

General Disclaimer

One or more of the Following Statements may affect this Document

- This document has been reproduced from the best copy furnished by the organizational source. It is being released in the interest of making available as much information as possible.
- This document may contain data, which exceeds the sheet parameters. It was furnished in this condition by the organizational source and is the best copy available.
- This document may contain tone-on-tone or color graphs, charts and/or pictures, which have been reproduced in black and white.
- This document is paginated as submitted by the original source.
- Portions of this document are not fully legible due to the historical nature of some of the material. However, it is the best reproduction available from the original submission.

NASA Technical Memorandum

NASA TM-86507

THE EXTENDED RANGE X-RAY TELESCOPE

Center Director's Discretionary Fund Final Report

By R. B. Hoover, N. P. Cumings, E. Hildner,
R. L. Moore, and E. A. Tandberg-Hanssen

Space Science Laboratory
Science and Engineering Directorate

March 1985



NASA

National Aeronautics and
Space Administration

George C. Marshall Space Flight Center

1. REPORT NO. NASA TM-86507		2. GOVERNMENT ACCESSION NO.		3. RECIPIENT'S CATALOG NO.			
4. TITLE AND SUBTITLE The Extended Range X-Ray Telescope Center Director's Discretionary Fund Final Report			5. REPORT DATE March 1985		6. PERFORMING ORGANIZATION CODE		
			7. AUTHOR(S) R. B. Hoover, N. P. Cumings, E. Hildner, R. L. Moore, and E. A. Tandberg-Hanssen			8. PERFORMING ORGANIZATION REPORT #	
9. PERFORMING ORGANIZATION NAME AND ADDRESS George C. Marshall Space Flight Center Marshall Space Flight Center, Alabama 35812			10. WORK UNIT NO.				
			11. CONTRACT OR GRANT NO.			13. TYPE OF REPORT & PERIOD COVERED Technical Memorandum	
			12. SPONSORING AGENCY NAME AND ADDRESS National Aeronautics and Space Administration Washington, D.C. 20546			14. SPONSORING AGENCY CODE	
15. SUPPLEMENTARY NOTES Prepared by Space Science Laboratory, Science and Engineering Directorate.							
16. ABSTRACT <p>An Extended Range X-Ray Telescope (ERXRT) of high sensitivity and spatial resolution capable of functioning over a broad region of the X-ray/XUV portion of the spectrum has been designed and analyzed. This system has been configured around the glancing-incidence Wolter Type I X-ray mirror system which was flown on the Skylab Apollo Telescope Mount as ATM Experiment S-056. Enhanced sensitivity over a vastly broader spectral range can be realized by the utilization of a thinned, back-illuminated, buried-channel Charge Coupled Device (CCD) as the X-ray/XUV detector rather than photographic film. However, to maintain the high spatial resolution inherent in the X-ray optics when a CCD of 30 micron pixel size is used, it is necessary to increase the telescope plate scale. This can be accomplished by use of a glancing-incidence X-ray microscope to enlarge and re-focus the primary image onto the focal surface of the CCD.</p> <p>In the ERXRT program, several glancing-incidence hyperboloid/ellipsoid X-ray microscope optical elements were designed and analyzed. An 8X microscope of 2-m focal length was selected as the optimum configuration to couple the S-056 X-ray mirrors to a 30-micron pixel RCA CCD X-ray/XUV detector. Detailed ray trace analysis studies have shown that this system has theoretical performance which should permit sub-arc second images to be achieved over the entire field of view of the detector. This research has shown that the ERXRT concept is theoretically feasible and that this system may be of great value for future high-resolution X-ray telescope/X-ray spectroscopy instruments. It has also provided valuable insights into other hybrid X-ray optical systems, such as are now being developed in the Wolter/LSM X-ray telescope program, which is also a Center Director's Discretionary Fund program.</p>							
17. KEY WORDS X-Ray Telescopes Extended Range X-Ray Telescope X-Ray Microscope			18. DISTRIBUTION STATEMENT Unclassified - Unlimited <i>Richard D. Hoover</i>				
19. SECURITY CLASSIF. (of this report) Unclassified		20. SECURITY CLASSIF. (of this page) Unclassified		21. NO. OF PAGES 19	22. PRICE NTIS		

TABLE OF CONTENTS

	Page
SUMMARY OBJECTIVES.....	1
I. INTRODUCTION	1
II. COMPONENTS OF THE EXTENDED RANGE X-RAY TELESCOPE	2
A. X-Ray Microscope Optic.....	2
B. CCD Camera System.....	3
C. S-056 Primary Mirrors	3
D. ERXRT X-Ray Microscope Optics	4
III. DESIGN AND MATHEMATICAL ANALYSIS OF THE X-RAY MICROSCOPE COMPONENT OF THE EXTENDED RANGE X-RAY TELESCOPE.....	5
IV. X-RAY MICROSCOPE MIRROR PARAMETERS AND PERFORMANCE PREDICTIONS	8
V. SUMMARY AND CONCLUSIONS.....	9
PATENTS AND BIBLIOGRAPHY	11

PRECEDING PAGE BLANK NOT FILMED

LIST OF ILLUSTRATIONS

Figure	Title	Page
1.	Schematic of the optical layout of the Extended Range X-Ray Telescope	12
2.	Symbolic view of the ERXRT system	12
3.	Cross sectional diagram of the X-ray microscope optic for ERXRT	13
4.	Microscope intersection diameter versus the magnification	13
5.	Meridional line spread function	14
6.	Sagittal slice of point spread function	14

