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NASA
Technical
Memorandum

NASA TM- 103571

OPTICAL SYNTHESIZER FOR A LARGE QUADRANT-ARRAY CCD CAMERA

CENTER DIRECTOR'S DISCRETIONARY FUND FINAL REPORT (PROJECT NUMBER 90-11)

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Space Science Laboratory
Science and Engineering Directorate

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National Aeronautics and
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13. ABSTRACT *(Maximum 200 words)*

This document constitutes the final report for MSFC Center Director's Discretionary Fund Project Number 90-11. The objective of this program was to design and develop an optical device, an optical synthesizer, that focuses four contiguous quadrants of a solar image on four spatially separated CCD arrays that are part of a unique CCD camera system. This camera and the optical synthesizer will be part of the new MSFC Experimental Vector Magnetograph, an instrument developed to measure the Sun's magnetic field as accurately as present technology allows. This report outlines the tasks undertaken in the program and presents the final detailed optical design.

14. SUBJECT TERMS

Large-Array CCD Camera, Optical Synthesizer, Vector Magnetograph

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TECHNICAL MEMORANDUM

OPTICAL SYNTHESIZER FOR A LARGE QUADRANT-ARRAY CCD CAMERA - CENTER DIRECTOR'S DISCRETIONARY FUND FINAL REPORT (Project Number 90-11)

1. INTRODUCTION

The interaction of magnetic fields with the Sun's plasma is the controlling force in the dynamic, high-energy phenomena observed in solar active regions. The origin, evolution, and development of the Sun's magnetic field to produce these energetic processes are central themes in today's solar research, and extensive observational studies are carried out to develop an understanding of just how the solar magnetic field plays this pivotal role in solar activity.

MSFC has a unique instrument for observing the Sun's magnetic field, the MSFC Solar Vector Magnetograph [1-3]. Using this instrument, MSFC scientists have made many significant contributions over the past decade to an understanding of the magnetic Sun, with the result that MSFC is recognized worldwide as a leader in the study of solar magnetic fields.

As a consequence of this acknowledged leadership, MSFC scientists were funded by the Air Force in 1986 for a 2-year study to develop a design concept for a space-based solar vector magnetograph for flare research. In this study, a new technique in solar polarimetry was developed to yield measurements of photospheric magnetic fields that would be as accurate as present technology allows. Subsequently, MSFC was funded by NASA Headquarters to develop a prototype of this space instrument for ground-based observations, the new Experimental Vector Magnetograph (EXVM). When completed in early 1992, the EXVM will be tested side by side with the existing MSFC vector magnetograph so that MSFC scientists can quantitatively evaluate the performance of the EXVM and determine the degree to which it can improve measurements of the solar magnetic field. Present plans call for the evolution of the EXVM into a prototype for a balloon instrument to be flown on long-duration balloon flights in the years 1994-98. The design study for this prototype is presently underway with funding from NASA Headquarters.

Two major components of the EXVM, a unique CCD camera and a custom-designed data system, were developed under a Small Business Innovative Research (SBIR) program. The camera was designed to provide an exceptionally large imaging area (1024 x 2048 pixels) that is read out at an extremely fast rate (1.2×10^6 pixels per second) at eight different readout ports. The camera is presently configured to operate with four 1024 x 1024 frame-transfer CCD devices (but can be easily modified to operate with a single 2048 x 2048 chip). Using half the pixel area for imaging and an equivalent area for temporary image storage, the camera can operate at a cadence of $\approx$ 0.2 second: 0.2 second for image exposure and 0.2 second for simultaneous image readout. This process of simultaneous image exposure and readout produces the high temporal resolution needed for the study of dynamic magnetic processes on the Sun. The SBIR data system was custom-designed to accommodate the high data rates from this CCD camera, and to control instrument functions, perform data reduction, analysis, and storage, and provide communications with a host computer.

In interfacing this camera with an imaging optical system, the "dead space" produced by the area between the four non-buttable CCD chips presents a problem: a significant portion of a solar field of view focused on the camera faceplate is lost. It was the purpose of this CDDF program to develop an optical device, an optical synthesizer, to separate the solar image into four contiguous quadrants and focus each of them on the four separated CCD arrays, thereby producing a continuous image when the pixels are processed in the data system. In this report, we will describe this CDDF program: the tasks undertaken, the design of the imaging optics and optical synthesizer, modifications to the camera electronics, and a description of the integrated system.

2. THE CDDF PROJECT

The overall plan was to design the optical synthesizer, procure the necessary optics, modify the camera to operate in the four-chip, eight-port parallel-processing mode, install four chips, and integrate camera and optics into the EXVM. Four major tasks were defined in this plan:

(1) A detailed optical design for the EXVM optics and optical synthesizer. The basic requirement for the synthesizer is shown schematically in Figure 1. While the concept is clear, its optical design must be very precise to assure that each one of the four sections of the optical image is accurately focused on the imaging area of each CCD chip. Also, the synthesizer must be carefully integrated into the rest of the optics of the EXVM. Thus, the first major task was to obtain a detailed optical design for both the synthesizer and EXVM optics.

(2) Modification of camera electronics. Under the SBIR contract, the camera system was designed for operation of all eight readout ports but electronic components were furnished for only four ports (as a result of budgetary constraints). The second task involved acquiring the electronic design from the manufacturer of the camera, and procuring and installing the necessary electronic components to realize the full capabilities of the camera.

(3) CCD installation. Upon completion of the electronic modifications, the camera was to be shipped to the manufacturer for installation and testing of four CCD chips.

(4) System integration. The last major task was to integrate the modified camera system with the synthesizing optics, EXVM optics, and data system and to test the integrated

system.

3. THE OPTICAL DESIGN

A contract for the detailed optical design for the EXVM optics and the optical synthesizer was initiated in May 1990; the completed design was provided by the contractor in December 1990. This design was given to the MSFC Optical Systems Branch, EB23, to verify its performance using an optical design computer program. The analysis performed by EB23 showed that the contractor's design did not meet our specifications for off-axis performance; this result was subsequently confirmed by two more independent analyses. An agreement was established in April 1991 with EB23 for them to provide the necessary optical design for the EXVM optics and optical synthesizer. The EB23 design for the EXVM optics was completed in July 1991; the design is shown in Figure 2. Procurement of the optical lenses specified by this design is now in progress.

Calculations to determine the optical performance were done by EB23. The two-dimensional spatial distribution of the intensity of a point source at the final image plane was calculated using the computer design program. This distribution is displayed in Figure 3. This figure shows the distributions for a point source in the center of the field of view and at the far edge. In each case, the scale length corresponding to 1″ is indicated; the plate scale at the camera faceplate was specified to be 0.25″ per CCD pixel. In the case of the point source at the center of the field, the spread at the half-intensity mark is ≈ 0.25″. At the edge of the field, the spread is slightly greater than 1.0″.

Curves of the encircled energy at the center, mid-point, and far edge of the field are shown in Figure 4. Ideally, 80% of the encircled energy should fall within the resolution element; however, a figure of 65% is usually found acceptable. The vertical lines on the figure indicate the distances corresponding to one, two, etc. pixels. This figure shows that 65% of the encircled energy falls within ≈ 3-4 pixels at the center of the field. At the far edge, this spreads to ≈ 5-6 pixels. We should therefore expect the spatial resolution of this design to be 1.0″ at the center of the image and 1.5″ at the far edge. This resolution is within the specifications for a ground-based instrument since atmospheric seeing conditions are generally no better than 2″.

4. THE OPTICAL SYNTHESIZER

There were several iterations on a central theme for the optical synthesizer before a final design was achieved. Each iteration was based on a design using an initial four-sided mirrored pyramid to split the initial beam into four separate optical paths. The pyramid was then followed by four sets of mirrors and lenses to focus each of the separate optical beams onto the four CCD chips. The first iteration by EB23 produced a design that preserved the original orientation of the solar image on the CCD chips, but this required folding of one pair of ray paths over the other. Looking at the mechanical design for this concept, it became evident that there would be a problem with the physical location of the folding mirrors. Since the original solar image could be reconstructed by computer manipulation, it was decided to eliminate this complication. The final design that evolved is shown in Figure 5. The lenses and mirrors specified by this design are presently being procured. The optical performance of the synthesizer was analyzed as part of the analysis of the complete system discussed in Section 3.

The optics for this synthesizer will have to be housed in a special mechanical mounting; the design of this mounting is presently under way. It will permit separate focusing of the individual images by translational motion of the four lenses. Each image will be accurately positioned on each CCD chip by tilting the mirrors following the lenses.

5. THE CAMERA ELECTRONICS

The SBIR camera and data system were delivered to MSFC in March 1990 after a period of extensive testing by MSFC personnel and SBIR contractors that started in September 1989. The major task since delivery of the systems has been the development of computer software for the control and operation of the camera and data system. At present, this software has almost been completed and the camera can now be operated and test images displayed with the SBIR data system.

