (LSF) for the same system. For a given value of X, the meridional LSF has been evaluated by summing the number of rays along the Y axis which intercept the image plane. The sagittal LSF has been computed in a similar manner where the role of X and Y axes are reversed. The half field angle is AL = 5 arc-mins.

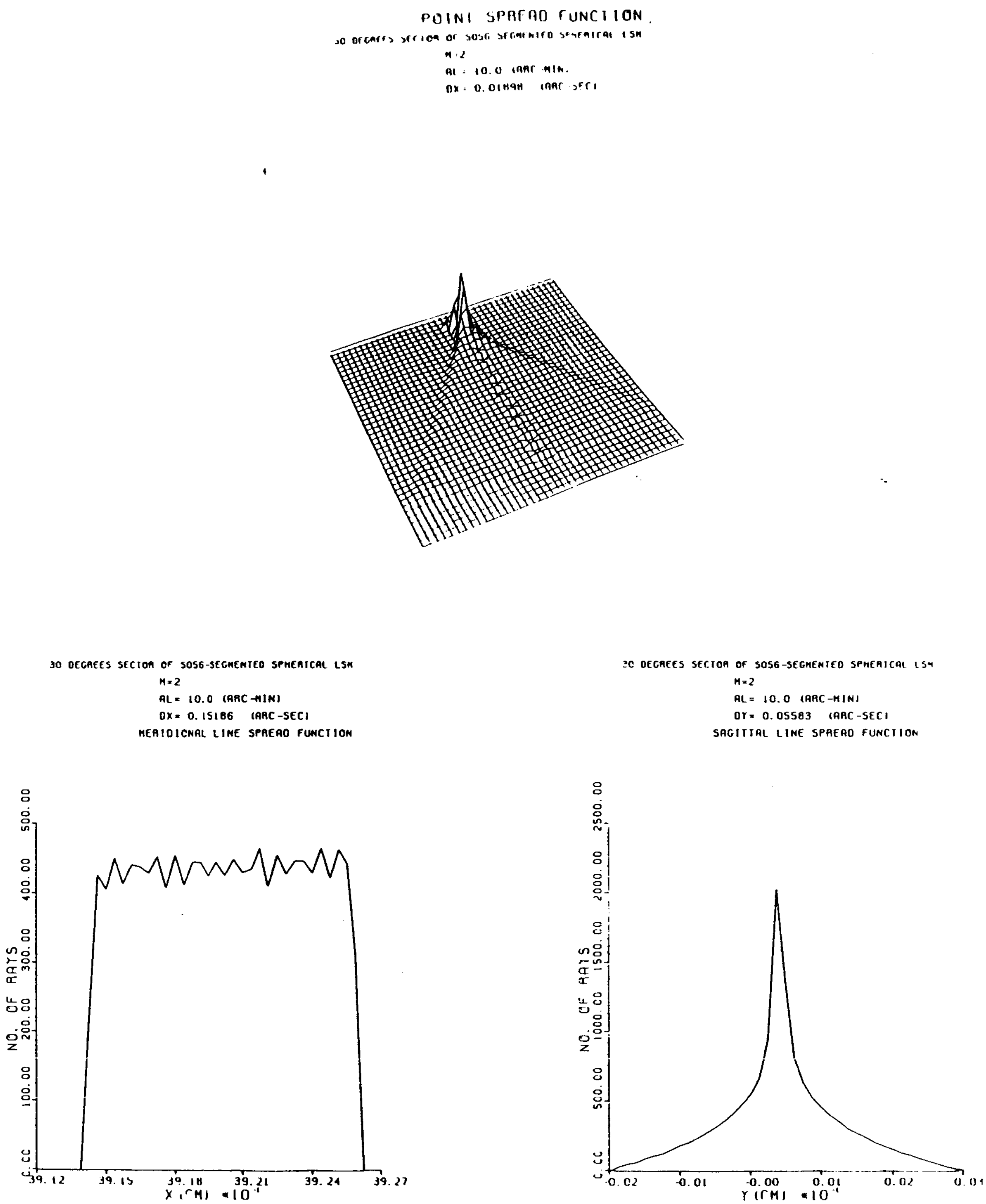


Figure 9g. Upper plot is the point spread function of the S056 Wolter I x-ray telescope (30° segmented aperture) and a spherical LSM with M=2X on the flat focal plane with minimum RMS for on axis light. The lower plots are meridional and sagittal line spread functions (LSF) for the same system. For a given value of X, the meridional LSF has been evaluated by summing the number of rays along the Y axis which intercept the image plane. The sagittal LSF has been computed in a similar manner where the role of X and Y axes are reversed. The half field angle is AL = 10 arc-mins.

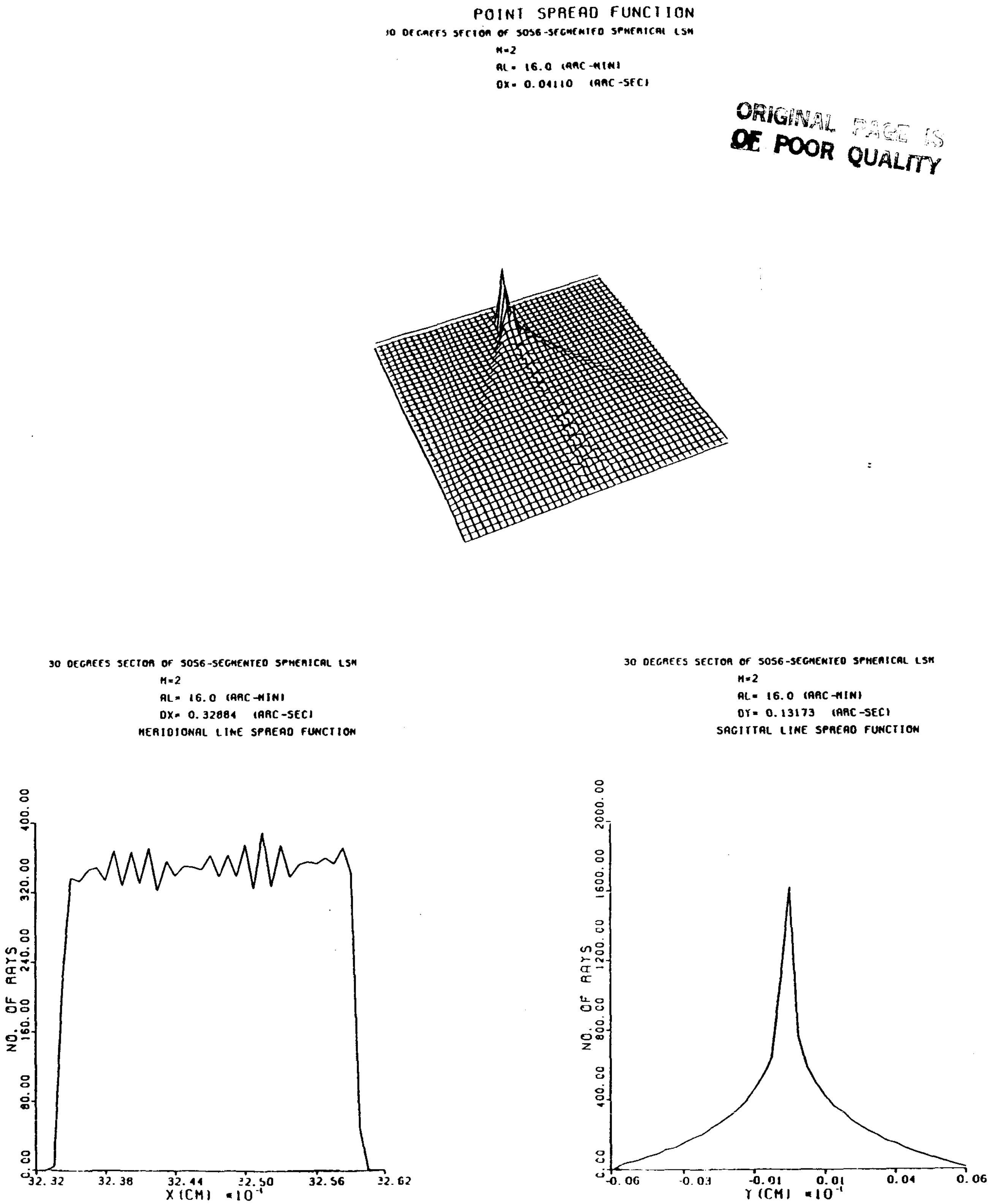


Figure 9h. Upper plot is the point spread function of the S056 Wolter I x-ray telescope (30° segmented aperture) and a spherical LSM with M=2X on the flat focal plane with minimum RMS for on axis light. The lower plots are meridional and sagittal line spread functions (LSF) for the same system. For a given value of X, the meridional LSF has been evaluated by summing the number of rays along the Y axis which intercept the image plane. The sagittal LSF has been computed in a similar manner where the role of X and Y axes are reversed. The half field angle is AL = 1 0 arc-mins.

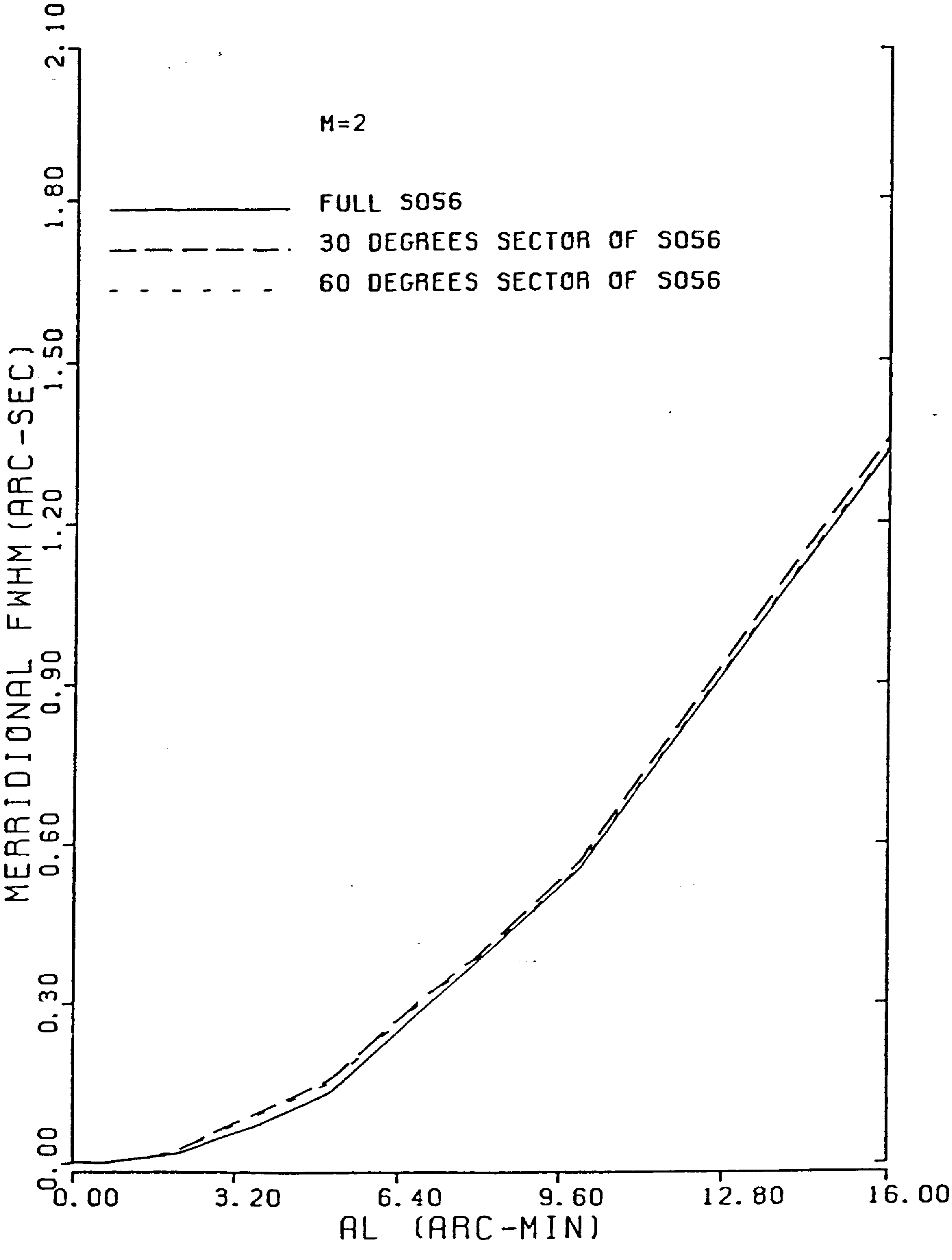


Figure 10. **Meridional FWHM versus field angle for full, 30° and 60° sector of S056 and convex spherical LSM for image at best focus for on-axis ray and M=2.**