TECHNICAL MEMORANDUM

THE EXTENDED RANGE X-RAY TELESCOPE

Final Report, Center Director's Discretionary Fund, Project Number 81-94

SUMMARY OBJECTIVES

The objective of this program was to develop techniques for extending the wavelength coverage of glancing-incidence X-ray telescopes into the soft X-ray/XUV portion of the spectrum which improved sensitivity. The previous work had shown that glancing-incidence X-ray optics were capable of superb spatial resolution over a very broad spectral region but that the system performance was limited in resolution, sensitivity, and wavelength coverage by the X-ray detector. High-resolution detectors, such as photographic films, have very low sensitivity and limit the wavelength response. Solid state devices, such as CCD's, have very high sensitivity and respond over a broad region of the X-ray/SUV spectrum, but they also have large pixels and thus exhibit low inherent spatial resolution. However, by using an X-ray microscope optic to magnify the primary image and re-focus it onto the CCD, it should be possible to produce an X-ray telescope of high sensitivity over an extended wavelength range, while still preserving the high spatial resolution provided by the X-ray telescope optics. Therefore, the immediate objective of this program was to verify the feasibility of the Extended Range X-Ray Telescope (ERXRT) by designing a family of glancing incidence X-ray microscope optics which could be used to couple the S-056 X-ray telescope mirror to a commercially available CCD of 30-micron pixel size. The performance characteristics of the various systems were analysed and the best system selected for fabrication of the X-ray microscope optic. The extensive theoretical studies completed in this program have shown that this approach is feasible and enhance the continued research capabilities in support of hybrid ERXRT systems for high sensitivity, broad wavelength response, and high spatial resolution images for solar X-ray/XUV research in support of future NASA missions.

I. INTRODUCTION

Skylab was launched over a decade ago. It carried the Apollo Telescope Mount (ATM) complement of instruments to Earth orbit for high-resolution observations of the Sun. These telescopes produced excellent X-ray, XUV, hydrogen-alpha and white light coronagraph images which have greatly expanded our knowledge of the Sun. One of these telescopes, the MSFC ATM Experiment S-056, produced over 35,000 high-resolution solar X-ray images that provided a wealth of information concerning solar flares, X-ray bright points, and coronal holes. This telescope used black and white (SO-212) and color (SO-242) films as X-ray detectors. The studies with Kodak high-resolution glass photographic plates (which have very high spatial resolution but low X-ray sensitivity) had shown the S-056 X-ray mirrors were capable of spatial resolution of 0.75 arc sec on-axis with response better than 3 arc sec over the entire solar disk. However, the more sensitive films utilized in flight limited the spatial resolution to 2.2 arc sec for the SO-212 film and to 1.8 arc sec for the S-242 film. Furthermore, the gelatin in the photographic emulsions strongly absorbs X-rays of wavelengths longer than 60 Å and therefore the wavelength response of the instrument was restricted.

The authors' research associated with the GOES X-ray Telescope Feasibility Demonstration program (carried out in collaboration with NOAA) had shown Charge Coupled Devices (CCD's) to be extremely sensitive detectors capable of responding over a broad wavelength range (5 to 600 Å) of X-ray and XUV radiation. However, these detectors have moderately large pixel sizes (typically 30 microns for the RCA devices) which would limit the spatial resolution of the Wolter Type I glancing-incidence S-056 X-ray telescope to around 6 arc sec unless the telescope plate scale could be altered. Of course, the plate scale of a telescope is directly related to its focal length. The S-056 telescope has a focal length of 1.9 m and a plate scale of 9 μ m per arc second. Therefore a telescope of greater than 16 m focal length would be required to achieve comparable resolution if one desired to adequately increase the plate scale by simply designing a longer focal length instrument. Such a large instrument would be difficult to transport to orbit. Hence, an alternate approach has been developed in the Extended Range X-Ray Telescope program.

To maintain the high spatial resolution capabilities inherent in the Wolter Type I glancing-incidence X-ray telescope and yet take advantage of the high-sensitivity broad-wavelength response of CCD's, it was proposed that an Extended Range X-Ray Telescope could be realized by use of a glancing incidence X-ray microscope optic to magnify the original X-ray telescope image and re-focus it onto the X-Ray detector. The optical layout for the Extended Range X-Ray Telescope is shown schematically in Figure 1. The primary image is formed by the Wolter I X-ray mirror, which consists of internally reflecting paraboloidal and hyperboloidal mirror elements arranged so as to be coaxial and confocal. An X-ray microscope mirror utilizes internally reflecting hyperboloidal and ellipsoidal elements to re-focus a magnified image onto the surface of the CCD X-ray detector. By using an RCA CCD of 30 micron pixels with an 8X microscope mirror, it should be possible to maintain the sub-arc second spatial resolution afforded by the Skylab ATM Experiment S-056 X-ray telescope. Without the X-ray microscope optic, a Wolter I telescope of 16-m physical length would be required to achieve this resolution with the CCD.

An array of glancing-incidence hyperboloid/ellipsoid X-ray microscope optical systems of the proper surface configurations was designed. In collaboration with Dr. David L. Shealy and Dr. S. Chao of the University of Alabama, Birmingham, the authors carried out extensive theoretical evaluations of the Wolter I X-ray telescope. A high sensitivity, thinned, back-illuminated buried channel CCD with a special vacuum suitable dewar was procured from PhotoMetrics, Ltd., in Tucson, Arizona, for use in X-ray experiments with this system. The Applied Optics Center (AOC) of Burlington, Massachusetts, was contracted with for the fabrication of the optimum X-ray microscope optic for this system. Computer programs were generated to analyze the measured performance characteristics of the ERXRT system in both visible light and X-rays.

II. COMPONENTS OF THE EXTENDED RANGE X-RAY TELESCOPE

A. X-Ray Microscope Optic

Several glancing-incidence hyperboloid/ellipsoid X-ray microscope systems were designed and analyzed theoretically to establish their predicted performance characteristics when used in conjunction with the ATM Experiment S-056 X-ray telescope optics. X-ray microscope optics were studied with focal lengths of 1.0, 1.5 and 2.0 m and with magnifications ranging from 5X to 8X. Section 3 presents the results of the

mathematical analysis of the Extended Range X-Ray Telescope System, in which a CCD camera is theoretically coupled to the S-056 optics with an optimally configured hybrid paraboloid/ellipsoid X-ray microscope optic.