During the development of software, personnel from the MSFC Data Management Branch (EB44) acquired the electronic design drawings from the manufacturer of the CCD camera and have designed the additional electronic control boards needed to activate all eight readout ports. The electronic components for these boards are now in procurement. Upon their delivery, EB44 personnel will install them in the camera.

Two new CCD chips have recently been procured from RTOP funds. With the two chips presently in the camera, these new chips will enable us to test the full potential of the camera. When the additional electronic boards have been installed, the modified camera will be sent to the manufacturer for installation of the new chips. The manufacturer will also conduct tests to verify the performance of all four chips and of the modified camera electronics.

6. SYSTEM INTEGRATION

At this time, the camera and data system have been integrated and are operational. Two tasks remain to complete the optical synthesizer: fabrication of the mechanical holder for it and installation of the pyramid, mirrors, and lenses upon their delivery. Following this, the performance of the synthesizer will be tested by setting up the necessary optics to form images of test patterns through the synthesizer on the CCD camera; the SBIR data system will be used to display the reconstructed test image.

The performance of the EXVM optics together with the optical synthesizer will be tested by setting them up on an optical table and integrating them with the other components of the EXVM: telescope, polarimeter, Fabry-Perot filter, image-motion compensator, and CCD camera. Standard resolution charts will be used to discern the actual spatial resolution of the total system and thus verify the performance characteristics predicted from the computer analyses.

7. SUMMARY

The final verification of the optical design for the EXVM and the optical synthesizer awaits the final system integration and testing. However, results from computer analyses indicate that we have achieved the objectives of this CDDF program: an optical design yielding a spatial resolution on-axis of 0.5″ and a workable optical synthesizer.

Several important lessons have been learned from this CDDF program. First, detailed optical designs require experienced personnel, with frequent reviews necessary to ensure that the designer is cognizant of all specifications of the *total* system (not just the optical portion). Second, even experienced personnel are subject to oversights, so it is imperative that any optical design be independently verified. Third, there is no unique optical design for achieving a particular imaging requirement; therefore, parameters such as allowable tolerances, size constraints, costs, and delivery schedules are important factors that the designer must consider. Last but not least, it is very important to work with an optical design expert who communicates openly with his customer to define the optimum optical design that meets the instrumental specifications under the constraints of these other parameters.

REFERENCES

[1] M. J. Hagyard, N. P. Cumings, E. A. West, and J. E. Smith: The MSFC Vector Magnetograph, *Solar Phys.* **80** (1982), p. 33.

[2] M. J. Hagyard, N. P. Cumings, and E. A. West: The New MSFC Solar Vector Magnetograph, in *Proceedings of Kunming Workshop on Solar Physics and Interplanetary Travelling Phenomena*, C. deJager and Chen Biao, eds., Science Press (1985), p. 204.

[3] M. J. Hagyard, E. A. West, and N. P. Cumings: The New MSFC Solar Vector Magnetograph, *NASA Technical Memorandum 82568* (1984).

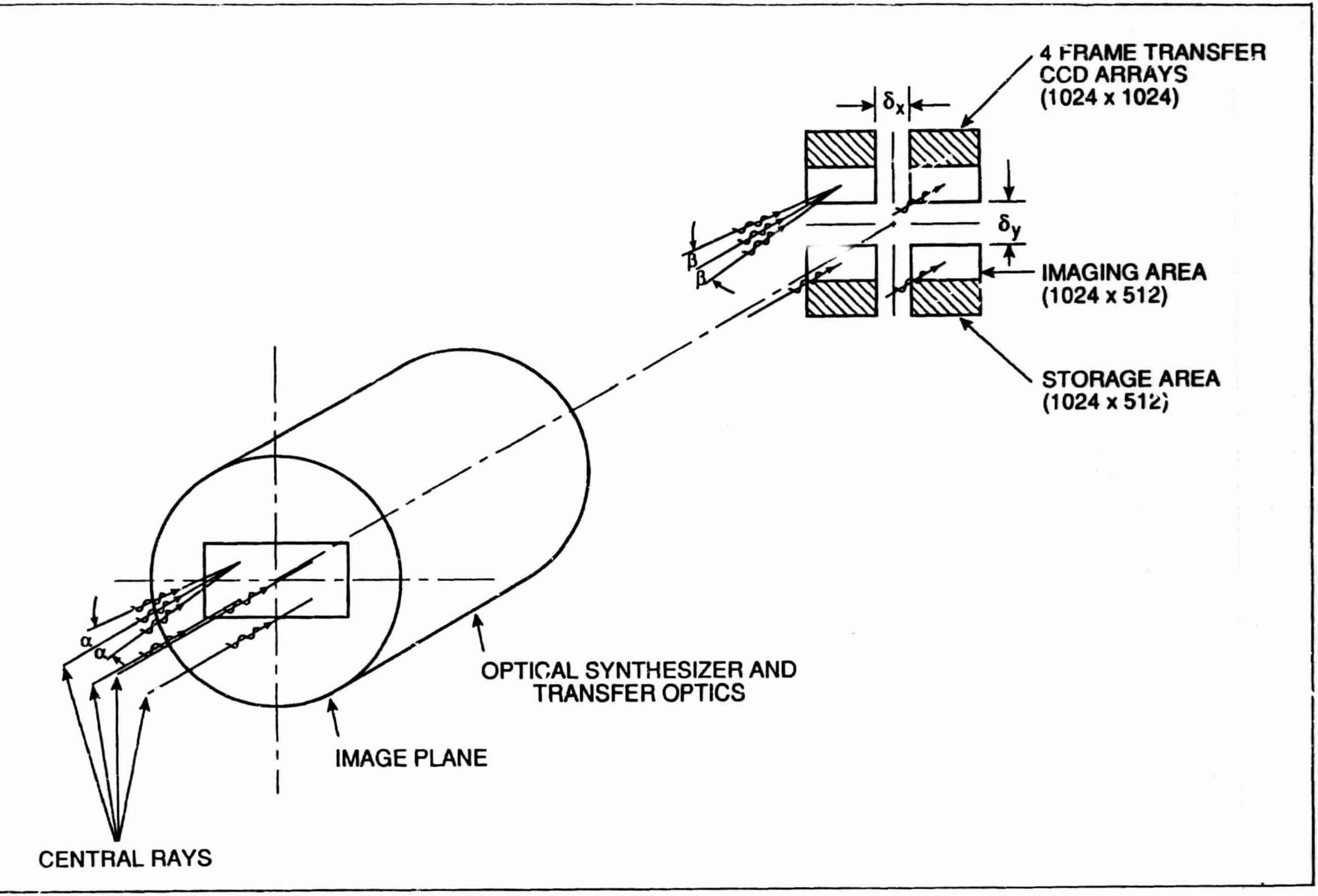
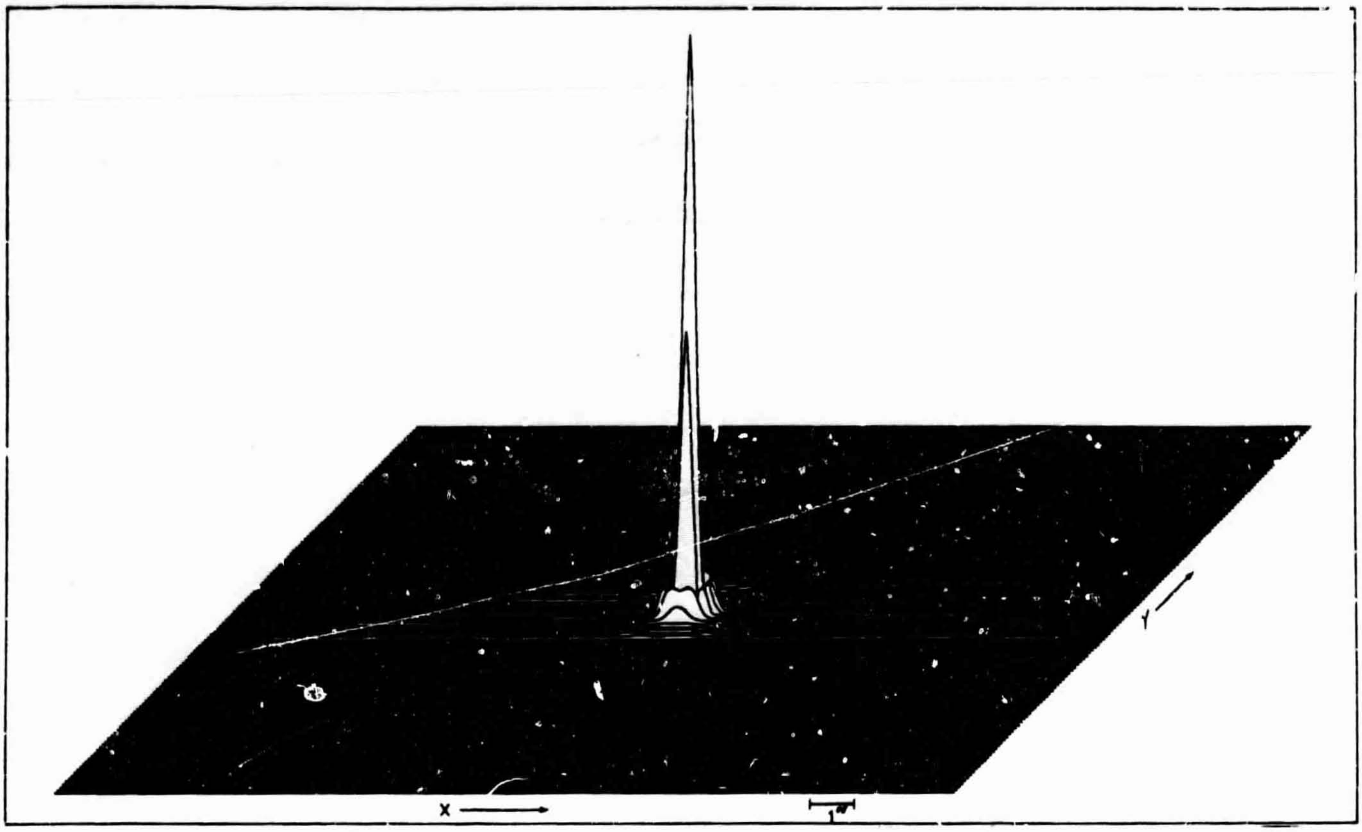