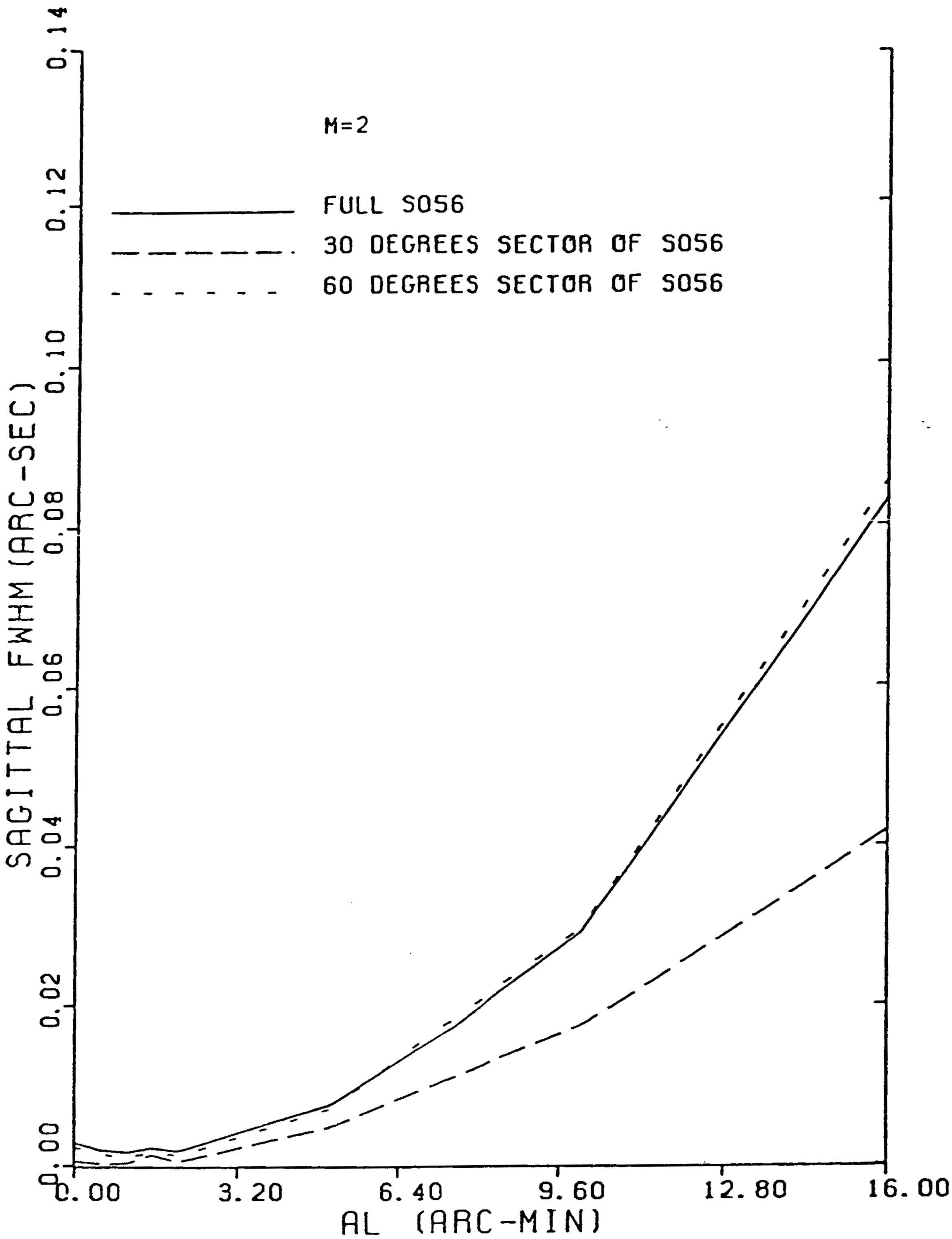


Figure 11. Saggital FWHM versus field angle for full, 30° and 60° sector of S056 and convex spherical LSM for image at best focus for on-axis ray and M=2.

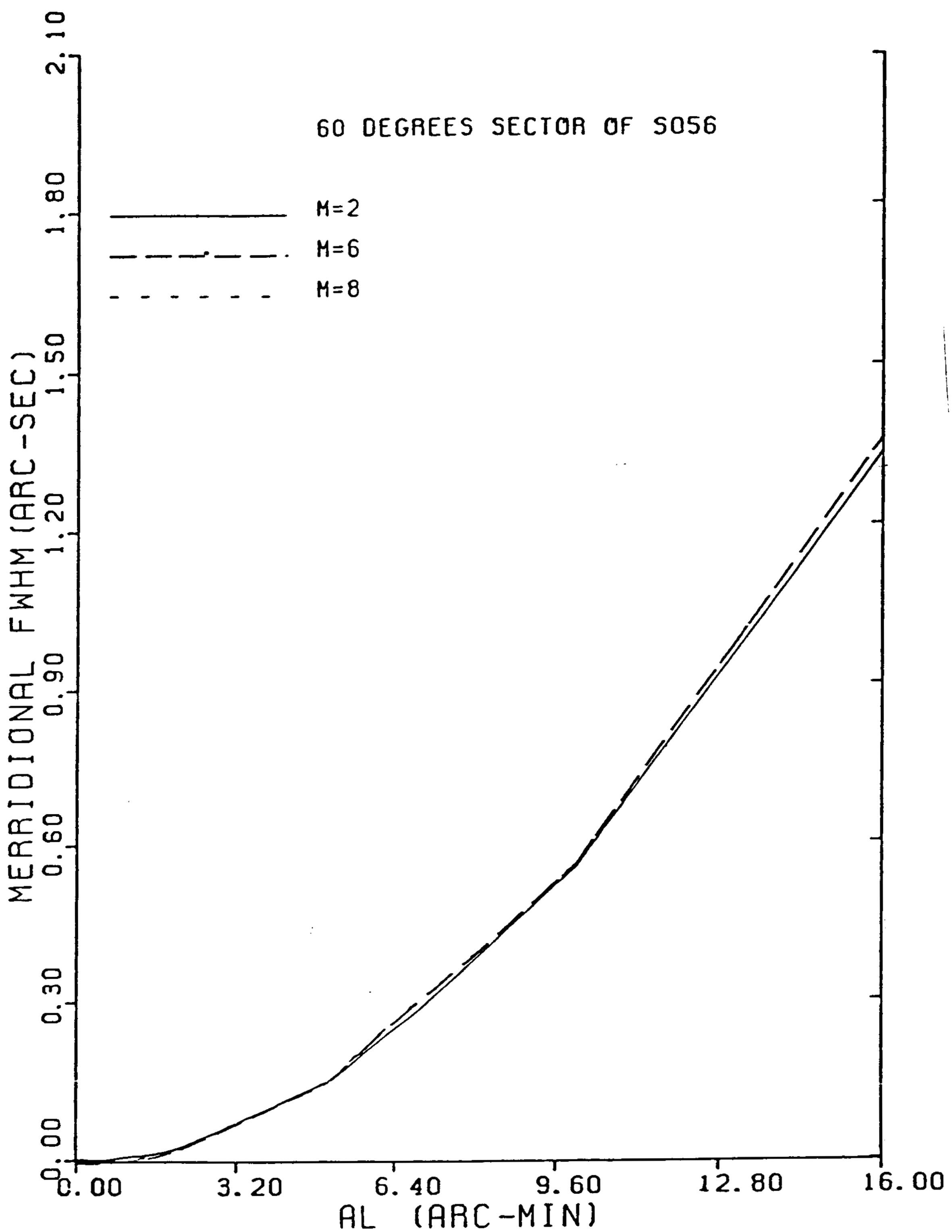


Figure 12. For 60° sector S056-convex spherical LSM the meridional FWHM as a function of field angle α for M=2,6,8. The image plane is at best focus for on-axis ray.

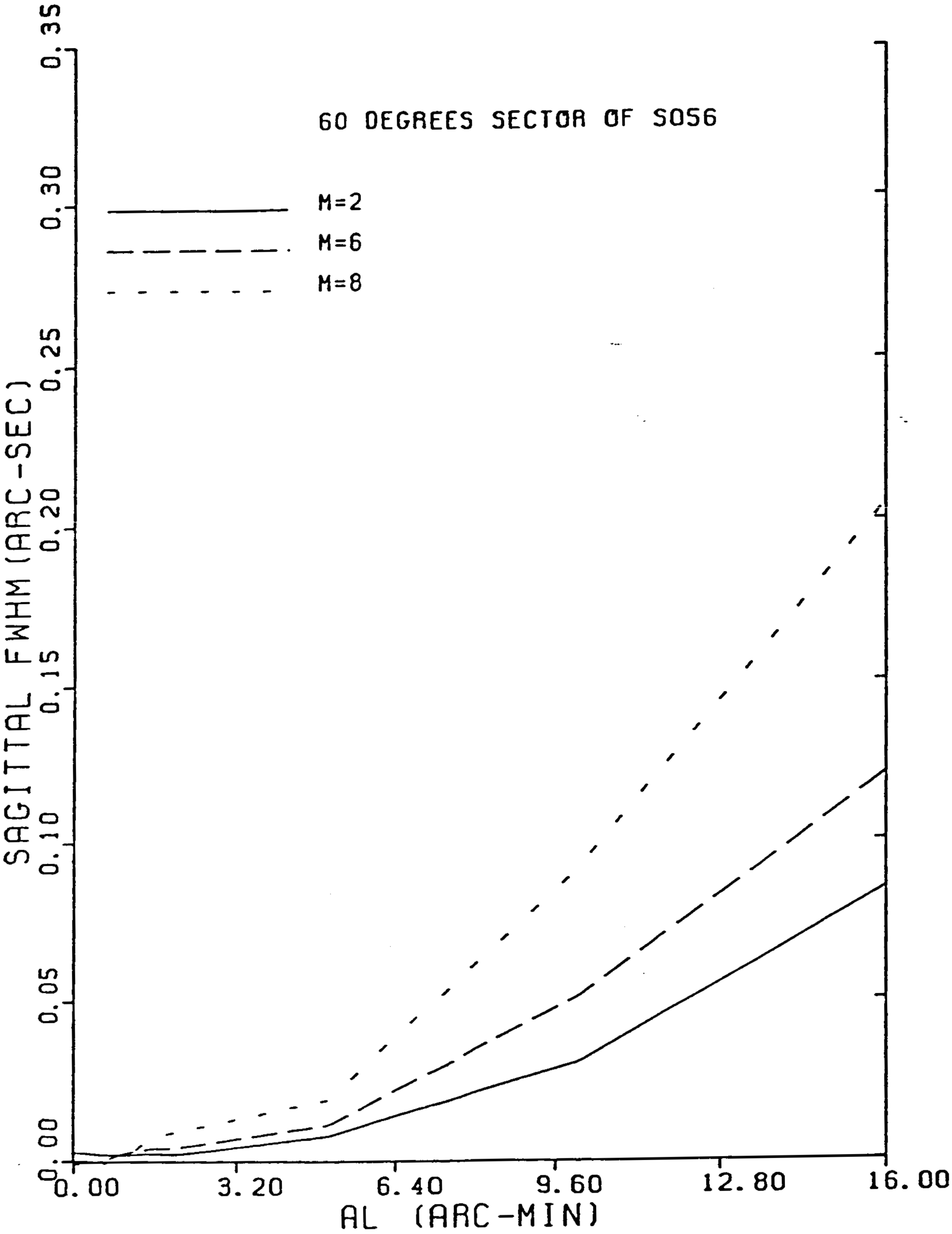


Figure 13. For 60° sector S056-convex spherical LSM the sagittal FWHM as a function of field angle α for M=2,6,8. The image plane is at best focus for on-axis ray.