B. CCD Camera System

For optimum sensitivity over the X-ray and XUV regions (5Å to 500Å) a thinned, back-illuminated, buried channel CCD was specified for use in the Extended Range X-ray Telescope. The CCD selected was similar to that which was utilized in the NOAA/NASA GOES X-ray imager program. X-ray/XUV tests on this chip had shown the device to have very high sensitivity. In comparison, it was found to be several hundred times more sensitive than the SO-212 film that was flown on Skylab as ATM Experiment S-056 in the 6 to 44 Å region. This detector was several thousand times more sensitive than the photographic emulsion in wavelength regions longward of 67 Å, where absorption of the XUV radiation by gelatin in the film becomes important. The GOES X-ray imager tests also demonstrated that this type of CCD is capable of resolution in visible light and X-rays at the Nyquist limit. (This limit is determined by the minimum angular separation of the sources required to produce illumination of alternate pixels.)

The CCD camera system (detector with camera controller, data output electronics and a special dewar for thermal control in the vacuum chamber) was fabricated by PhotoMetrics, Ltd., in Tucson, Arizona. The camera was first delivered with a visible, light-sensitive chip installed, and tests were performed on the CCD at MSFC. After RCA completed fabrication of the thinned, back-illuminated, buried channel CCD, the camera was returned to PhotoMetrics, Ltd., and the new X-ray/XUV-sensitive chip was installed. This CCD was tested at RCA and subsequently at PhotoMetrics, Ltd. It was found to meet the specifications for signal-to-noise, sensitivity, and linearity. Tests at MSFC demonstrated that the camera system, with controller and data output electronics, function as specified.

The microprocessor-driven data acquisition, processing, and display system for use with the Extended Range X-Ray Telescope system and for other future hybrid X-ray telescope systems was developed in SSL and found to perform satisfactorily. The authors plan to use this CCD camera system in their ongoing CDDF project for investigating Wolter telescopes used with magnifying layered synthetic microstructure mirrors.

C. S-056 Primary Mirrors

The quality and performance characteristics of the ATM Experiment S-056 flight back-up telescope mirrors were studied in the Space Science Laboratory at MSFC. The telescope solar shield was removed and a careful inspection of the optics was performed. No significant particulate contamination was detected with critical glancing-incidence illumination techniques, even though the optics had remained in storage in the ATM cannister for over a decade. This has provided valuable information regarding the protection of X-ray mirrors from particulate contaminants. During the S-056 program, several events of particulate contamination were experienced, even with the optics maintained in clean rooms and on laminar flow clean benches. It was concluded that small particulates adhere to the optics and can only be removed by physical cleaning methods. Hence, even though clean benches have very few particulates per cubic meter of air, since the air is continuously flowing, a significant

contamination level can build up over a long duration exposure. However, if the mirrors are sealed so that no air flow is possible, once the particulates in the sealed environment settle out onto the available surfaces, a super clean environment is obtained which remains until the seal is broken. The very clean state that the S-056 optics exhibited after over a decade of storage in a sealed environment clearly demonstrated the merit of this method for protecting X-ray mirrors from contamination by particulates.

The S-056 mirrors were tested in visible light and found to be capable of spatial resolution of the order of 0.75 arc sec. These results were comparable to those achieved under the best conditions when the mirrors were first tested a decade and a half ago. This demonstrates that no detectable surface figure changes or errors in the alignment of the paraboloidal and hyperboloidal elements has been experienced since the optics were first tested at MSFC after their delivery from the Perkin Elmer Corp., Norwalk, Conn., where they were fabricated.

D. ERXRT X-Ray Microscope Optics

The goal in the ERXRT program was to design and theoretically analyze a family of X-ray microscope optics which could be used to couple the S-056 optics to a 30-micron pixel size X-ray/XUV-sensitive CCD. After detailed considerations of the ability of potential vendors to fabricate the various microscope mirror configurations possible, and intensive studies of the off-axis resolution and vignetting characteristics of various systems, the microscope configuration for optimum system performance was selected. Discussions with several potential vendors in the U.S. and the U.K. clearly revealed that glancing-incidence hyperboloid/ellipsoid X-ray microscope mirrors of similar sizes and tolerance had previously been fabricated for laser fusion research. Hence, the mirror design was feasible and could be manufactured.

The mathematical analysis, which will be detailed below, demonstrated that Extended Range X-Ray Telescope systems utilizing X-ray microscope optics such as this are feasible and should be capable of producing sub-arc second resolution over the entire field of view of the detectors when used to re-focus the primary image from Wolter I X-ray telescopes onto the CCD image plane.

The optimal X-ray microscope mirror parameters were generated and provided as specifications in the request for proposals for the mirror fabrication effort. Several potential vendors submitted acceptable proposals with demonstrated capability for fabricating glancing-incidence X-ray microscope optics. The contract was awarded to the low bidder, the Applied Optics Center (AOC), Burlington, Massachusetts, for the fabrication of these mirrors. This company had successfully completed a number of superior glancing-incidence X-ray telescope and X-ray microscope optics. They possessed a proprietary superpolishing technique and had produced excellent metal X-ray optics for the MSFC/Stanford Rocket X-Ray Spectroheliograph and for the NOAA/MSFC GOES X-Ray Telescope Feasibility Demonstration Program. AOC was also fabricating an externally reflecting metal X-ray microscope optic for American Science and Engineering (AS&E) and had proven expertise in diamond turning and super-polishing X-ray mirrors. However, during the ERXRT microscope optic fabrication effort, AOC experienced significant problems in their manufacturing facility. Air bearings failed on the diamond turning machine, which was critical to the fabrication of this highly specialized mirror element. Prior to the completion of the X-ray microscope optic, the AOC Burlington facility was closed on December 31, 1984, and the hyperboloid/ellipsoid X-ray microscope optic contract was not fulfilled.