Figure 1. Schematic diagram showing concept of optical synthesizer for the MSFC Experimental Vector Magnetograph (EXVM).

Figure 2 - see insert page.



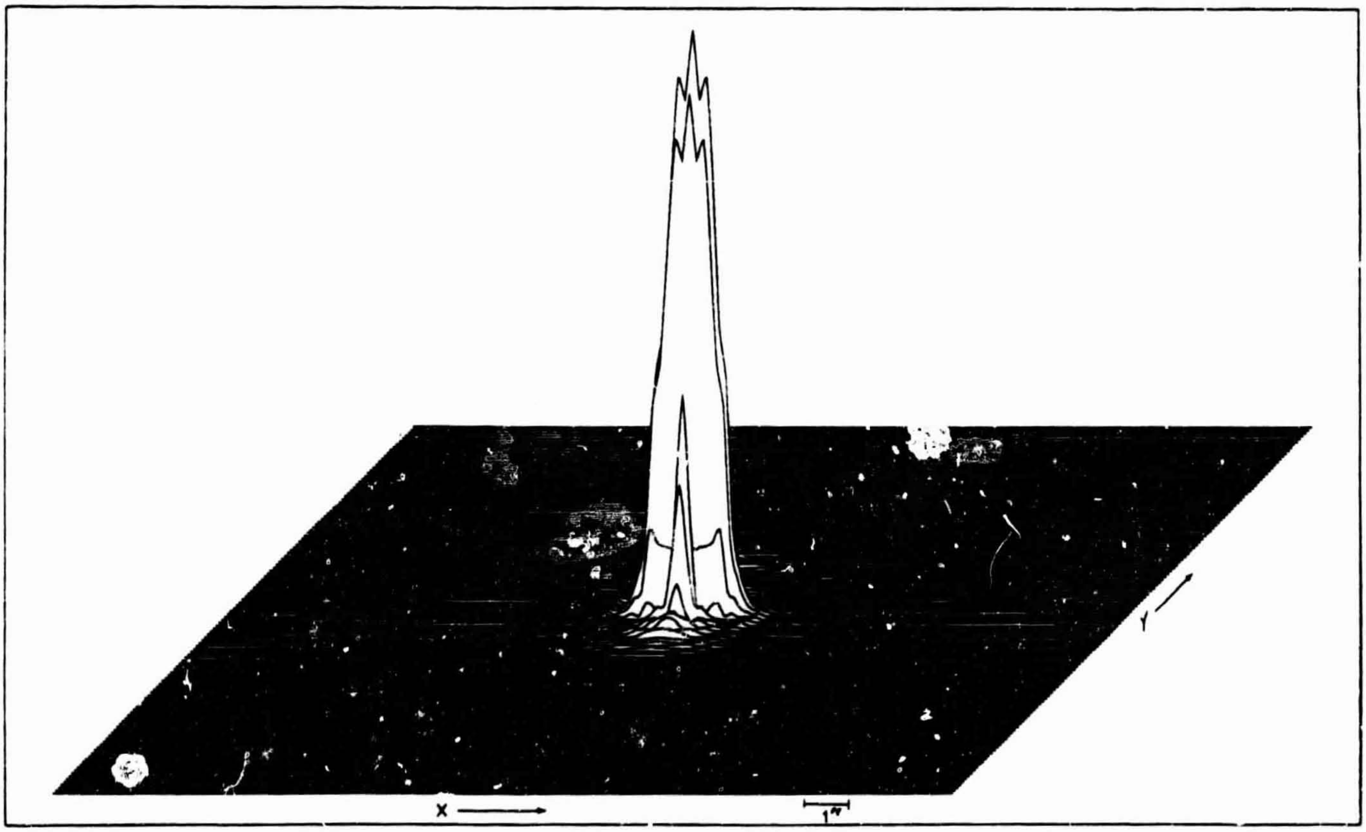


Figure 3. Two-dimensional spatial distribution of the intensity of an image of a point source. Upper panel: point located at the center of the field of view. Lower panel: point located at the edge of the field of view.

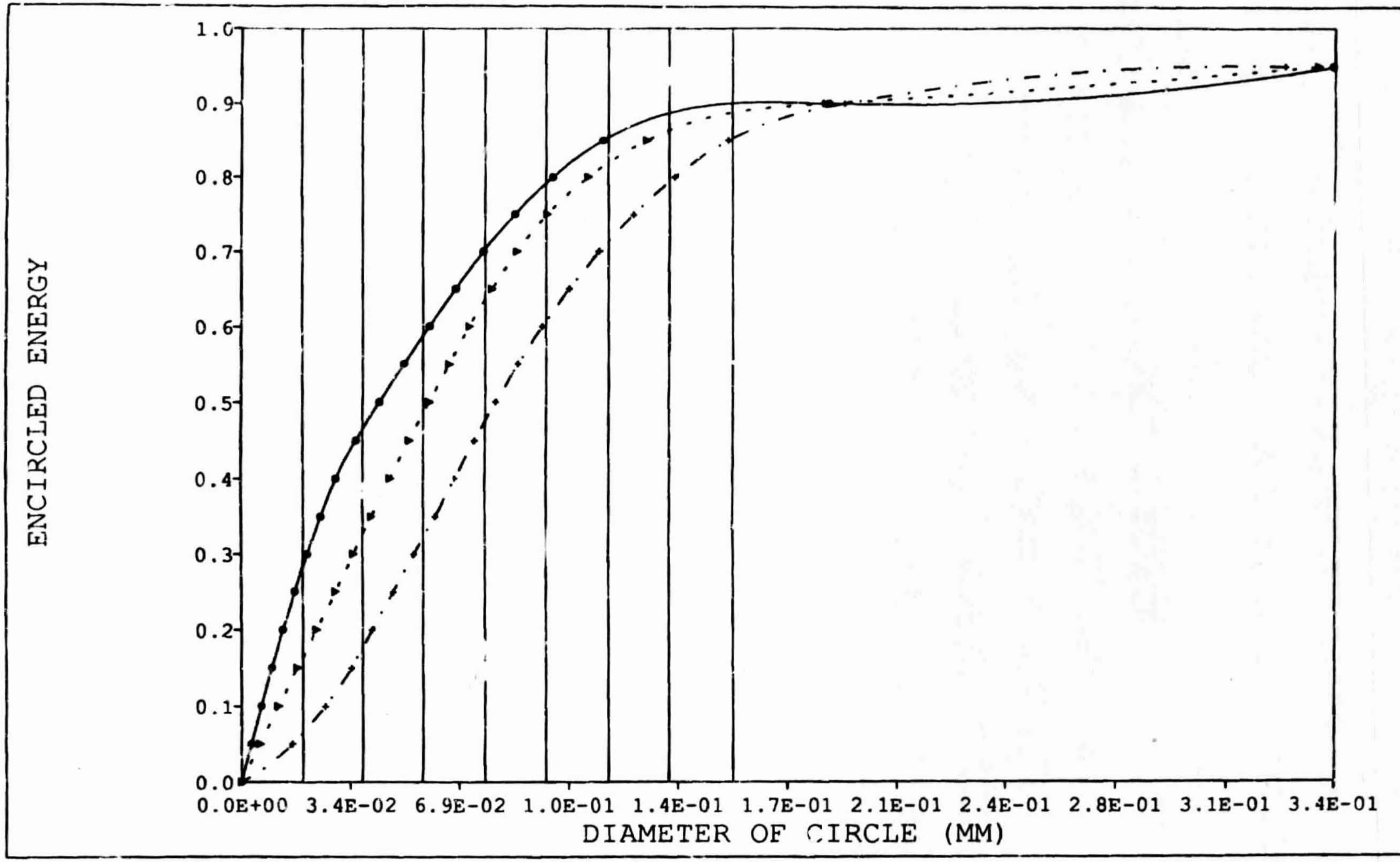


Figure 4. Encircled energy of a point source in the image plane versus diameter of circle. The solid, dotted, and dash-dotted curves represent points at the center, mid-point, and edge of the field of view, respectively. The vertical lines indicate the dimensions of one, two, etc., CCD pixels.