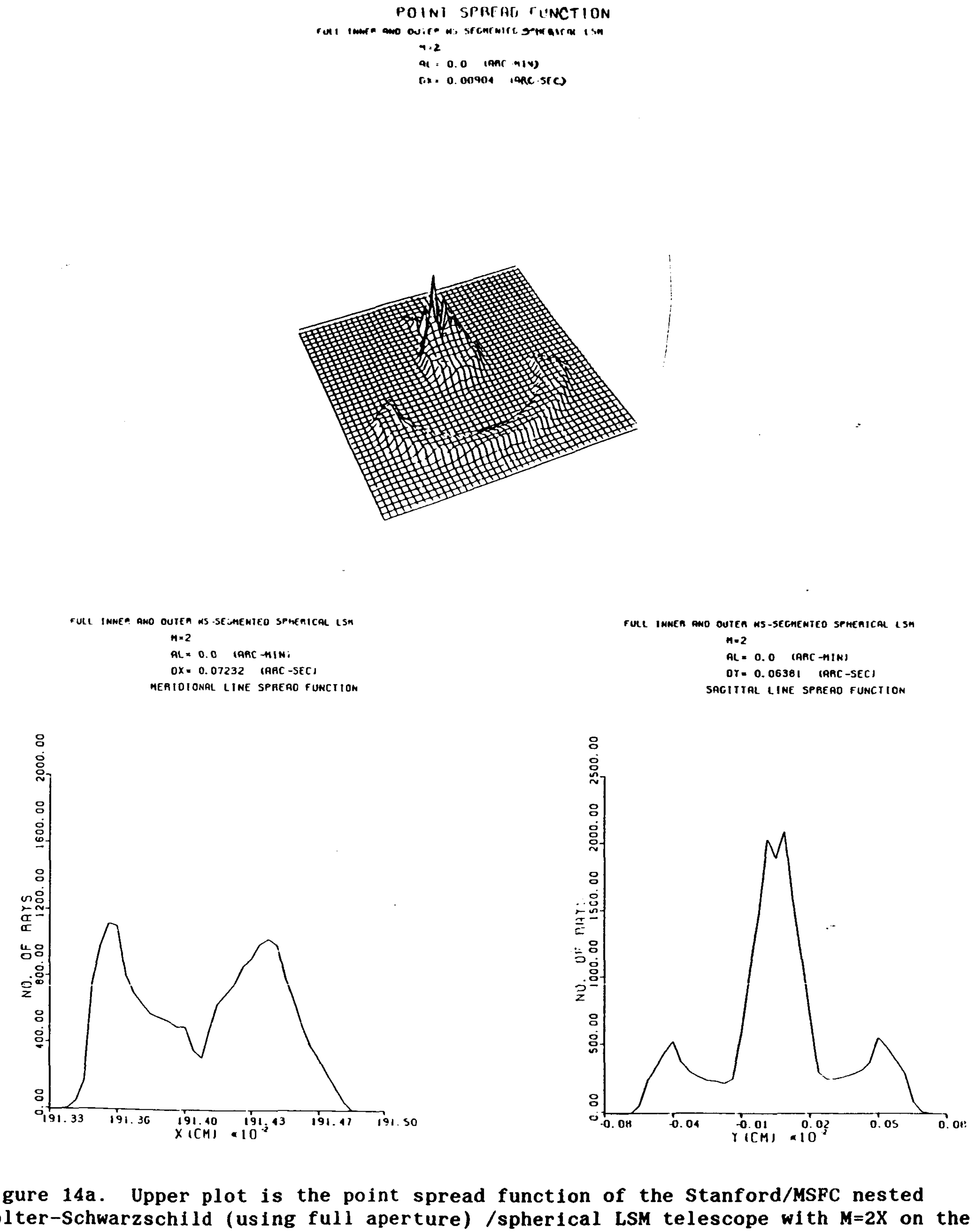
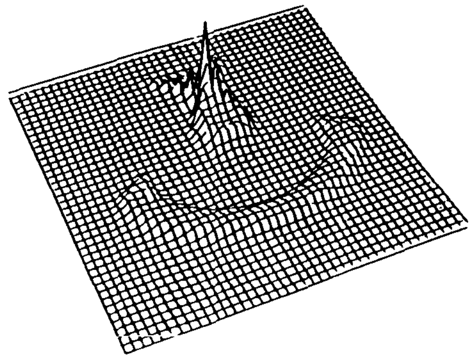
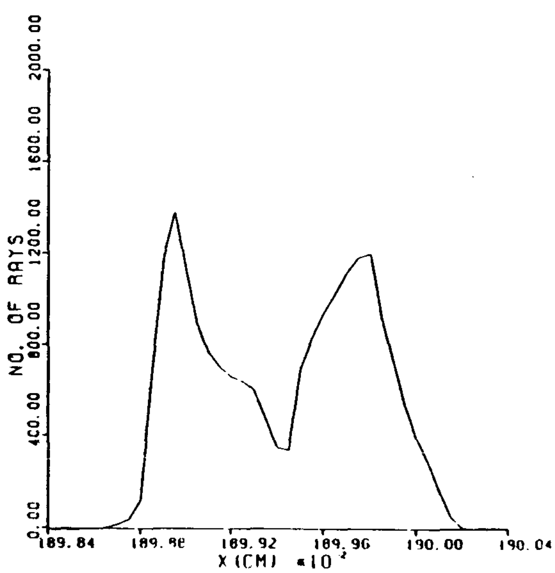


Figure 14a. Upper plot is the point spread function of the Stanford/MSFC nested Wolter-Schwarzschild (using full aperture) /spherical LSM telescope with M=2X on the flat focal plane with minimum RMS for on axis light. The lower plots are meridional and sagittal line spread functions (LSF) for the same system. For a given value of X, the meridional LSF has been evaluated by summing the number of rays along the Y axis which intercept the image plane. The sagittal LSF has been computed in a similar manner where the role of X and Y axes are reversed. The half field angle is AL = 0 arc-mins.

POINT SPREAD FUNCTION
FULL INNER AND OUTER WS-SEGMENTED SPHERICAL LSM
M=2
AL= 0.5 (ARC-MIN)
DX= 0.01037 (ARC-SEC)



FULL INNER AND OUTER WS-SEGMENTED SPHERICAL LSM
M=2
AL= 0.5 (ARC-MIN)
DX= 0.08296 (ARC-SEC)
MERIDIONAL LINE SPREAD FUNCTION



FULL INNER AND OUTER WS-SEGMENTED SPHERICAL LSM
M=2
AL= 0.5 (ARC-MIN)
DY= 0.05956 (ARC-SEC)
SAGITTAL LINE SPREAD FUNCTION

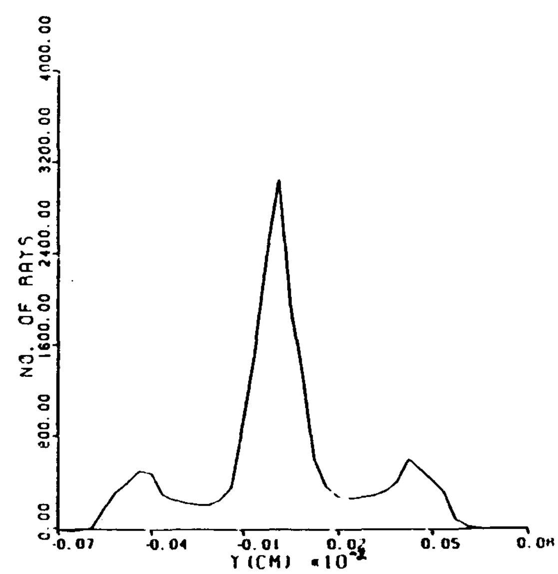


Figure 14b. Upper plot is the point spread function of the Stanford/MSFC nested Wolter-Schwarzschild (using full aperture) /spherical LSM telescope with M=2X on the flat focal plane with minimum RMS for on axis light. The lower plots are meridional and sagittal line spread functions (LSF) for the same system. For a given value of X, the meridional LSF has been evaluated by summing the number of rays along the Y axis which intercept the image plane. The sagittal LSF has been computed in a similar manner where the role of X and Y axes are reversed. The half field angle is AL = 0.5 arc-mins.

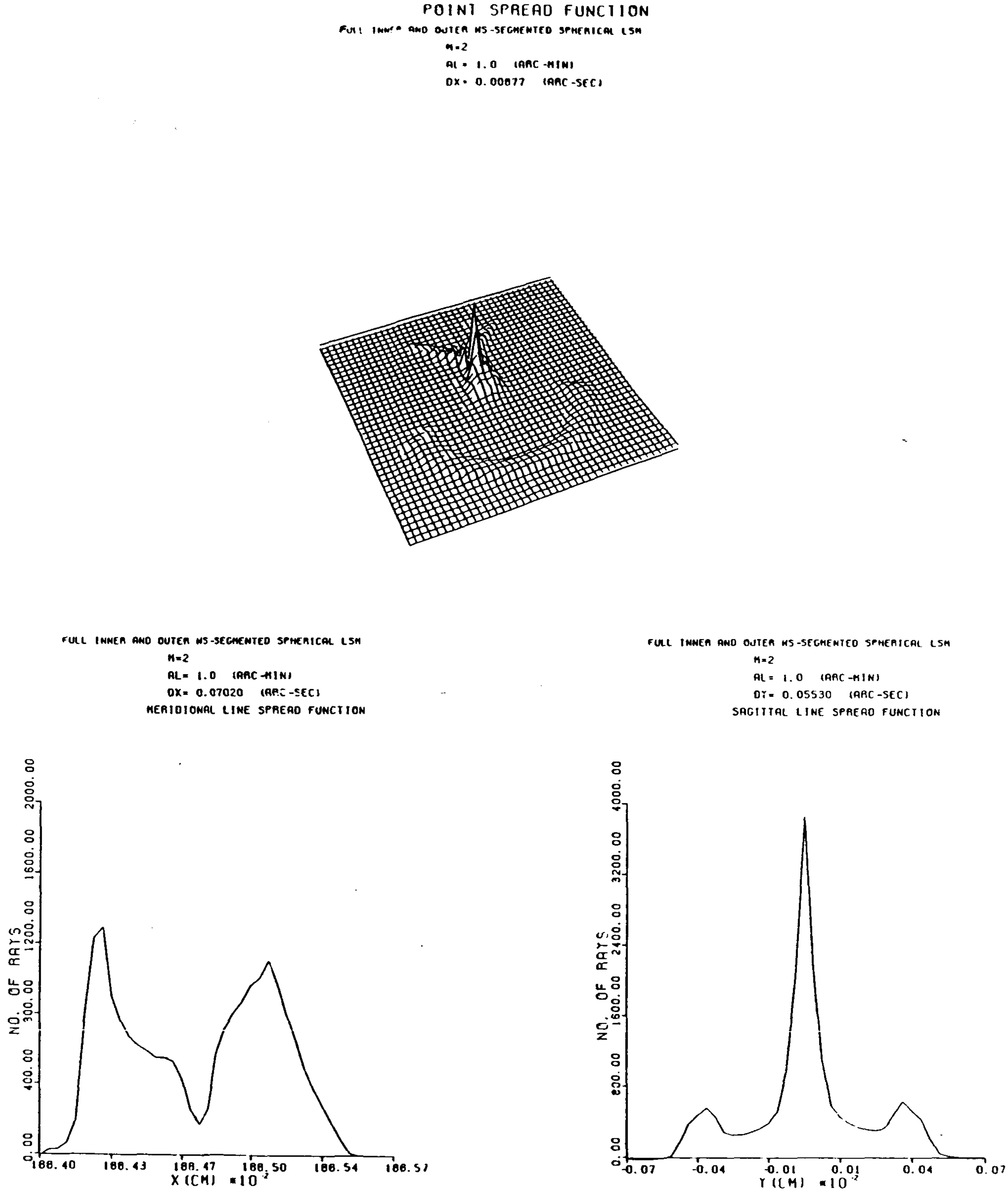
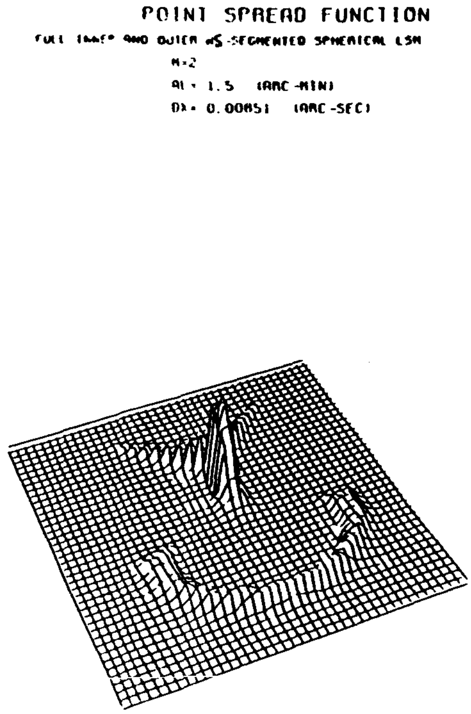
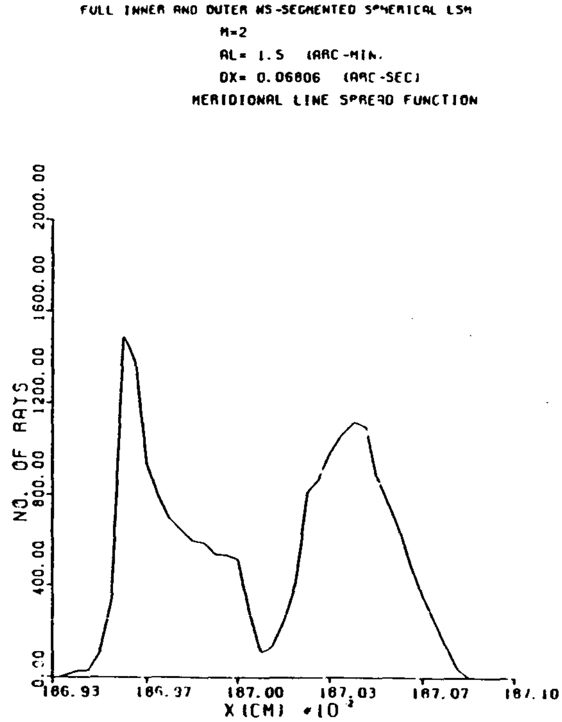


Figure 14c. Upper plot is the point spread function of the Stanford/MSFC nested Wolter-Schwarzschild (using full aperture) /spherical LSM telescope with M=2X on the flat focal plane with minimum RMS for on axis light. The lower plots are meridional and sagittal line spread functions (LSF) for the same system. For a given value of X, the meridional LSF has been evaluated by summing the number of rays along the Y axis which intercept the image plane. The sagittal LSF has been computed in a similar manner where the role of X and Y axes are reversed. The half field angle is AL = 1.0 arc-mins.