Consequently, the X-ray tests of the completed ERXRT system that were scheduled to occur in the MSFC X-Ray Test Facility in January 1985 could not be performed. However, from the extensive theoretical analysis research that had been carried out in this program, a great many of the potential benefits of this technology have been established. The next section considers in detail the results of these theoretical investigations of Extended Range X-Ray Telescope systems in which a glancing-incidence, internally reflecting hyperboloid/ellipsoid X-ray microscope is used to couple a Wolter I X-ray telescope to an X-ray/XUV detector.

III. DESIGN AND MATHEMATICAL ANALYSIS OF THE X-RAY MICROSCOPE COMPONENT OF THE EXTENDED RANGE X-RAY TELESCOPE

The design and mathematical analysis of the ERXRT X-ray microscope yielded several interesting results. Since the mirror was to be coupled to an existent X-ray telescope optic (e.g., ATM Experiment S-056), the nature and characteristics of the incoming beam was well defined. The S-056 primary mirror operates at a glancing angle θ_m of 54 min of arc. Therefore, paraxial rays reflected by this telescope will cross the optical axis at an angle of $4 \theta_m$ (216 arc min). This places constraints on the glancing angle of incidence suitable for the X-ray microscope, and consequently upon its position and size.

Figure 2 shows a symbolic view of the ERXRT system. Figure 3 is a cross-sectional diagram of the X-ray microscope with the relevant parameters identified.

Using the coordinate system set forth in Figure 2, the equations of the S-056 X-ray telescope paraboloidal mirror surface are:

$$x^2 = p (2z + p)$$

$$z = \frac{x^2}{2p} - \frac{p}{2}$$

The surface of the hyperboloidal element of the S-056 X-ray telescope is defined by the following equations:

$$\frac{(z-c)^2}{a^2} - \frac{x^2}{b^2} = 1$$

$$z = c + a \sqrt{1 + x^2/b^2}$$

The basic mirror surface parameters for the S-056 primary optic (with all linear dimensions given in inches) are as follows:

Glancing Angle, $\theta_m = 0.916^\circ$

Paraboloid Parameters:

$$X_p \text{ min} = 4.792\ 896\ 48$$

$$Z_p \text{ min} = 149.846\ 697$$

$$X_p \text{ max} = 4.848\ 790\ 7$$

$$Z_p \text{ max} = 154.631\ 134\ 5$$

$$\text{Paraboloid length: } L_p = 4.784\ 437\ 7$$

$$p = 0.076\ 631\ 56$$

Hyperboloid Parameters:

$$X_h \text{ min} = 4.576\ 677\ 6$$

$$Z_h \text{ min} = 145.353\ 53$$

$$X_h \text{ max} = 4.792\ 896\ 48$$

$$Z_h \text{ max} = 149.846\ 697$$

$$\text{Hyperboloid length: } L_h = 4.493\ 167$$

$$a = 37.461\ 664\ 4$$

$$b = 1.695\ 198\ 8$$

$$c = 37.500\ 000$$

For the following considerations, let:

$F_w = 2\ c$; the focal length of the S-056 primary optic.

F_m = the distance along the optical axis from the image point to the object point of the X-ray microscope.

M = magnification of X-ray microscope optic.

θ_m' = glancing angle at the point of intersection of the hyperboloidal and ellipsoidal components of the X-ray microscope.

The equations of the surfaces of the hyperboloidal and ellipsoidal components of the X-ray microscope mirror are given by:

$$\frac{(z - z_{OH})^2}{A_H^2} - \frac{x^2}{B_H^2} = 1$$

$$\frac{(z - z_{OE})^2}{A_E^2} + \frac{x^2}{B_E^2} = 1$$

where

$$z_{oH} = F_W + C_H$$

$$C_H = \frac{F_M \sin(4\theta_m)}{2M \sin(4\theta_m')} \frac{\sin(2\theta_m')}{\sin(4\theta_m - 2\theta_m')}$$

$$A_H = \frac{F_M \sin(4\theta_m)}{2M \sin(4\theta_m')} \left[\frac{\sin(4\theta_m)}{\sin(4\theta_m - 2\theta_m')} - 1 \right]$$

$$B_H^2 = C_H^2 - A_H^2$$

$$\theta_m' = \theta_m + \frac{1}{4} \sin^{-1} \left[\frac{\sin(4\theta_m)}{M} \right]$$

$$A_E = \frac{F_M \sin(4\theta_m)}{2 \sin(4\theta_m')} \left[1 + \frac{\sin(4\theta_m)}{M \sin(4\theta_m - 2\theta_m')} \right]$$

$$C_E = \frac{F_M \sin(4\theta_m)}{2 \sin(4\theta_m')} \frac{\sin(2\theta_m')}{\sin(4\theta_m - 2\theta_m')}$$

$$B_E^2 = A_E^2 - C_E^2$$

The coordinates for the intersection points of the hyperboloidal and ellipsoidal mirror elements are given by:

$$X^* = \frac{F_M}{M} \frac{\sin^2(4\theta_m)}{\sin(4\theta_m')}$$

$$Z^* = \frac{-F_M \sin(8\theta_m)}{2M \sin(4\theta_m')} + F_W$$

It is most interesting to note that in accordance with these constraints, the X-ray microscope optic surfaces are entirely specified in terms of the glancing angle on the primary telescope θ_m , and the microscope magnification M and focal length F_m .