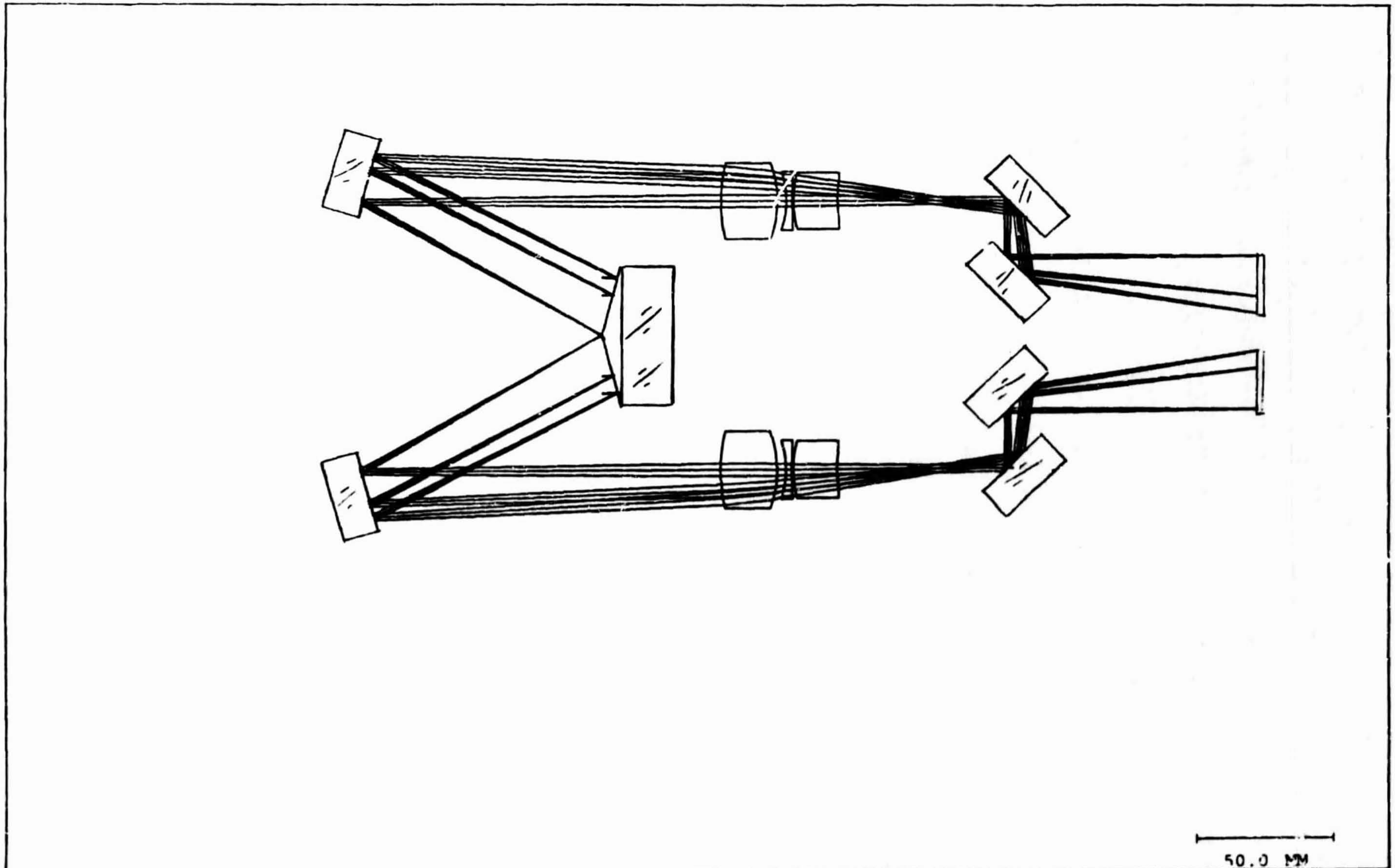


Figure 5. Final design of the EXVM optical synthesizer.

APPROVAL

OPTICAL SYNTHESIZER FOR A LARGE QUADRANT-ARRAY CCD CAMERA
CENTER DIRECTOR'S DISCRETIONARY FUND FINAL REPORT
(PROJECT NUMBER 90-11)

By Mona J. Hagyard

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.

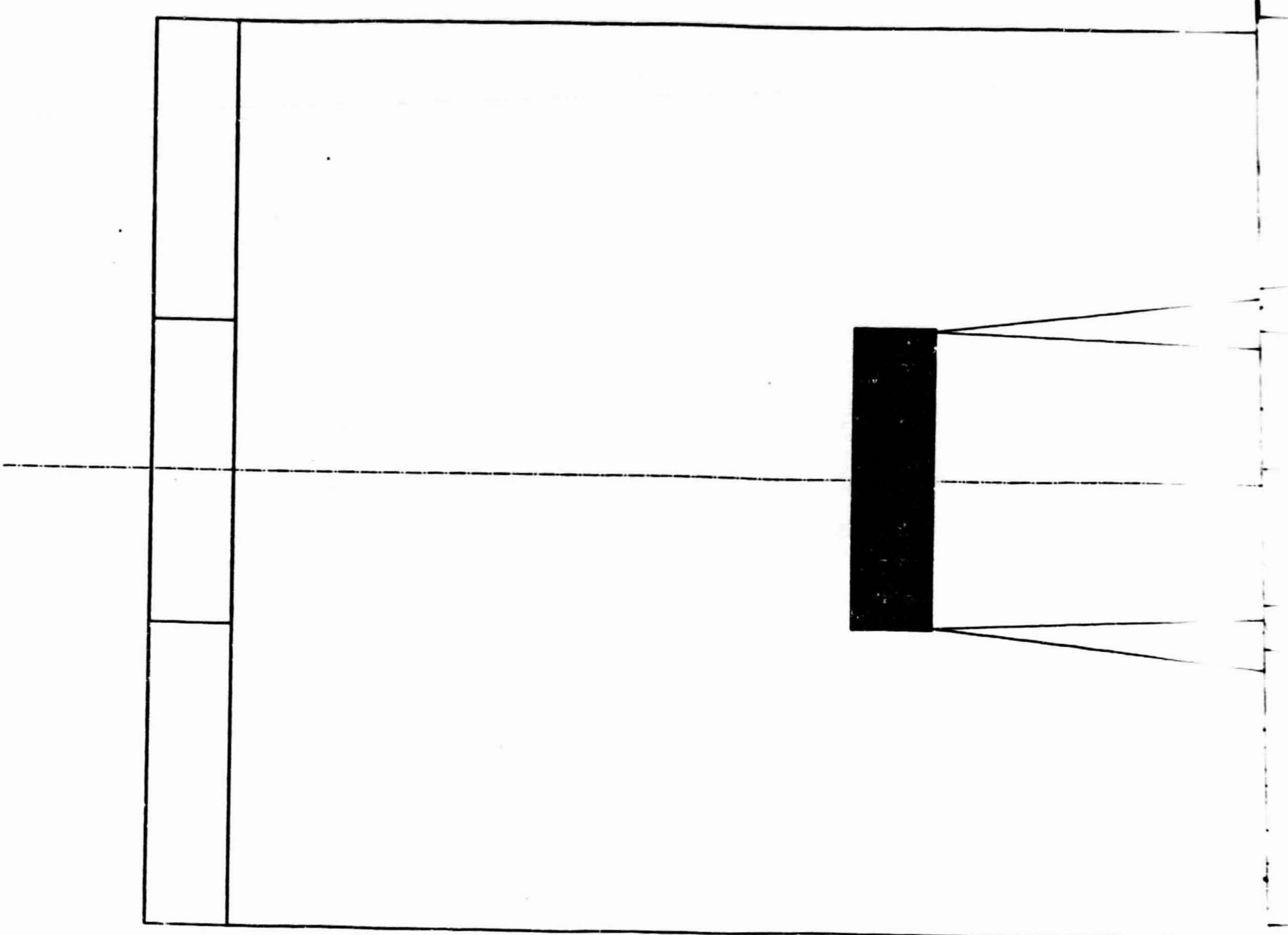
E. Tandberg-Hanssen

E. TANDBERG-HANSSEN
Director
Space Science Laboratory

NASA—MSFC

FOLDOUT FRAME

1.