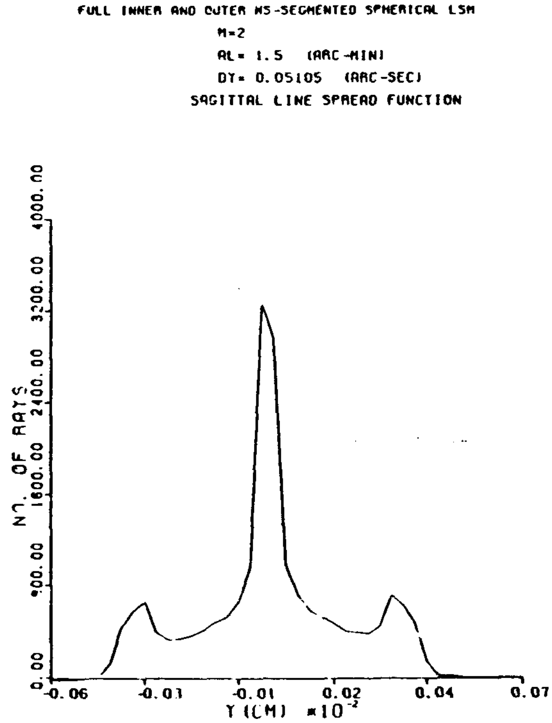
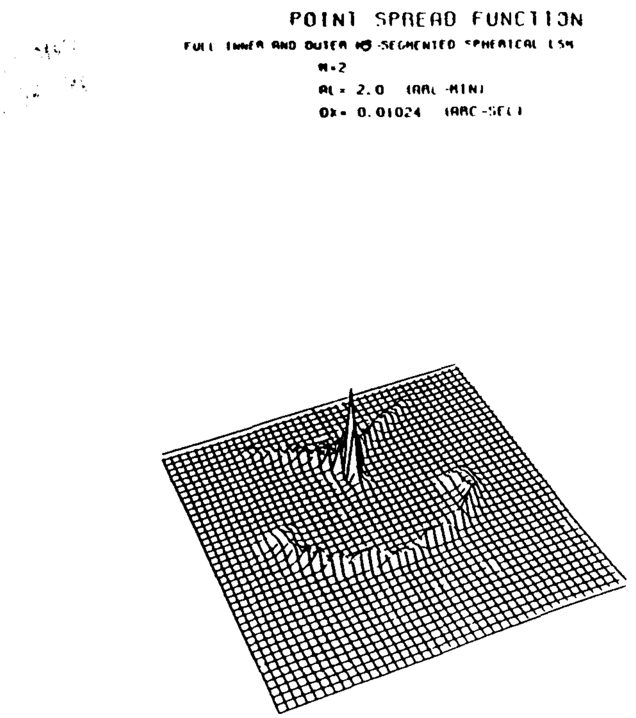
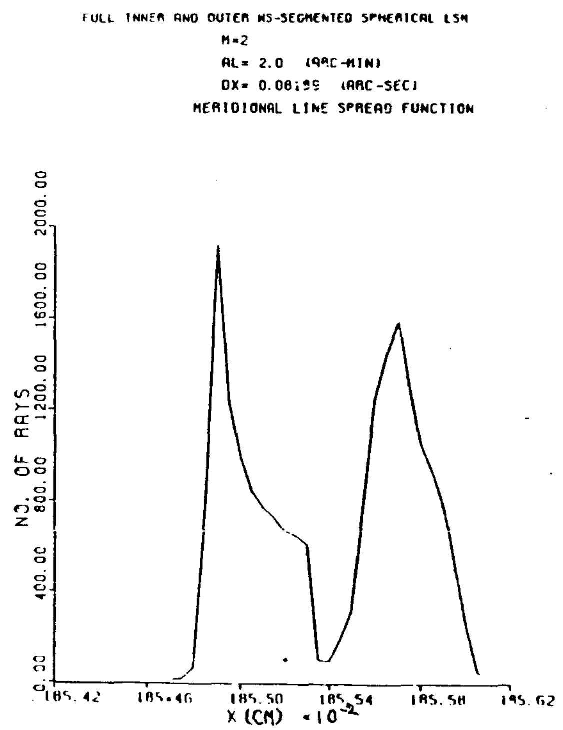


Figure 14d. Upper plot is the point spread function of the Stanford/MSFC nested Wolter-Schwarzschild (using full aperture) /spherical LSM telescope with M=2X on the flat focal plane with minimum RMS for on axis light. The lower plots are meridional and sagittal line spread functions (LSF) for the same system. For a given value of X, the meridional LSF has been evaluated by summing the number of rays along the Y axis which intercept the image plane. The sagittal LSF has been computed in a similar manner where the role of X and Y axes are reversed. The half field angle is AL = 1.5 arc-mins.





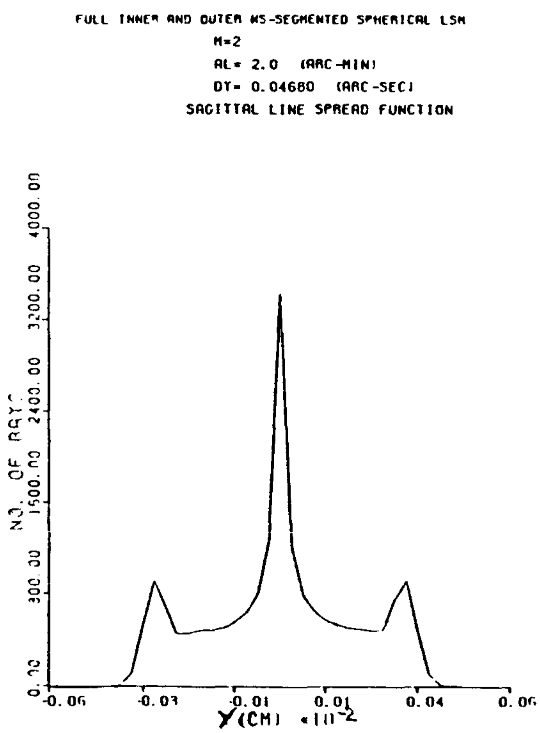


Figure 14e. Upper plot is the point spread function of the Stanford/MSFC nested Wolter-Schwarzschild (using full aperture) /spherical LSM telescope with M=2X on the flat focal plane with minimum RMS for on axis light. The lower plots are meridional and sagittal line spread functions (LSF) for the same system. For a given value of X, the meridional LSF has been evaluated by summing the number of rays along the Y axis which intercept the image plane. The sagittal LSF has been computed in a similar manner where the role of X and Y axes are reversed. The half field angle is AL = 2 arc-mins.

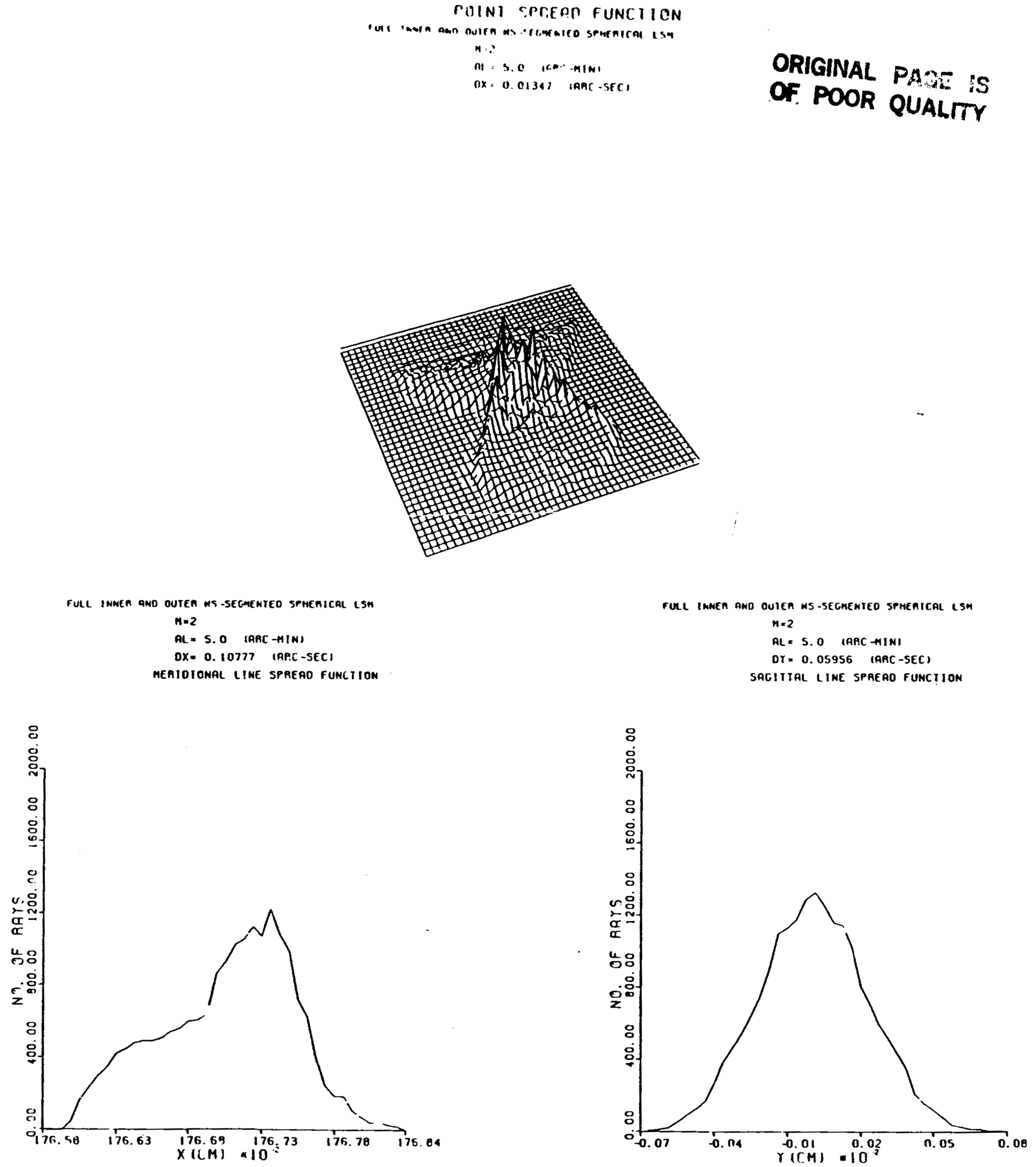


Figure 14f. Upper plot is the point spread function of the Stanford/MSFC nested Wolter-Schwarzschild (using full aperture) /spherical LSM telescope with M=2X on the flat focal plane with minimum RMS for on axis light. The lower plots are meridional and sagittal line spread functions (LSF) for the same system. For a given value of X, the meridional LSF has been evaluated by summing the number of rays along the Y axis which intercept the image plane. The sagittal LSF has been computed in a similar manner where the role of X and Y axes are reversed. The half field angle is AL = 5 arc-mins.