Calculations established the minimum axial lengths required for the hyperboloidal and ellipsoidal elements such that all paraxial rays incident upon the S-056 optics would be reflected by the microscope to the ERXRT focal point. The parameter K was defined as the ratio of sum of the minimum lengths of the hyperboloid and ellipsoid elements to the diameter of the microscope at the hyperboloid/ellipsoid intersection. As the lengths of these elements are increased, off-axis efficiency is increased since vignetting is diminished, but the off-axis resolution degrades. The design of an optimum X-ray microscope element is then relegated to achieving a proper balance of resolution, defocussing and vignetting effects for optimal performance over the entire field of view of the system. Defocussing considerations are important, since the Petzval surface of best focus is sharply curved toward the X-ray microscope optic. If the detector to be used has a flat surface, it is desirable to move the detector toward the microscope optic to achieve the best balance of resolution over the entire detector surface. Of course, optimum performance would be achieved with a detector curved such that its surface precisely matches the contour of the optical system surface of best focus (the Petzval surface). This however poses difficult constraints upon detector fabrication, and for most applications the defocus compromise is preferred. Indeed, on-axis, this system is theoretically capable of spatial resolution of the order of a few thousandths of an arc second, which far exceeds what can be achieved with any existent X-ray detector. Hence, intentional defocussing to balance the performance of the system to the capabilities of existent X-ray detectors is the most sensible approach.

The primary factor in the selection of the microscope magnification was the characteristics of the X-ray detector and the S-056 optics. The CCD pixel size (30 microns) dictates that for resolution at the Nyquist limit, the sources would have to be separated more than 60 microns at the detector surface. The S-056 X-ray telescope plate scale is 9 microns/arc sec and a resolution of 0.75 arc sec has been demonstrated. From these considerations, an X-ray microscope magnification of 8X was selected. RMS spot size calculations and ray trace analysis results indicated that sub-arc second spatial resolution was possible over the entire 3.5 arc min field of view afforded by the CCD X-ray detector. To minimize vignetting effects, a K factor of 2.5 was selected for an X-ray microscope of 2-m focal length. Optimization of efficiency over the entire field resulted in a hyperboloid length of 3.82 cm and an ellipsoid length of 3.2591 cm. The microscope was designed for use with the flat image plane defocused by 4 mm towards the microscope optic.

IV. X-RAY MICROSCOPE MIRROR PARAMETERS AND PERFORMANCE PREDICTIONS

During the ERXRT design and analysis effort an array of X-ray microscope optics of several different focal lengths and mirror magnifications and size configurations was studied. The microscope mirror diameter at the hyperboloid/ellipsoid point of intersection varies with the focal length as is shown in Figure 4. From physical constraints imposed by the potential vendor's ability to fabricate these optics, it was determined that the microscope focal length should be 2 m so as to allow an intersection diameter greater than 2.8 cm for a magnification of 8X. The parameters of the 2-m focal length, 8X microscope mirror designed and selected for the fabrication effort are as follows:

$$A_H = 14.272934 \text{ cm}$$

$$B_H = 0.604141 \text{ cm}$$

$C_H = 14.285714$ cm
 $Z_{OH} = 204.785714$ cm
 $A_E = 114.298488$ cm
 $B_E = 1.708770$ cm
 $C_E = 114.285714$ cm
 $Z_{OE} = 104.785714$ cm
 $X^* = 1.420480$ cm
 $Z^* = 168.317533$ cm

(The microscope surface parameters for 2-m focal length systems designed for magnifications of 5X, 6X, 6.5X, 7X, and 8X are summarized in Table 1.)

Theoretical ray trace analysis reveals that an 8X mirror of 2-m focal length utilized to couple the ATM Experiment S-056 Wolter I X-Ray Telescope to a CCD of 30-micron pixel size should yield sub-arc second spatial resolution over the entire 3.5-min field of view dictated by the 320X512 pixel detector. Figures 5 and 6 show the results of a ray trace analysis of the meridional and sagittal line spread functions, respectively, of the system at 1 arc min off-axis. The Full Width Half Maximum (FWHM) is 0.086 arc sec for the meridional rays. It is important to note that the 50 percent energy width is only 0.355 arc sec. These results indicate that this instrument should perform superbly in investigations of small solar X-ray emission features, such as X-ray bright points and for definition of small coronal loop features in the X-ray and XUV regions. Furthermore, the ERXRT configuration is ideal for instruments wherein the second focus of the X-ray microscope is placed on the entrance slit of a high-resolution X-ray/XUV spectrometer. For these types of applications, the very long effective focal length that can be delivered by the ERXRT configuration (~ 16 m or more) is of paramount importance.

Vignetting effects were also thoroughly analyzed for the ERXRT systems and it was found that the transmittance exceeds 20 percent at the edge of the field and is more than 60 percent over the central arc minute field. In view of the fact that the CCD is several orders of magnitude more sensitive in the X-ray/XUV region than photographic emulsions, these vignetting effects should pose no significant observational restraints and are deemed totally acceptable.

V. SUMMARY AND CONCLUSIONS

At the completion of this Discretionary Fund Program, the authors have designed and analyzed an Extended Range X-Ray Telescope system with a glancing-incidence X-ray microscope mirror used for coupling a high sensitivity CCD X-ray detector to an existent Wolter I X-Ray Telescope system. Since the X-ray microscope optic that was designed and specified was not delivered by the vendor, the experimental phase of this program could not be carried out. However, a great deal of valuable information was obtained in the experimental study of the ATM Experiment S-056 flight backup

optics after their long period of storage. These observations should be of relevance to many future X-ray telescope programs.

Furthermore, in this program, we performed extensive theoretical calculations and ray trace studies of the ERXRT system to determine the RMS spot size, vignetting effects, and defocussing effects as well as investigations of the sagittal and meridional line spread functions to establish the Full Width Half Maximum and the 50 percent energy width of the entire system as a function of field angle. These results demonstrate that ERXRT systems are feasible and can provide sub-arc second resolution over reasonable fields of view.