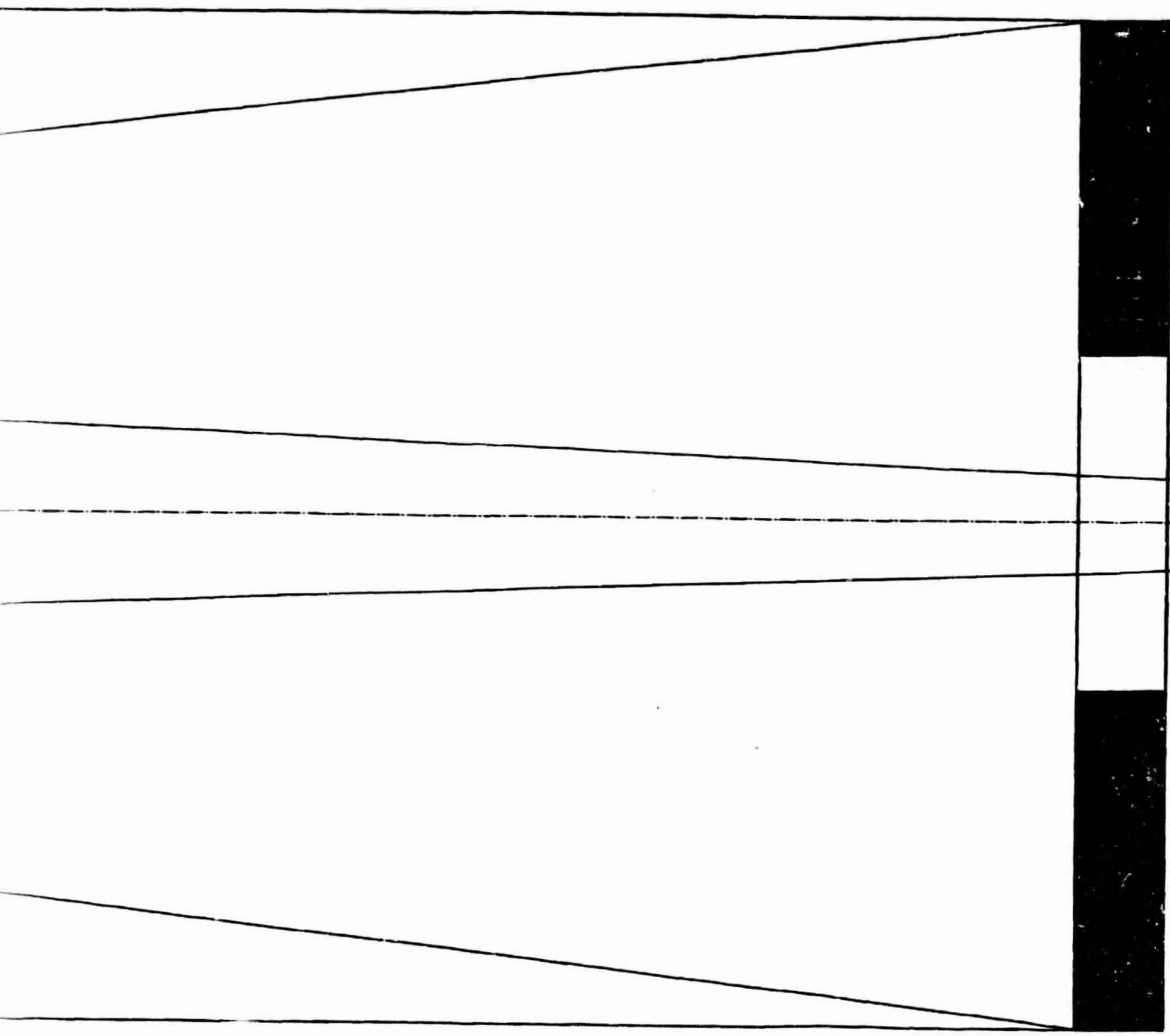
HEAT REJECTION PREFILTER
Diameter = 12.0" ± 0.40 or 304.8 mm
Center Hole = 2.5" or 63.5 mm
Thickness = 2.0"
Flatness = 1/10 λ
Transmission = 60% at 5,250 Å ± 100 Å (<600 Å)
Shortward Transmission < 1% to 4,000 Å
Longward Transmission < 1% to 10,000 Å
Material = Schlieren grade fused silica
Manufacture = Microcoatings
(Note: Special prefilter is being designed with bandpasses at 5,250, 6,302, and 6,530 Å)

FOLDOUT FRAME

2.

FOLDOUT FRAME

3



CASSEGRAIN TELESCOPE
PRIMARY (and SECONDARY):
Diameter = 12" or 304.8 mm (4.25"
Thickness = 2" or 50.8 mm (9/16" or
Primary hole = 3.925" or 99.72 mm
Material = Cer-Vit (Cer-Vit
Focal length = 47.25" or 1,200.15 mm
Focal ratio = 4 (–)
Coating = Al
Flatness = 1/10 λ
Radius of curvature = 2,394.7374 (8
Aspheric constant = –1.0 538)
Figure type = Parabolic (Hyperbolic)
SYSTEM:
Overall focal ratio = 15.45
Overall focal length = 186" or 4,724.4
Overall correction = 1/4 λ
Separation of mirrors = 34 or 882
Primary focus to final focus range
Baffling = 17" 5/6 on axis and 1/4
Manufacture = Ealing
APERTURE STOP/MIRROR
Field stop = 4.27 by 8.53 arc min (e.
Half-diagonal = 4.769 arc min
RETICLE
Moveable from field = yes
Type = grid pattern
Material = BK7 glass

F/16 TELESCOPE CASSEGRAIN S

Primary	2,394.7340	–87
	Aspheric deformation co	
Secondary	–858.2406	+1.
	Aspheric deformation co	

FOLDOUT FRAME

4

7.95 mm)
29 mm)
to primary ratio = 0.327)

2406)

n (12 in * F-ratio)

mm
2.5" or 317.5 mm
0.8-degree diameter

048 pixels * 0.25 arc/sec/60 = 8.53 arc/min)

TEM
398 152.4
nt = 1.0 (parabolic)
7355 42.0432
ant = −2.82538 (hyperbolic) $(z = -(c/2)[x^2 + y^2 + (\kappa + 1)z^2]$

LENS
L1a/3
L1a/4
L1b/5
L1b/6
Effectiv

FOLDOUT FRAME

5.

FULL STOKES POLARIMETER

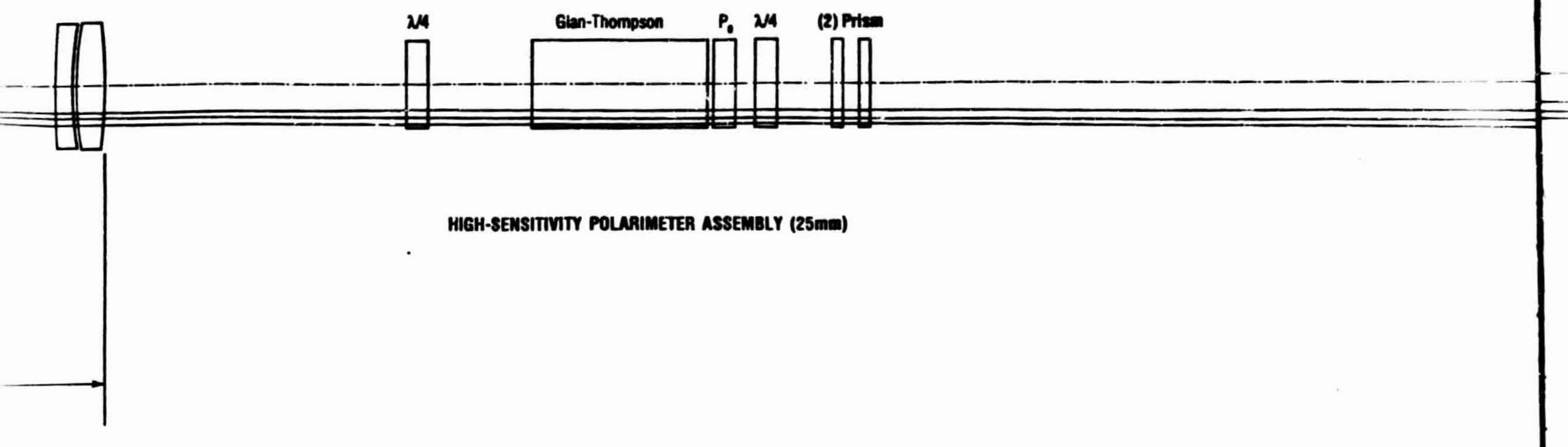
ANALYZER QUARTER-WAVE PLATE
Diameter = 25 mm
Materiall= double cemented, zero-order quartz
Retardence = 1/4 λ at 5,250.2 ± 50 Å
Thickness = 7 mm
Coating = High efficiency antireflection (99.75%), 2 layers
Manufacture = Karl Lambrecht
Part number = WPQC4-25-v
[**alternate: ANALYZER QUARTER-WAVE PLATE**
Diameter = 22 mm
Material = crystal quartz and MgF
Retardence = 5/4 λ (450 ± 1 degree at 5,250.2 and 6,302.5 Å)
Thickness = 2.98 mm (1.646972 quartz and 1.333893 MgF)
Variation = ±1 degree between 0 and 40C
Manufacture = Karl Lambrecht]