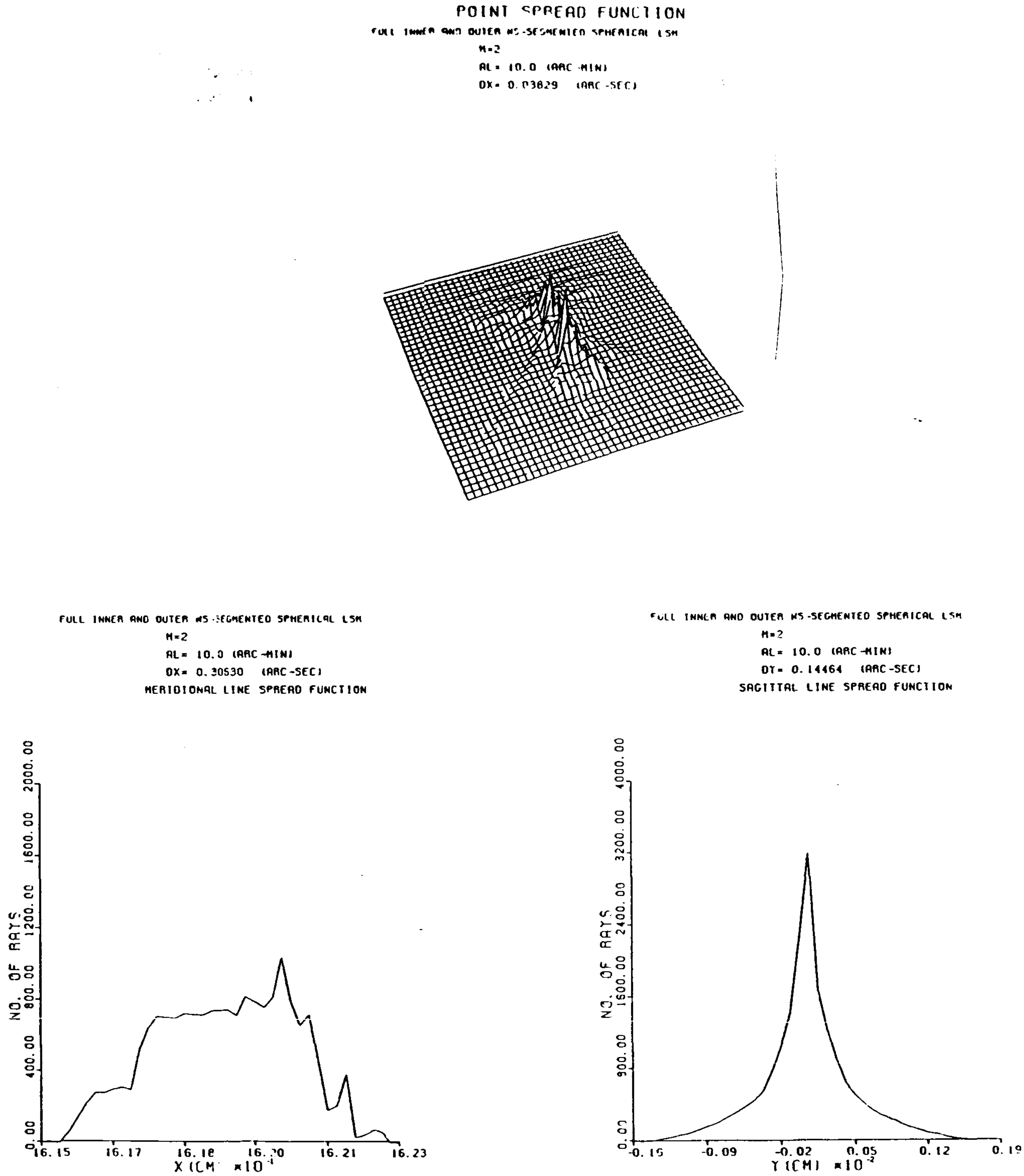


Figure 14g. Upper plot is the point spread function of the Stanford/MSFC nested Wolter-Schwarzschild (using full aperture) /spherical LSM telescope with M=2X on the flat focal plane with minimum RMS for on axis light. The lower plots are meridional and sagittal line spread functions (LSF) for the same system. For a given value of X, the meridional LSF has been evaluated by summing the number of rays along the Y axis which intercept the image plane. The sagittal LSF has been computed in a similar manner where the role of X and Y axes are reversed. The half field angle is AL = 10 arc-mins.

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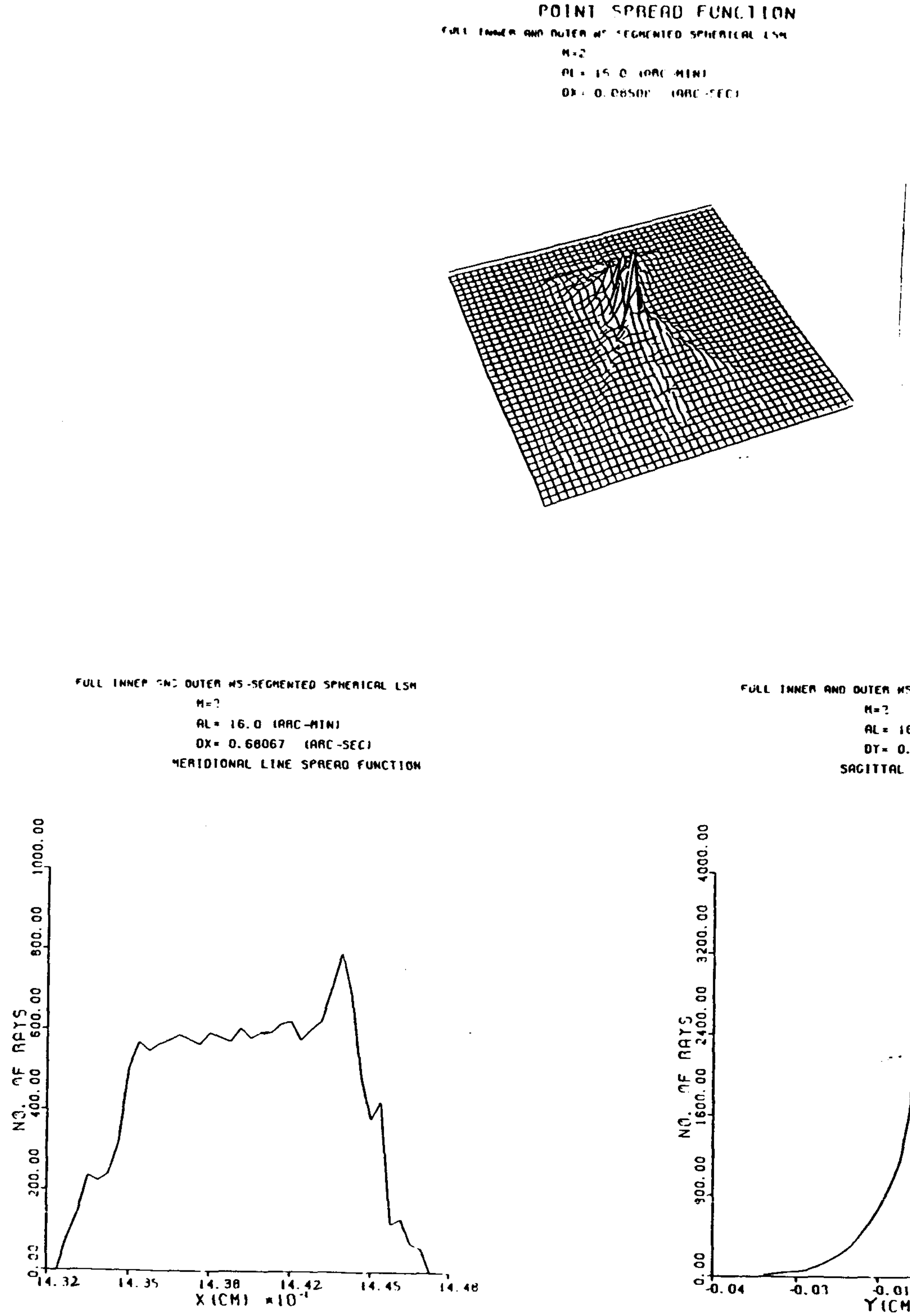

Figure 14h. Upper plot is the point spread function of the Stanford/MSFC nested Wolter-Schwarzschild (using full aperture) /spherical LSM telescope with M=2X on the flat focal plane with minimum RMS for on axis light. The lower plots are meridional and sagittal line spread functions (LSF) for the same system. For a given value of X, the meridional LSF has been evaluated by summing the number of rays along the Y axis which intercept the image plane. The sagittal LSF has been computed in a similar manner where the role of X and Y axes are reversed. The half field angle is AL = 16 arc-mins.

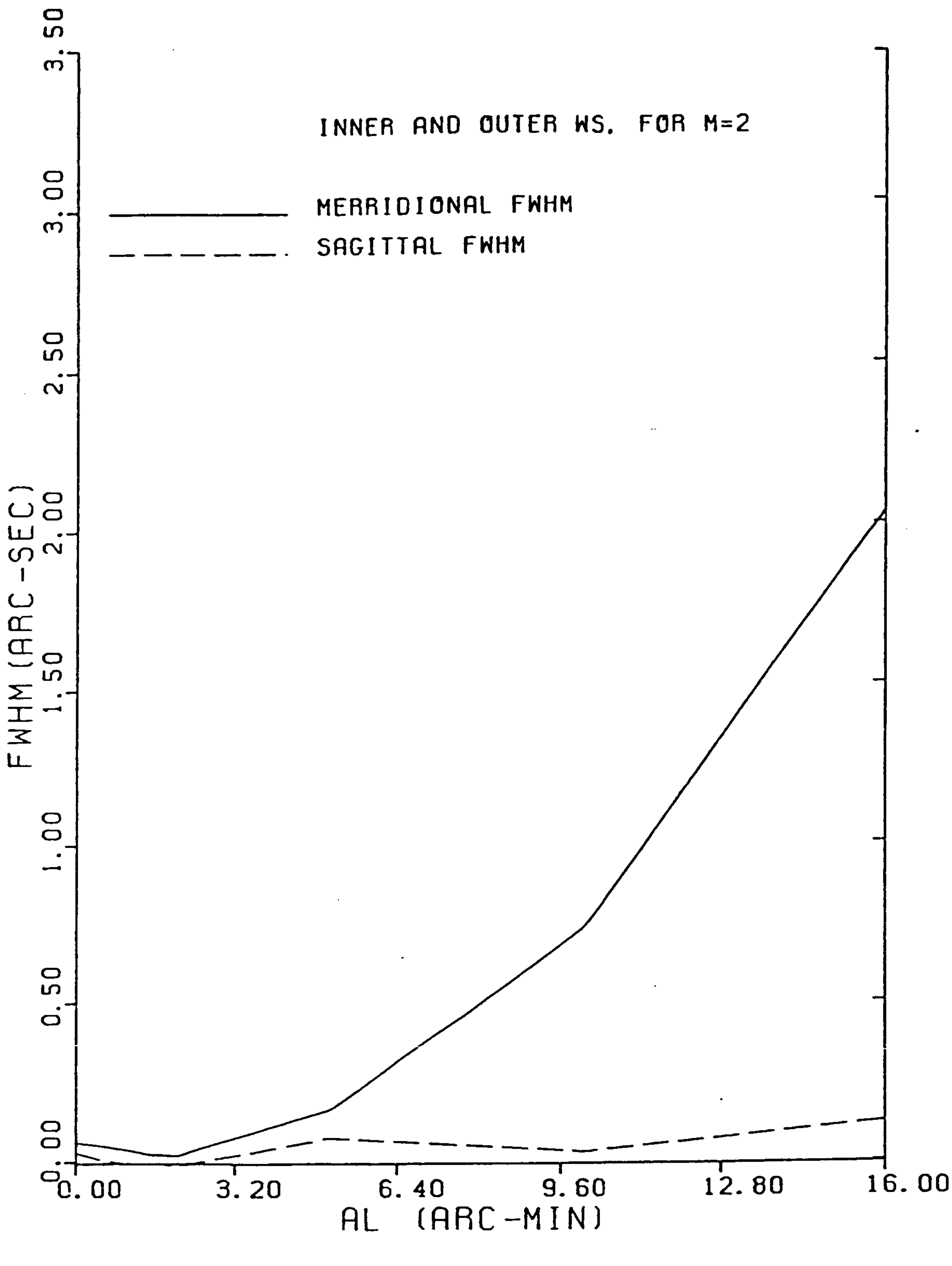

Figure 15. Variation of the meridional and sagittal FWHM for nested WS-convex spherical LSM and M=2 as a function of the field angle. The image plane is at best focus for on-axis ray.