The ERXRT approach should have great value in high resolution solar X-ray imaging experiments as well as in solar and cosmic X-ray spectroscopic experiments where it is desirable to feed a very narrow cone of X-rays from a large X-ray telescope to the entrance slit of an X-ray spectrometer. In collaboration with Prof. A. B. C. Walker, Jr. of Stanford University, the authors have proposed an instrument of similar configuration for flight on the Advanced X-Ray Astrophysical Facility (AXAF).

Another valuable spin-off of the ERXRT effort is research into other methods of coupling solid state detectors to glancing-incidence Wolter I mirror systems. Of great promise is the work currently being carried out under CDDF support for the use of contoured Layered Synthetic Microstructure (LSM) optics to magnify narrow spectral slices of the image provided by the Wolter I mirror. Although the spectral coverage is not as broad as is possible with the ERXRT system, superb spatial resolution is realizable over very large fields of view. Indeed, our calculations even indicate that these normal incidence LSM optics are capable of correcting image defects inherent in the original Wolter I mirrors, such that the off-axis performance of the primary mirror system can even be further improved. Of course, each LSM optic effectively reflects only a single narrow spectral slice of the incident radiation, and therefore enhanced spectral resolution is obtained, but the broad spectral imaging features of the ERXRT system are somewhat compromised.

It is anticipated that the ERXRT configuration will find many future applications as a high-resolution imaging system and for X-ray spectroscopy of solar X-ray features.

PATENTS AND BIBLIOGRAPHY

- Cessna, James R., Hoover, Richard B., Grubb, Richard N., Orswell, Prentice L., and Taylor, John H.: 'The GOES X-Ray Imager Feasibility Demonstration. NOAA Technical Report ERL 423-SEL41, February 1983.
- Hoover, Richard B.: Extended Range X-Ray Telescope. U.S. Patent No, 4,370,750, January 25, 1983.
- Hoover, Richard B.; Wriston, Robert S.; and Froechteniht, Joseph F.: Behavior of the Glancing Incidence X-Ray Optics for ATM Experiment S-056. Proceedings of the X-Ray Optics Symposium Held at the Mullard Space Science Laboratory of University College London, April 1973, P. W. Sanford (Ed.), pp. 137-161.
- Shealy, D. L.; Kassim, A.; and Chao, S.: Extended Range X-Ray Telescope: X-ray Microscope Design. Final Report, Contract NAS8-34728, June 30, 1982, pp. 1-113.
- Underwood, J. H.; Milligan, A. E.; deLoach, A. C.; and Hoover, R. B.: S-056 X-Ray Telescope Experiment on the Skylab Apollo Telescope Mount. Appl. Opt., Vol. 16, 1977, pp. 858-869.

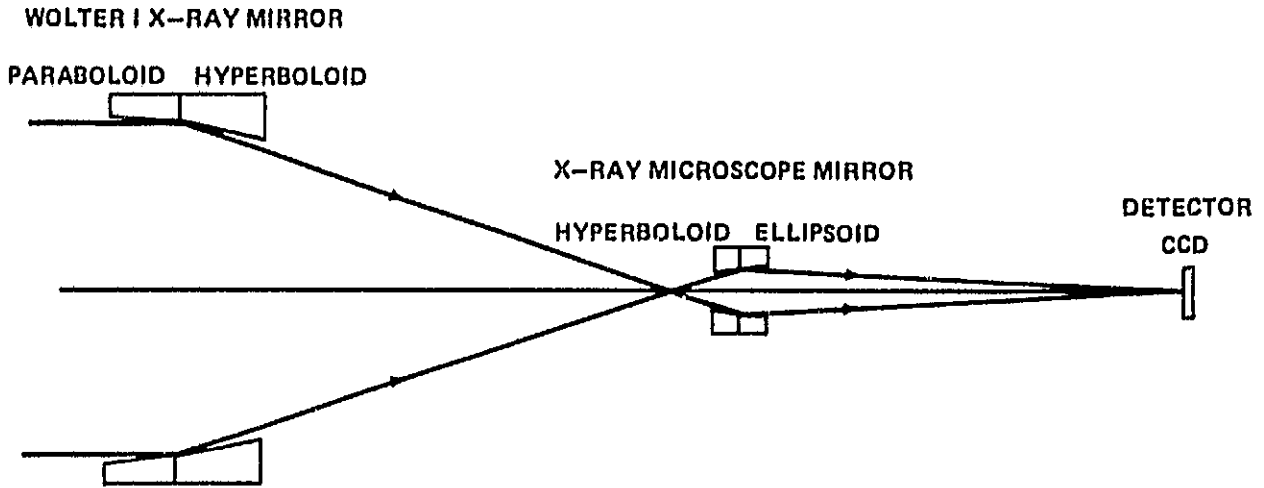


Figure 1. Schematic of the optical layout of the Extended Range X-Ray Telescope.