GLAN-THOMPSON POLARIZER
Clear Aperture = 25 mm
Extinction = 1×10^{-6}
Length = 65 mm
Field of View = 25°
Material = Calcite
Manufacture = Karl Lambrecht
Part number = MGT3E20 (MGTxE25)
Coating = None

POLAROID
Diameter = 25.4 mm
Thickness = 6 mm (0.097–0.275")
Type = G-T HN38
Transmission = 38%
Glass type = BK7
(Flatness = λ/10)
Flatness = 1/4 λ
Coating = Antireflection coating (99.5%)
Manufacture = Meadowlark

CIRCULARIZING QUARTER-WAVE PLATE
Diameter = 25 mm
Material = double cemented, zero-order quartz
Retardence = 1/4 λ at 5,250.2 ± 50 Å
Thickness = 7 mm
Coating = High efficiency antireflection (99.75%), 2 layers
Manufacture = Karl Lambrecht

PAIR WEDGE PRISM
Diameter = 25 mm
Material = BK7 w/ MgF coating
Wedges Angles = 1.9333 degrees (±0.0083)
Thickness = 3 mm (minimum)
Coating = High efficiency MgF antireflection
Manufacture = Melles Griot
Part number = 02PRW001 (3)



HIGH-SENSITIVITY POLARIMETER ASSEMBLY (25mm)

COLLIMATOR LENS (2 elements)

192.55696	3.349963	F2	13.8360
59.79813	1.148315	Air	13.8126
60.13446	6.809985	BK7	13.9825
−147.94785	423.7358	Air	14.0296

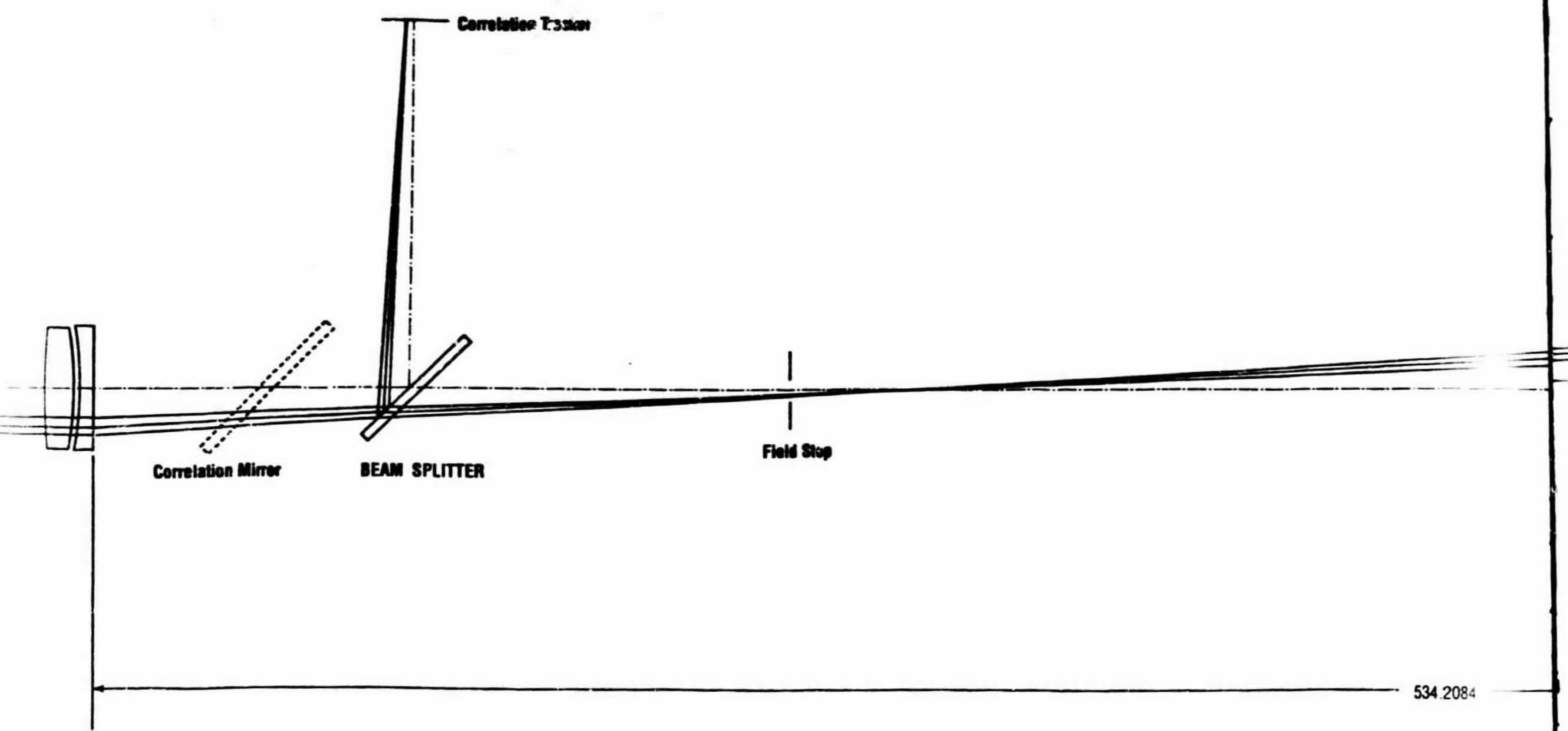
focal length = 200.0

LENS
L2a
L2a
L2b
L2b
Effec

FOLDOUT FRAME

6

BEAM SPLITTER FOR CORRELATION TRACKER
Clear aperture = 25 mm
Transmission (through) = 90%
Transmission (at 90°) = 10%
Coating = antireflection coating 99.75%



COLLIMATOR LENS (2 elements)

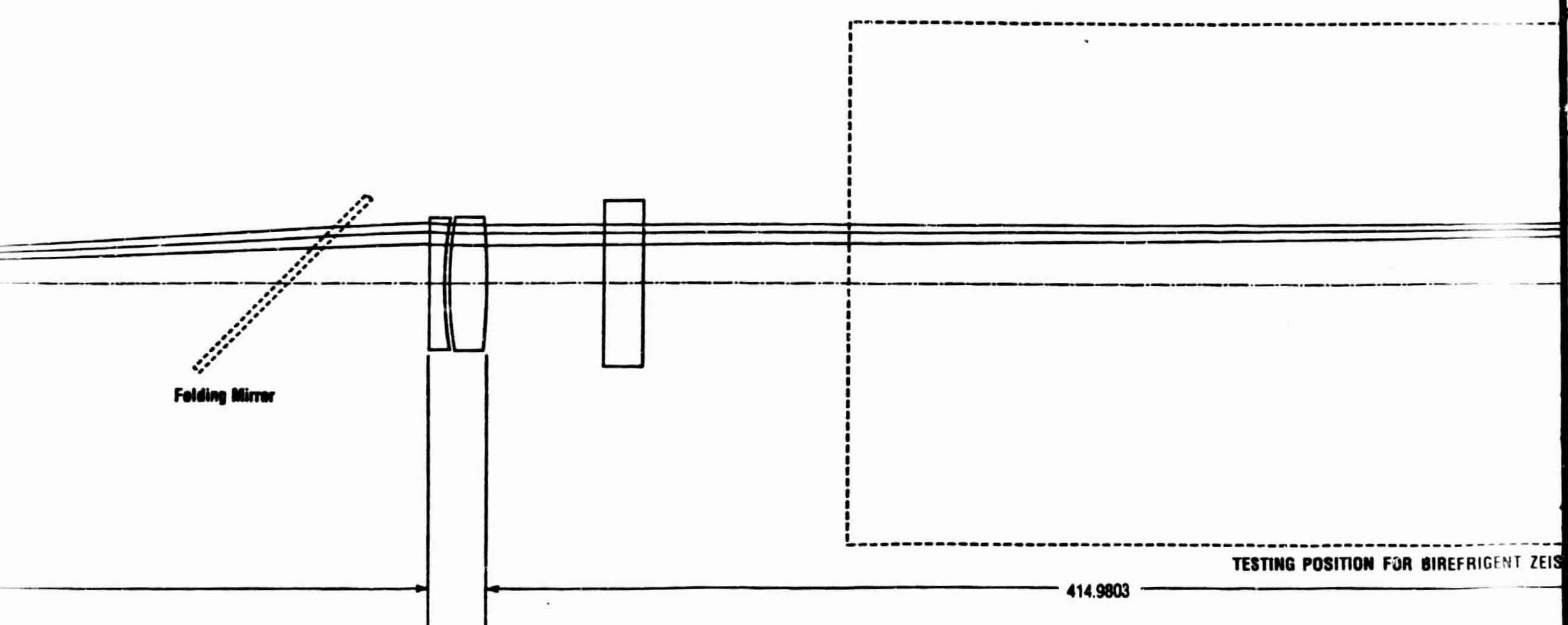
147.94785	6.809985	BK7	13.1803
−60.13446	1.148315	Air	13.1397
−59.79813	3.349963	F2	12.9841
−192.55696	534.2084	Air	13.0108