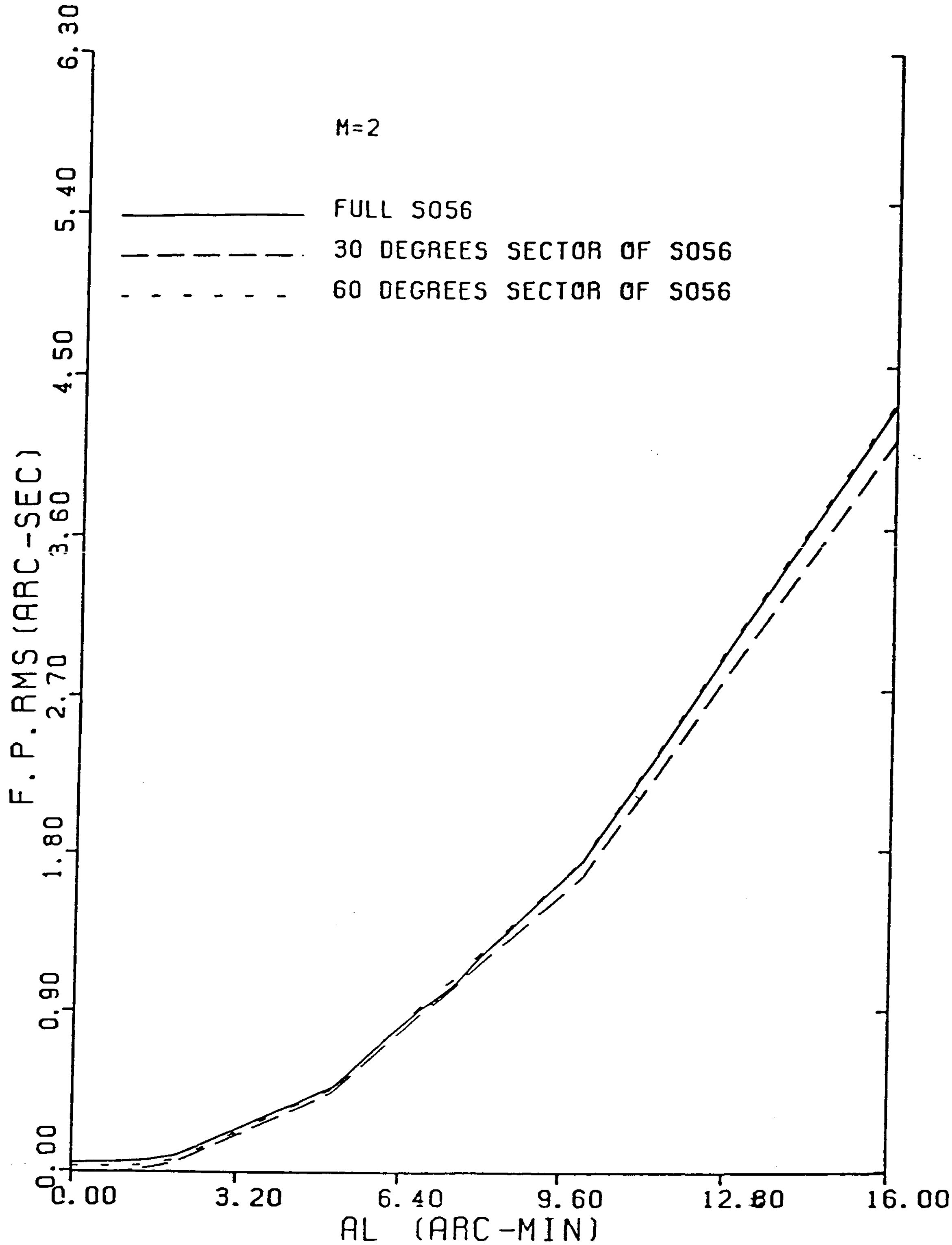

Figure 16. Variation of the RMS blur radius with field angle for M=2 and full, 60°, 30° sector of S056-spherical LSM at the best focal plane for on-axis ray.

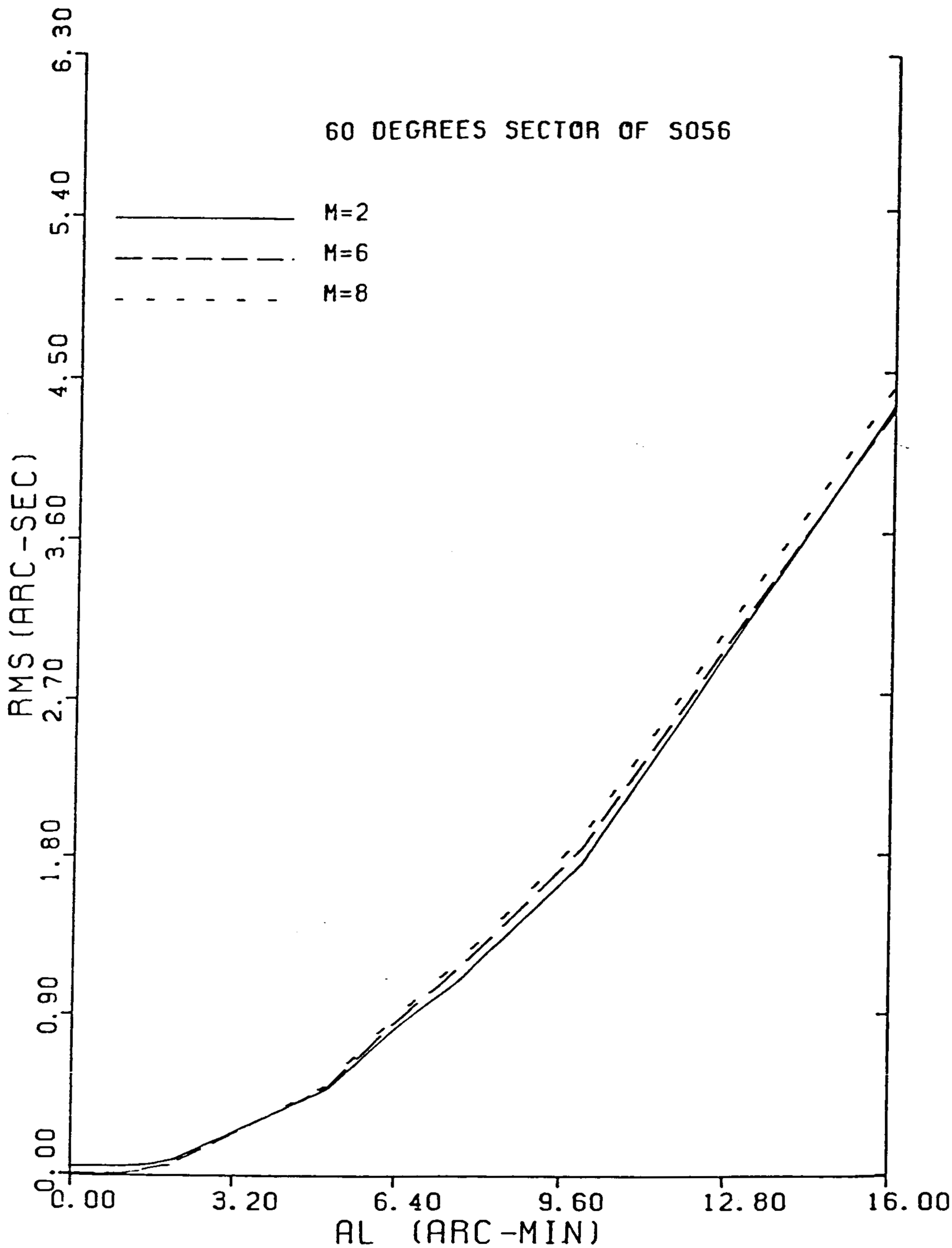

Figure 17. Variation of the RMS blur radius with field angle for M=2,6,8 and 60° sector of S056 at the best focal plane for on-axis ray.

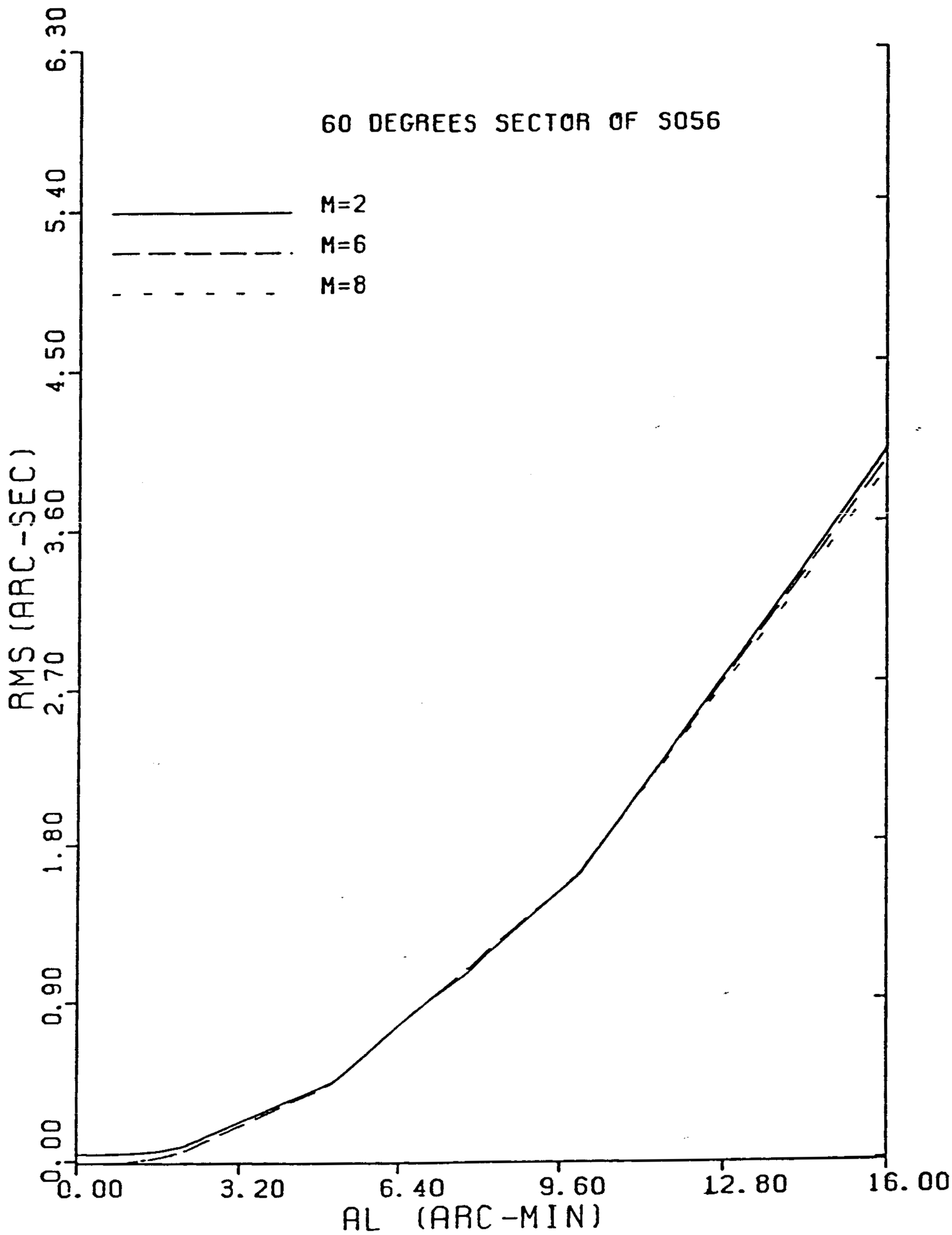

Figure 18. Variation of the RMS blur circle radius for optimally curved image plane as a function of field angle for M=2,6,8 and 60° sector of S056-spherical LSM.

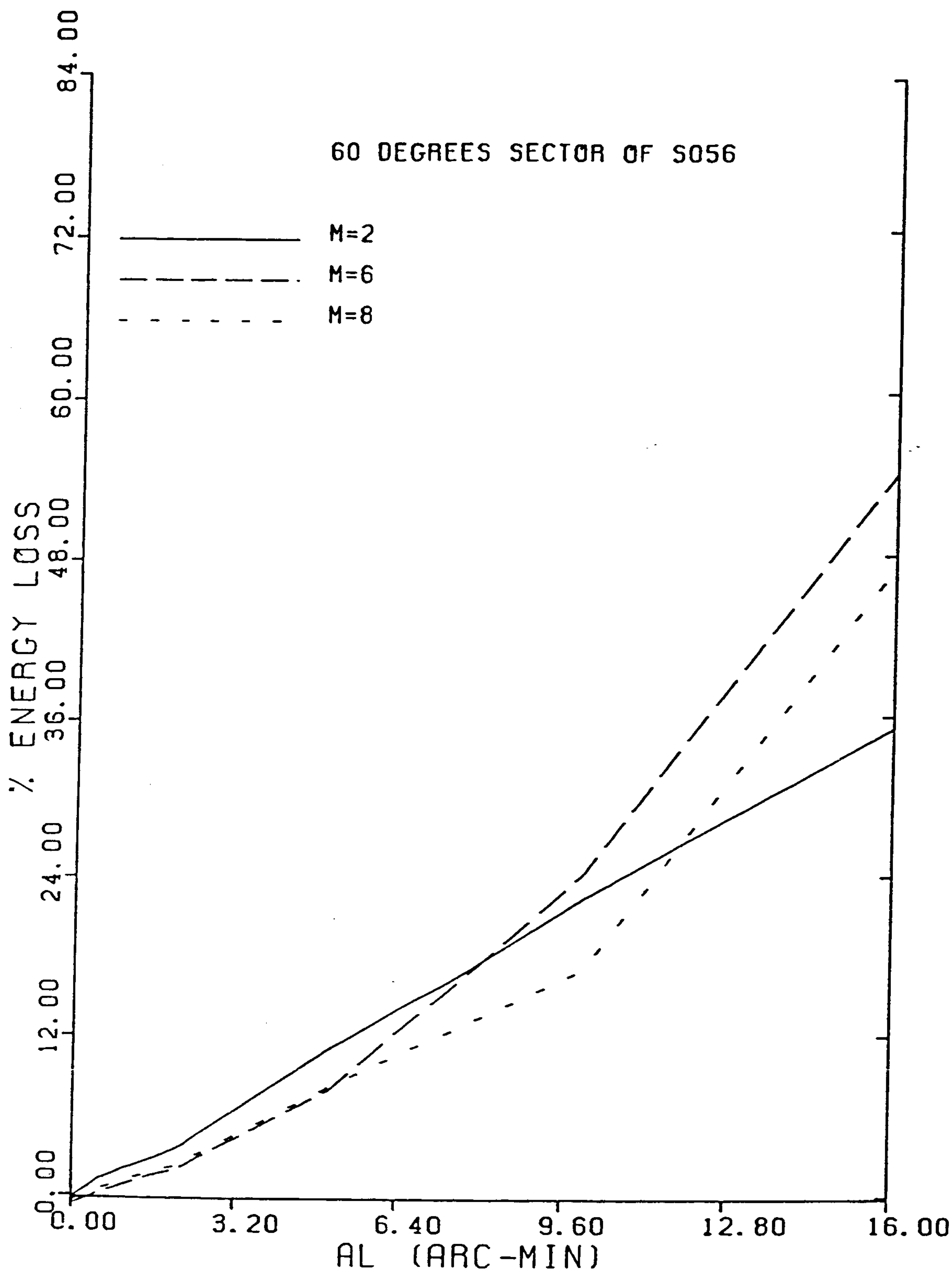

Figure 19. Percent energy loss for M=2,6,8 and 60° sector of S056-spherical LSM at the best focal plane for on-axis ray.