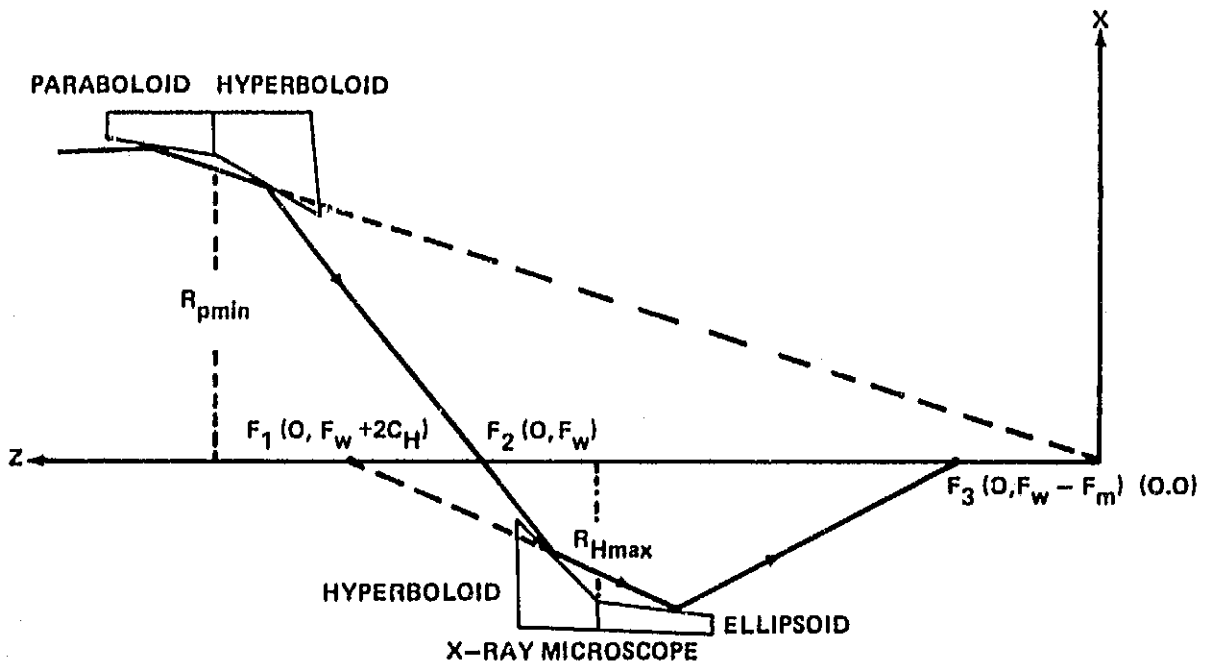


Figure 2. Symbolic view of the ERXRT system.

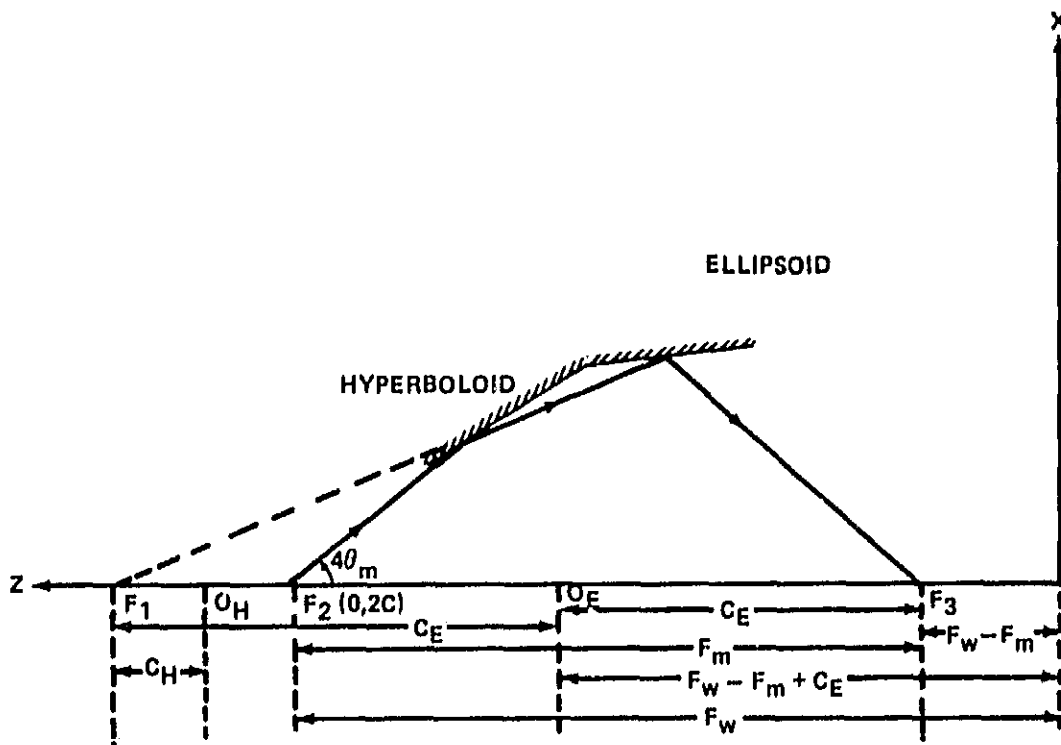


Figure 3. Cross sectional diagram of the X-ray microscope optic for ERXRT.

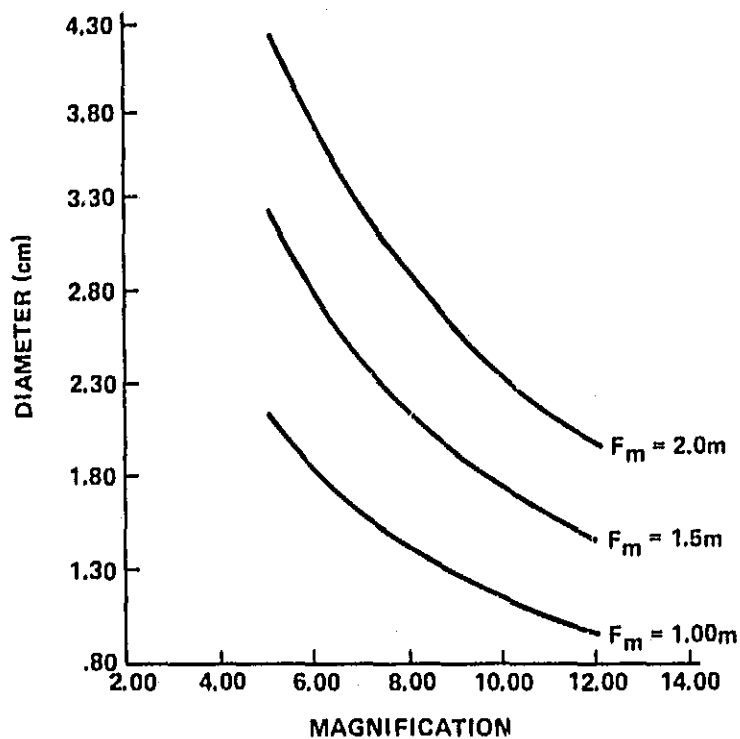


Figure 4. Microscope intersection diameter versus the magnification.