focal length = 200.0

FOLDOUT FRAME

7

NARROW BANDPASS BLOCKING FILTER
Diameter = 46 mm
Thickness = 9.5 mm
Flatness = 1/4 λ
Transmission = 38.6% at 5,250.22 Å
Offband Transmission = 10^{-4} from 3,000 Å to 20 microns % at 5,250.22 Å
Bandpass = 2.26 Å at temperature 26.7 C and zero degree incidence
Material = Schlieren grade fused silica
Temperature sensitivity = 5 A/C
Infrared Extinction = yes to 12,000 Å
Manufacture = Andover Corp./Microcoaings
Part number = ANDV2029 Serial no. 1



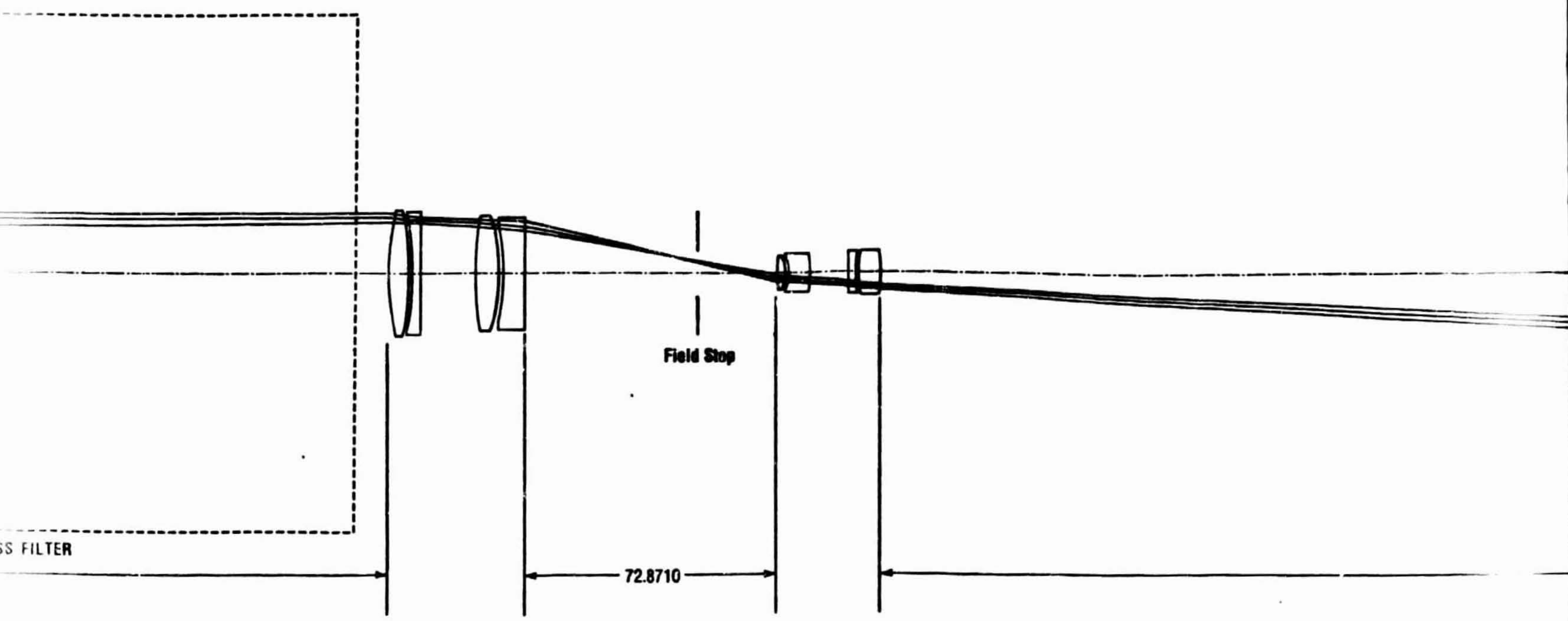
LENS 3 BIREFRIGENT TELECENTRIC LENS (2 elements)

L3a/11	367.97757	3.869572	F2	17.7219
L3a/12	108.25985	1.261878	Air	17.7278
L3b/13	108.00145	10.489197	BK7	17.8663
L3b/14	−246.55587	414.9803	Air	17.9693

Effective focal length = 350.0

FOLDOUT FRAME

8.



LENS 4 RELAY LENS (4 elements)

L4a/15	64.06573	4.353881	BK7	12.6580
L4a/16	−59.68031	0.510316	Air	12.5596
L4b/17	−52.21663	1.848562	F2	12.4918
L4b/18	−375.92212	11.823679	Air	12.4108
L4c/19	74.32216	4.6573336	BK7	11.6015
L4c/20	−52.60477	0.992611	Air	11.3620
L4d/21	−56.65[illegible]15	4.927469	F2	11.0465
L4d/22	−379.74179	72.871000	Air	10.5590

Effective focal length = 75.0

LENS 5 MICROSCOPE TRANSFER LENS (4 elements)

L5a/23	27.28219	1.500000	SK16	3.5676
L5a/24	−11.42906	0.892456	Air	3.5954
L5b/25	−9.76081	4.790054	SF5	3.4740
L5b/26	−30.62566	9.411786	Air	3.8376
L5c/27	256.12428	1.891451	SF5	4.1478
L5c/28	22.63481	0.539543	Air	4.1758
L5d/29	31.28154	5.000000	SK16	4.2430
L5d/30	−23.09221	597.061445	Air	4.4120

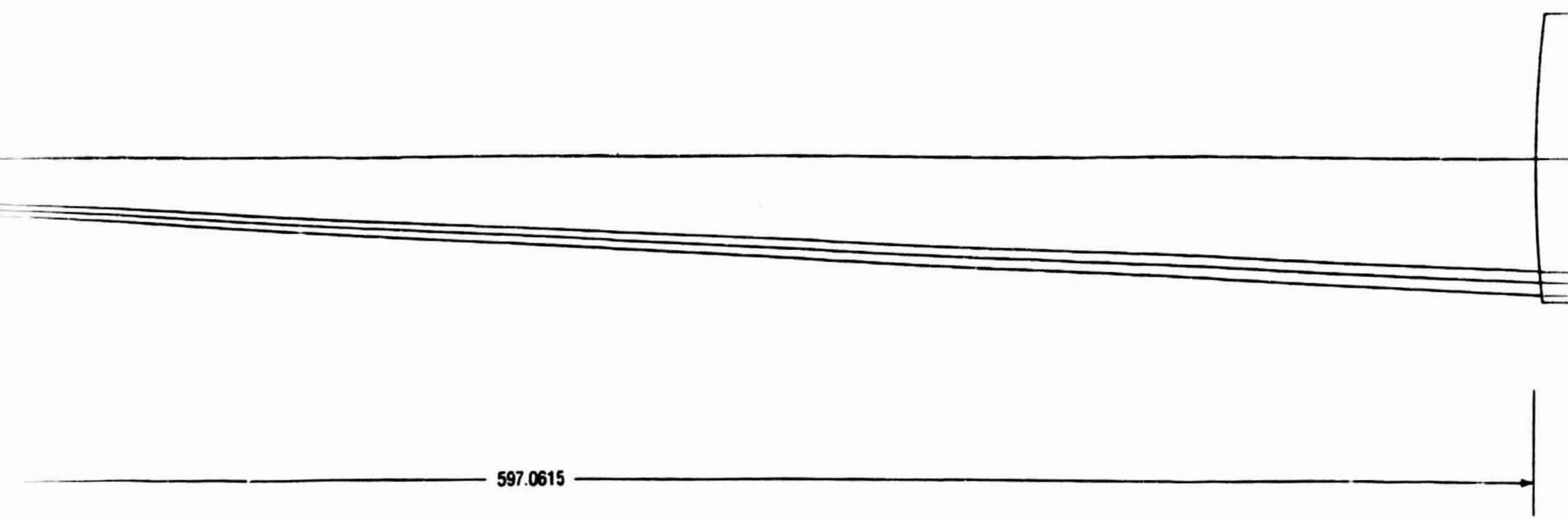
Effective focal length = 25.0

1

FOLDOUT FRAME

9

FABRY-PEROT SPECTRAL FILTER FOR 5250.2 Å
Clear aperture = 65 mm (74 mm aperture)
Air spacing = 275 microns ± 3 microns with 3 micron tuning
Coating = dielectric multilayers
Collimated spectral resolution = 0.064 Å (at Hα 0.156 for F=
Telecentric spectral resolution = 0.125 Å
Flatness = 1/200 λ (after coating = 1/100–1/150 λ)
Transmission = 60% at 5,250.2 Å
Reflectance = 98 ± 1% (and at Hα (6,563 Å) > 95 (99.2% a
6,563 at OC)
Finesse = 70 (wanted 78)
Free spectral range = 5.0 Å (at Hα 7.8 Å)
Maximum angle of incident range in air (4.769°300/65) = 22.0
Material = fused silica
Wedge angle = 15 arc/min
Manufacture = Queensgate
Model number = ET70
Front window = 4 mm (next surface 12 mm)
Front etalon assembly = 21 ± 0.25 mm (with next surface 275
Middle etalon assembly = 18 ± 0.25 mm (with next surface op
Back etalon assembly = 21 ± 0.25 mm (with next surface 12
Back window = 4 mm