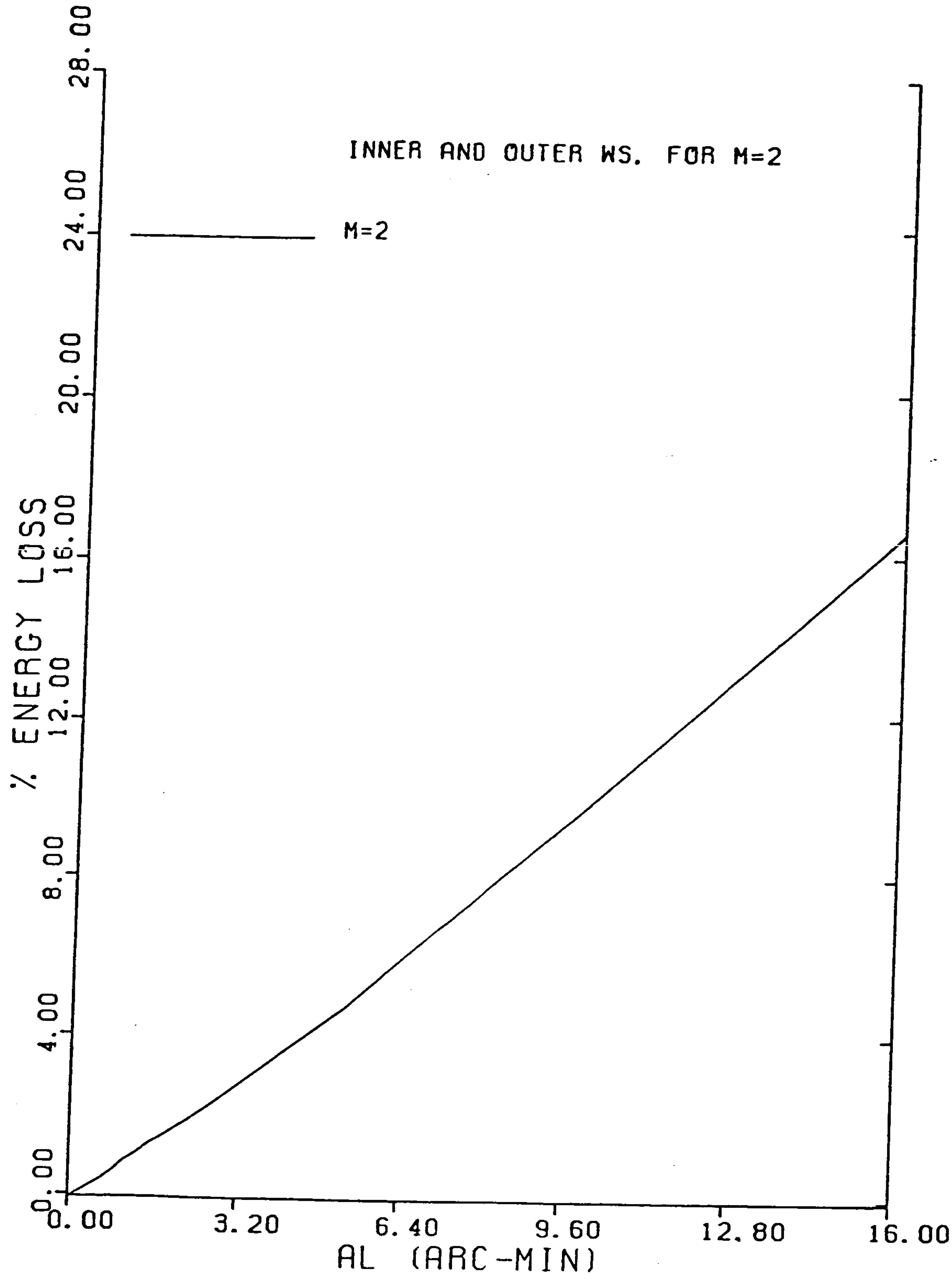

Figure 20. Percent energy loss for M=2 and nested WS-spherical LSM at the best focal plane for on-axis ray.

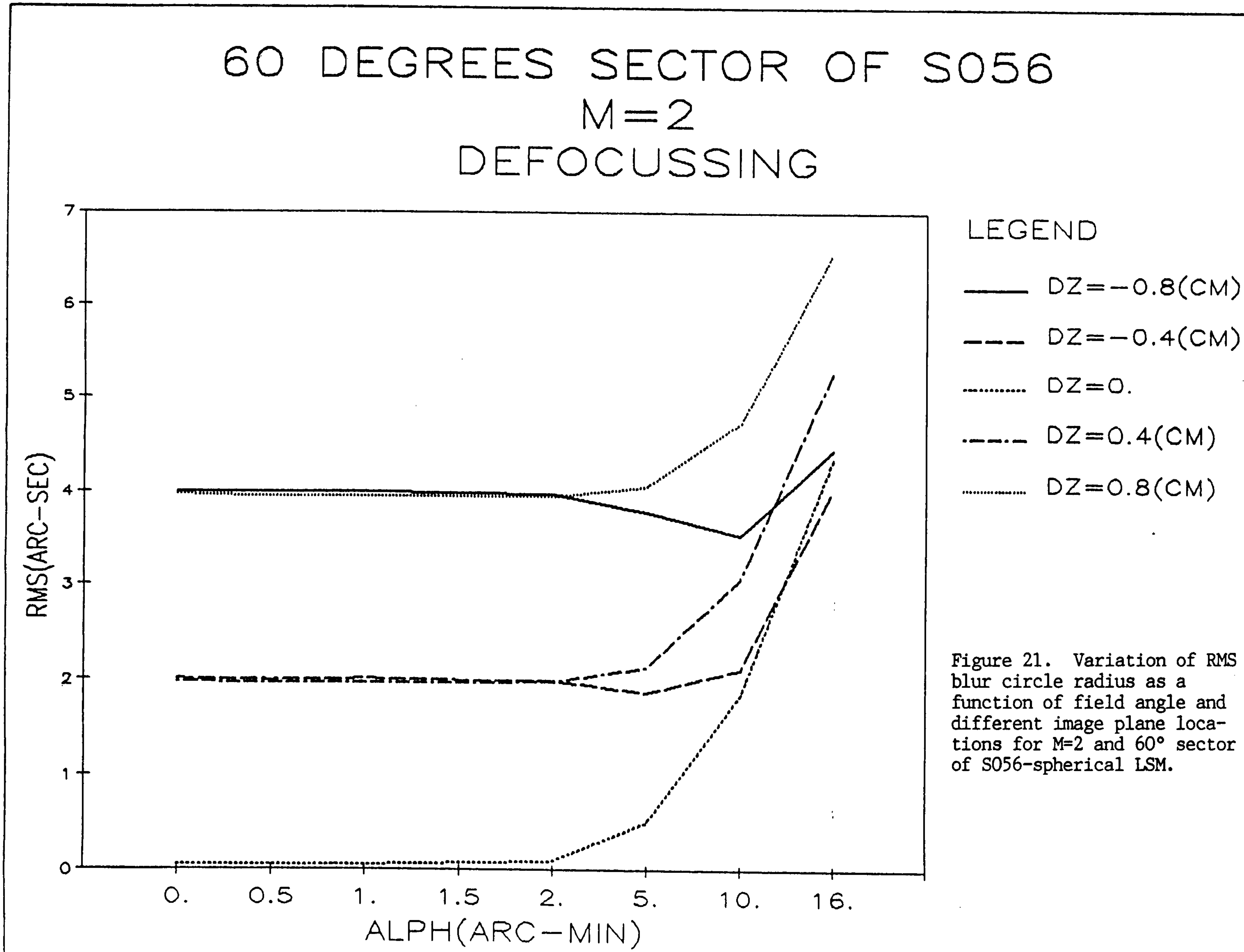

Figure 21. Variation of RMS blur circle radius as a function of field angle and different image plane locations for M=2 and 60° sector of S056-spherical LSM.

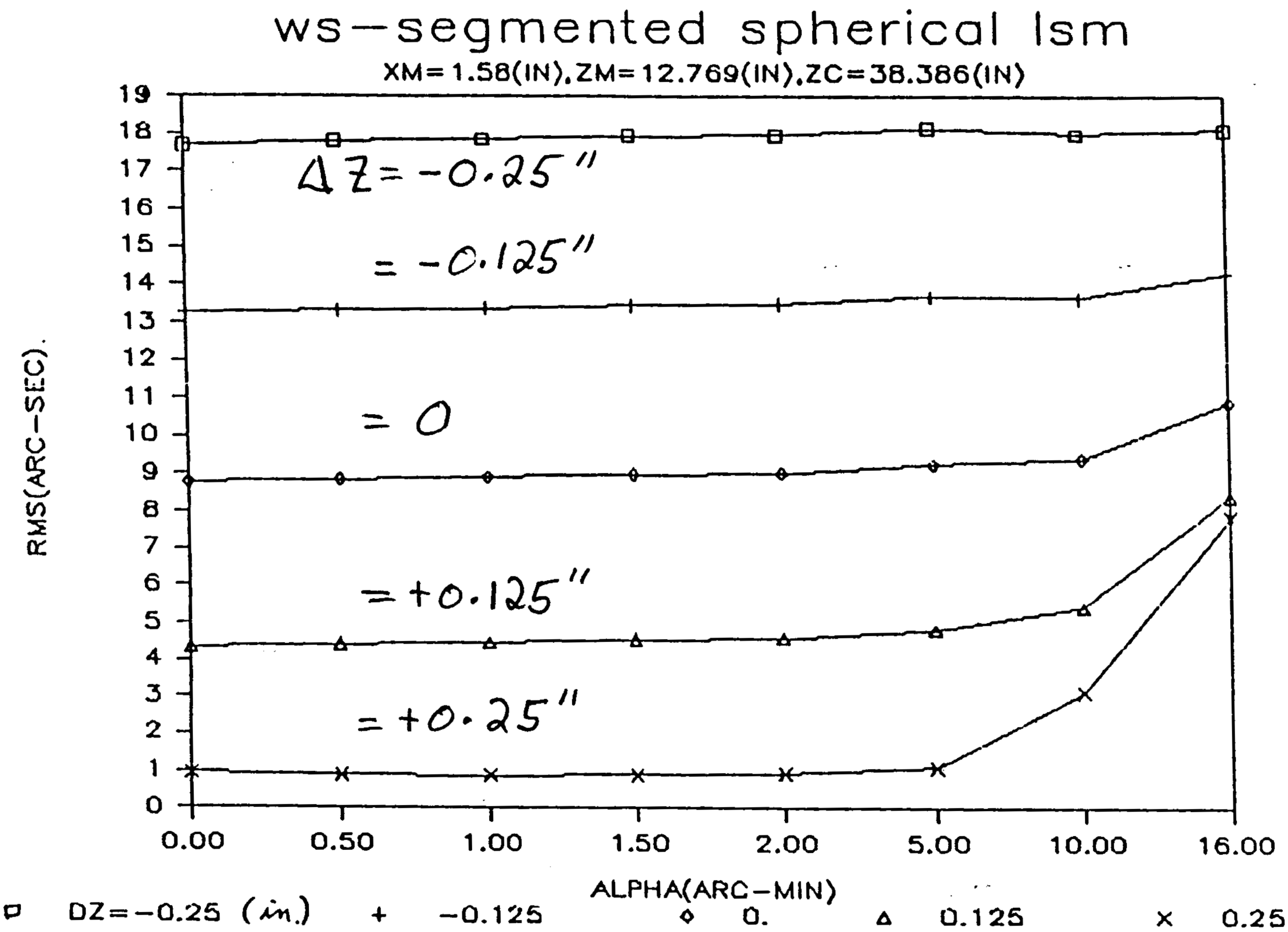

Figure 22. The defocussing effect of the image plane as indicated by the variation of RMS blur radius as a function of field angle for M=2 and nested WS-spherical LSM, γ=0.068 (rad).