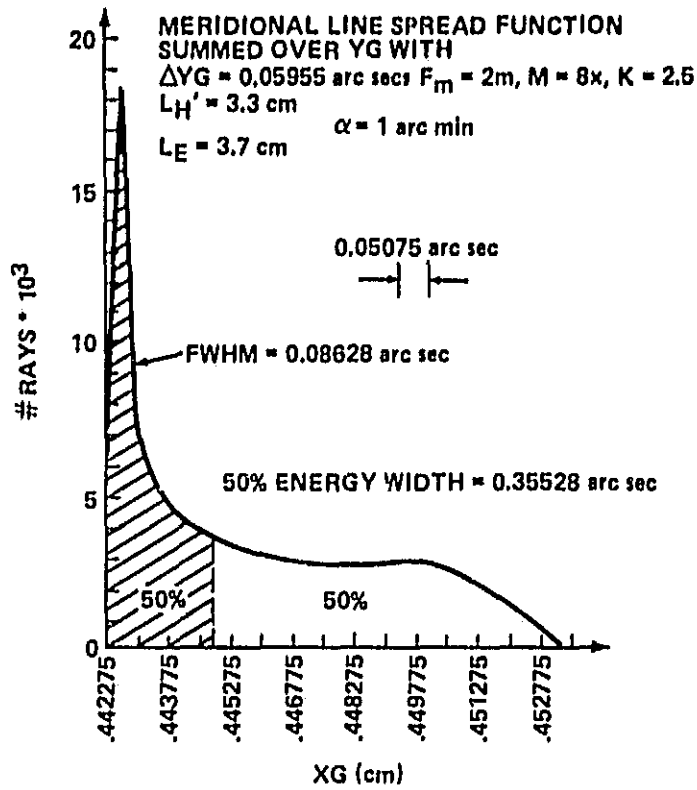


Figure 5. Meridional line spread function.

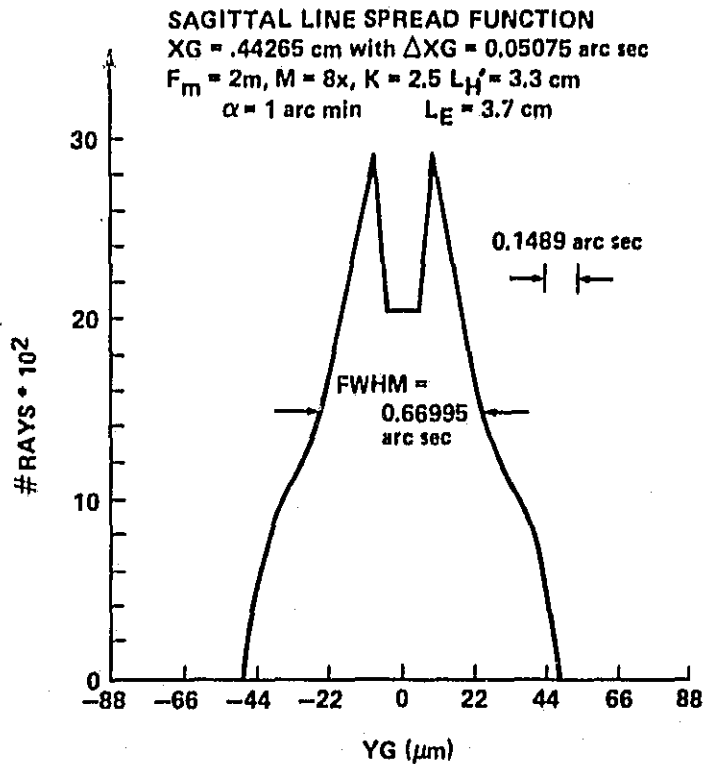


Figure 6. Sagittal slice of point spread function.

TABLE 1. MICROSCOPE SURFACE PARAMETERS FOR $F_m = 2 \text{ m}$

cm	Magnification (X)				
	5	6	6.5	7	8
A_H	24.979550	19.982959	18.166088	16.652060	14.272934
B_H	1.010989	0.825444	0.756146	0.697613	0.604141
C_H	25.0	20.0	18.181818	16.666666	14.285714
Z_{OH}	215.50	210.50	208.681818	207.166667	204.785714
L_H	1.684717	1.4831618	1.3988602	1.323375	1.194006
A_E	125.020440	120.017033	118.197540	116.681266	114.298488
B_E	2.260641	2.021917	1.927801	1.845711	1.708770
C_E	125.0	120.0	118.181818	116.666667	114.285714
Z_{OE}	115.50	110.50	108.681818	107.166667	104.785714
L_E	1.75736	1.551702	1.46524	1.387609	1.254123
X^*	2.131047	1.826487	1.704677	1.598099	1.420480
Z^*	157.221199	161.977257	163.879471	165.543814	168.317533

Minimum axial lengths of microscope mirror surfaces required to reflect on axis radiation incident upon the Wolter I telescope towards the focal point of the ERXRT system. L_H and L_E are measured from the microscope intersection point (X^* , Z^*).

APPROVAL

THE EXTENDED RANGE X-RAY TELESCOPE

By R. B. Hoover, N. P. Cumings, E. Hildner, R. L. Moore,
and E. A. Tandberg-Hanssen

The information in this report has been reviewed for technical content. Review of any information concerning Department of Defense or nuclear energy activities or programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.



A. J. DESSLER
Director, Space Science Laboratory