LENS 6 FABRY-PEROT TELECENTRI

L6a/31	357.65088	1
L6a/32	−203.68706	(
L6b/33	−206.25988	1
L6b/34	−856.52480	16

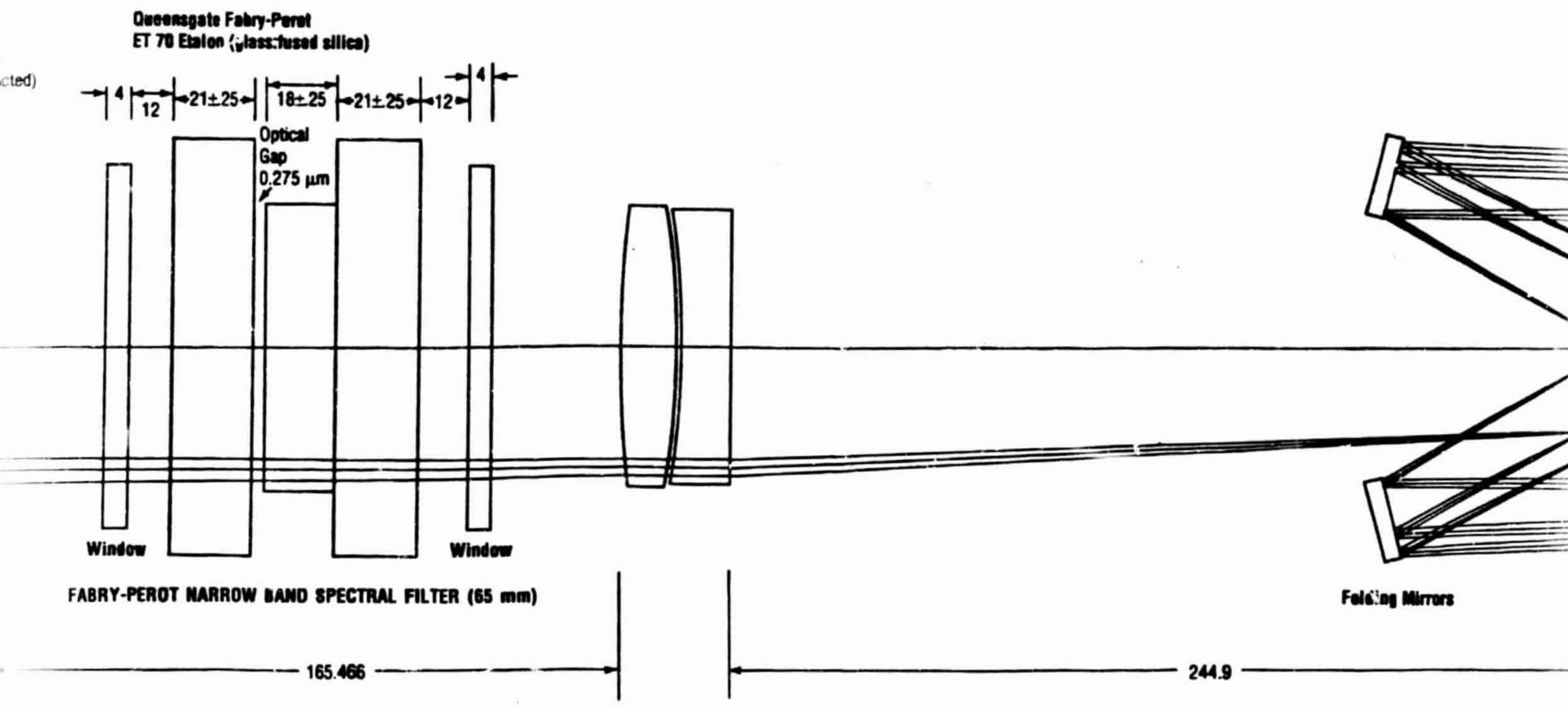
Effective focal length = 591.0

1

FOLDOUT FRAME

10.

9% at 6,302, 97.4% at



elements)

	BK7	37.6359
	Air	37.6500
	F2	37.6255
	Air	37.8316

LENS 7 IMAGING LENS (2 elements)

L7a/35	431.62139	15.000000	BK7	36.6465
L7a/36	−247.48416	0.500000	Air	36.2829
L7b/37	−250.74932	15.000000	F2	36.2119
L7b/38	−1,069.18003	244.942887	Air	35.8264

Effective focal length = 720.4

15-DEG

LENS 8
L8a/39
L8a/40
L8b/41
L8b/42
L8c/43
L8d/44
Effective

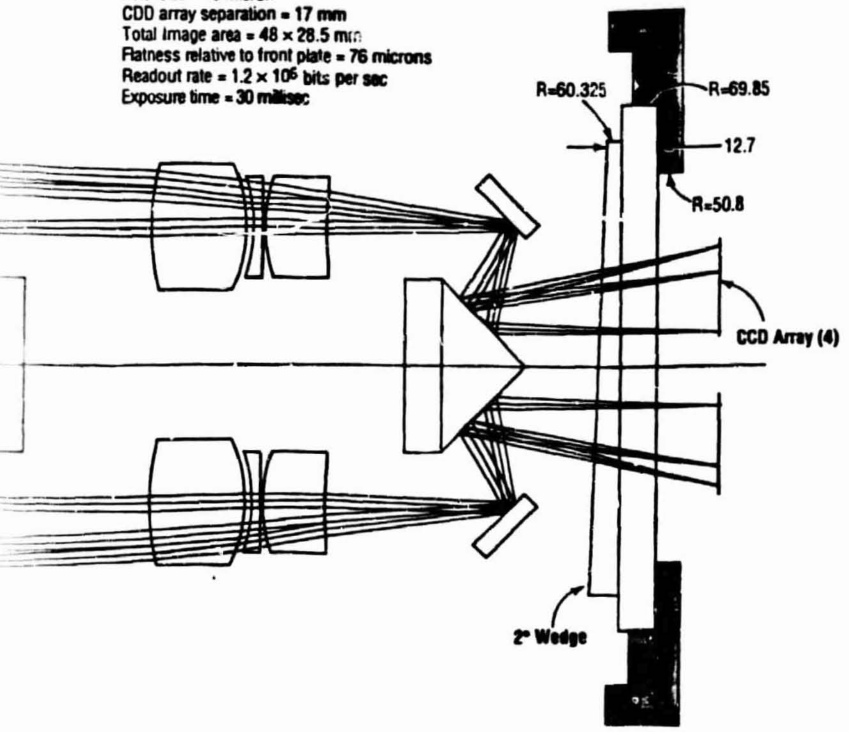
F

0

FOLDOUT FRAME

11.

CCD DETECTOR
FRONT PLATE
Frame transfer mask = yes, on front plate
Front plate wedge = 2 degrees
Front plate flatness = 1/4 wave at 6,328 Å
Front plate thickness = 12.7 mm (min)
Front plate diameter = 120.65 mm
Front plate coating = antireflection coating 100 Å peak at 5,250
Back of plate to CCD - 16.4 mm
CCD CLUSTER ARRAY
Number = 4 detector arrays
Type = Thomson Thx 31,156
Size per array = 1,024 × 1,024 pixels
Imaging size per array = 1,024 × 512 pixels
Pixel size = 19 micron
CDD array separation = 17 mm
Total image area = 48 × 28.5 mm
Flatness relative to front plate = 76 microns
Readout rate = 1.2×10^6 bits per sec
Exposure time = 30 millisec



MIDAL IMAGE SPLITTER AND FRONT FOLDING MIRRORS

NG CAMERA LENS (3 elements)

—	Glass	—
—	Air	—
—	Glass	—
—	Air	—
—	Glass	—
—	Air	—

= 720.4

2. EB23 design for the EXVM optics.