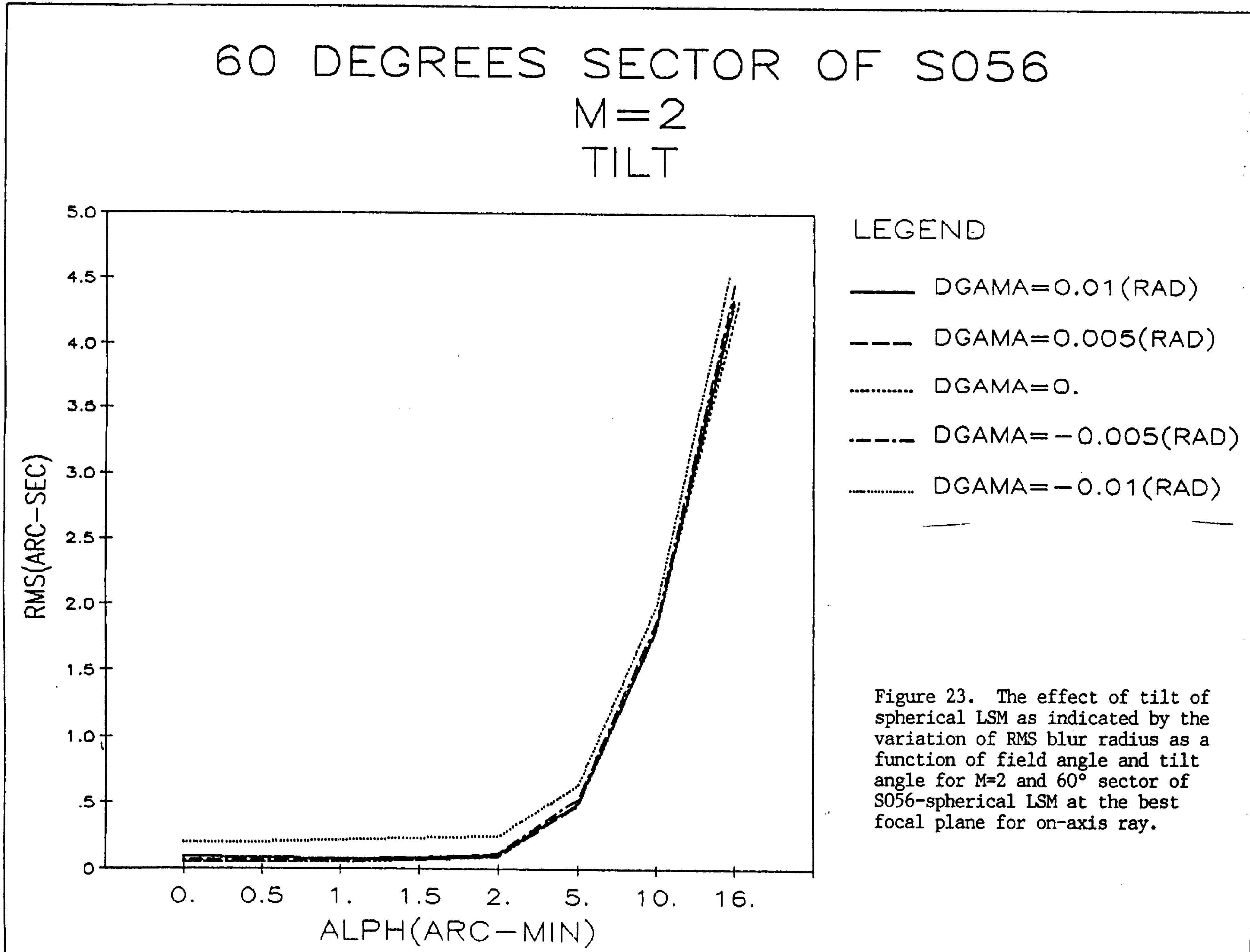

Figure 23. The effect of tilt of spherical LSM as indicated by the variation of RMS blur radius as a function of field angle and tilt angle for M=2 and 60° sector of S056-spherical LSM at the best focal plane for on-axis ray.

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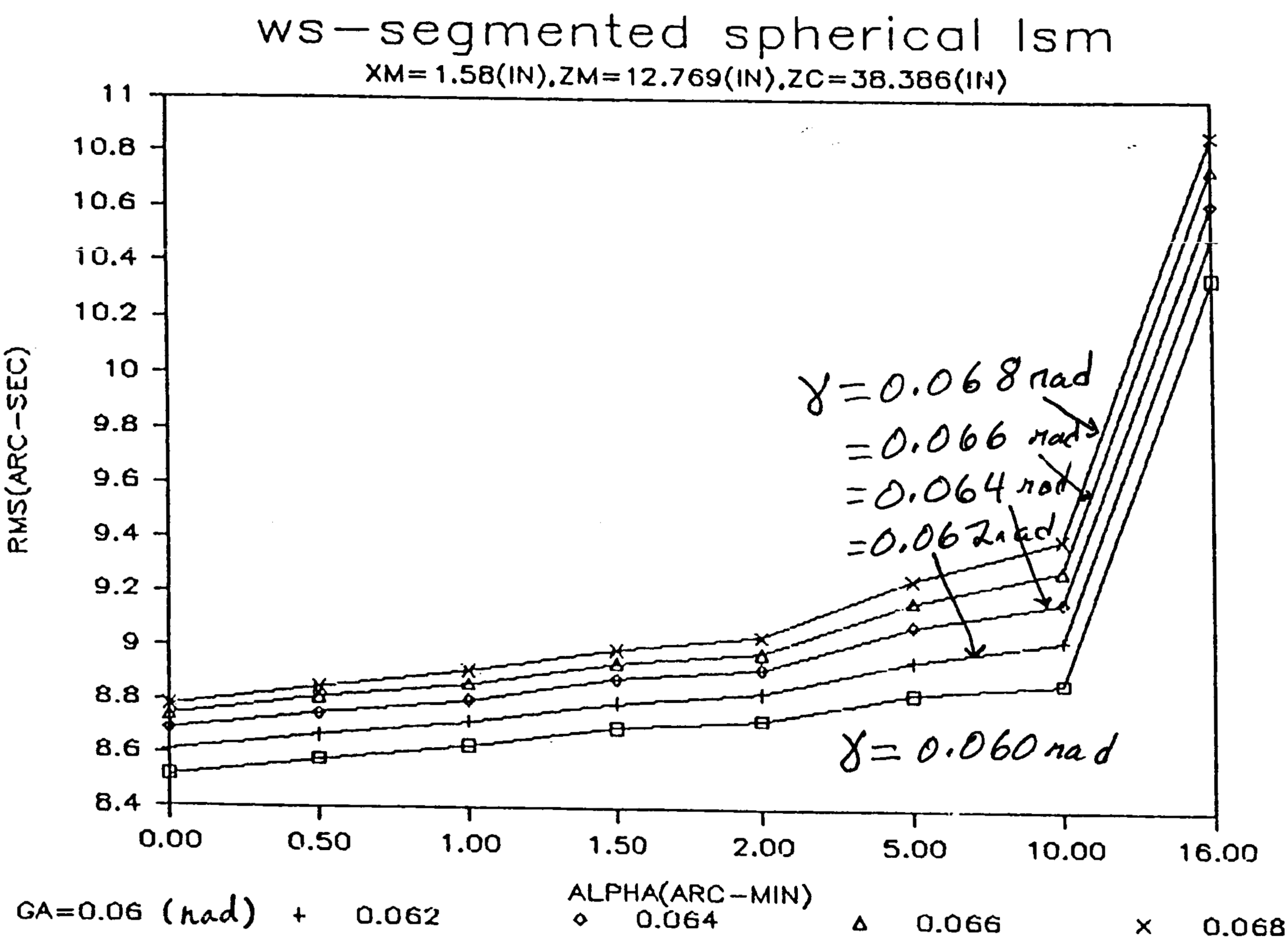

Figure 24. For nested WS-spherical LSM and M=2, the tilt effect of spherical LSM indicated by the variation of RMS blur radius as a function of field angle and tilt angle at the Gaussian focal plane.

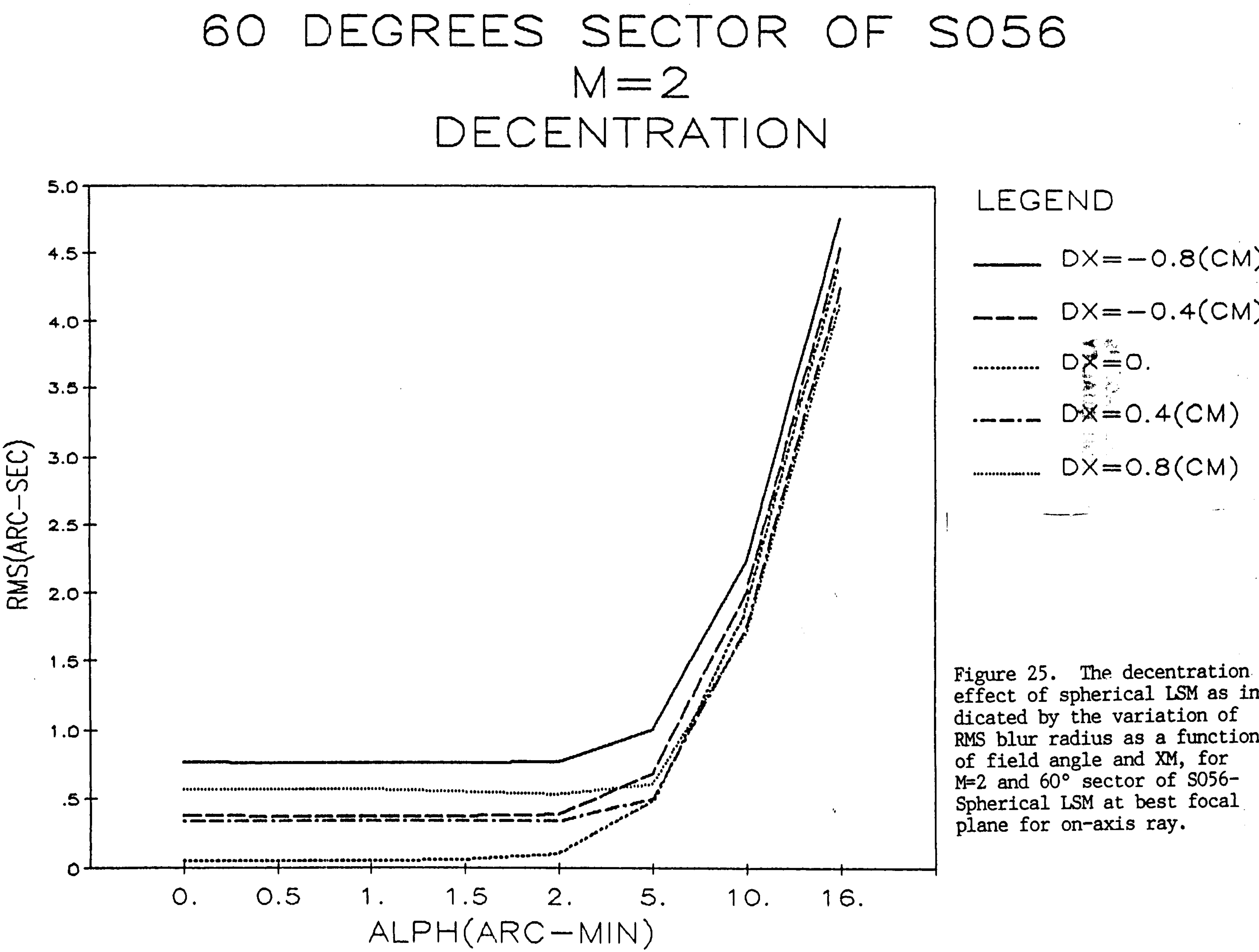

Figure 25. The decentration effect of spherical LSM as indicated by the variation of RMS blur radius as a function of field angle and XM, for M=2 and 60° sector of S056-Spherical LSM at best focal plane for on-axis ray.