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FINAL REPORT:

PRISM Spectrograph Optical Design

To:

NASA/Marshall Space Flight Center
Redstone Arsenal, AL

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1 Summary

The objective of this contract is to explore optical design concepts for the PRISM spectrograph and produce a preliminary optical design.

The status at the end of this contract is as follows:

1. An exciting optical configuration has been developed which will allow both wavelength bands to be imaged onto the same detector array. The slit image is first dispersed by a low resolution prism spectrograph with two exit slits, one for each of the two wavebands. The light enters a grating spectrograph which uses the 5th order for the 17 micron band and the 3d order for the 28 micron band, yielding two high resolution spectra several mm apart, with excellent rejection of the rest of the spectrum. This configuration will save the expense of a second camera and a second optical train and avoids the development of special spectral filters.

2. At present the optical design is only partially complete because PRISM will require a fairly elaborate optical system to meet its specification for throughput (area*solid angle).

3. The most complex part of the design, the spectrograph camera, is complete, providing proof of principle that a feasible design is attainable. This camera requires 3 aspheric mirrors to fit inside the 20x60 cm crossection package.

4. A complete design with reduced throughput (1/9th) has been prepared. This design documents the optical configuration concept.

5. A suitable dispersing prism material, CdTe, has been identified for the prism spectrograph, after a comparison of many materials.

2 Suggested Tasks For Follow-on

UAH is eager to continue work on the PRISM optical system and complete an end-to-end optical design. The following tasks are the priority action items needed to complete this preliminary optical design:

1. Complete the optical design for the prism spectrograph and grating spectrograph, specifying all surfaces and documenting its optical performance.

2. Design the required diffraction grating specifying the groove profile, estimating the grating efficiency, and preparing materials for a quotation.

3. Produce a solid model representation of the system in optical CAD/CAM software and prepare color representations and presentation materials of the system.

3 Optical Design Requirements

Optical Design Specifications:

Primary Wavelength	28.221 microns
Secondary Wavelength	17.035 microns
Field of view	1 degree by 30 seconds
Instantaneous Field of View	30x30 second^2 per pixel

Cassegrain Telescope

aperture	60 cm diameter
focal length,	360 cm
f/6	

Articulated secondary mirror

Slit mask at image plane to establish field of view

Spectrometer

Resolution objective --

Resolve longitudinal velocities of +-500 km/sec

Spectral Resolution	4000, 3000 acceptable
Wavelength Resolution	0.007 microns
Spectrum width	10-15 pixels in each spectrum

Detector

Antimony Doped Silicon BIB Hybrid Focal Plane Array

Pixel size	75 x 75 microns center to center

4 Optical Design Studies

The PRISM optical system consists of the following components in order:

1. Cassegrain telescope,
2. Image plane slit,
3. Prism spectrometer, low spectral resolution,
4. Double slits, 17 and 28 micron bands,
5. Grating spectrograph,
6. Focal plane detector array.

Item 1 was designed separately by John Jackson. This report documents the design for items 2-5. First the conceptual design with the low throughput (1/9th) requirement is presented. Then the design for the spectrograph camera is presented.

5 Prism Spectrometer - Grating Spectrograph Lower Throughput Design

The required throughput for the PRISM system follows from the following parameters. The telescope aperture is 60 cm with a field of view of +/- 1 degree. Alternatively the image height (total) at the focal plane of the telescope is 62.8 mm with a numerical aperture of 0.083. The Lagrange invariant for this beam is

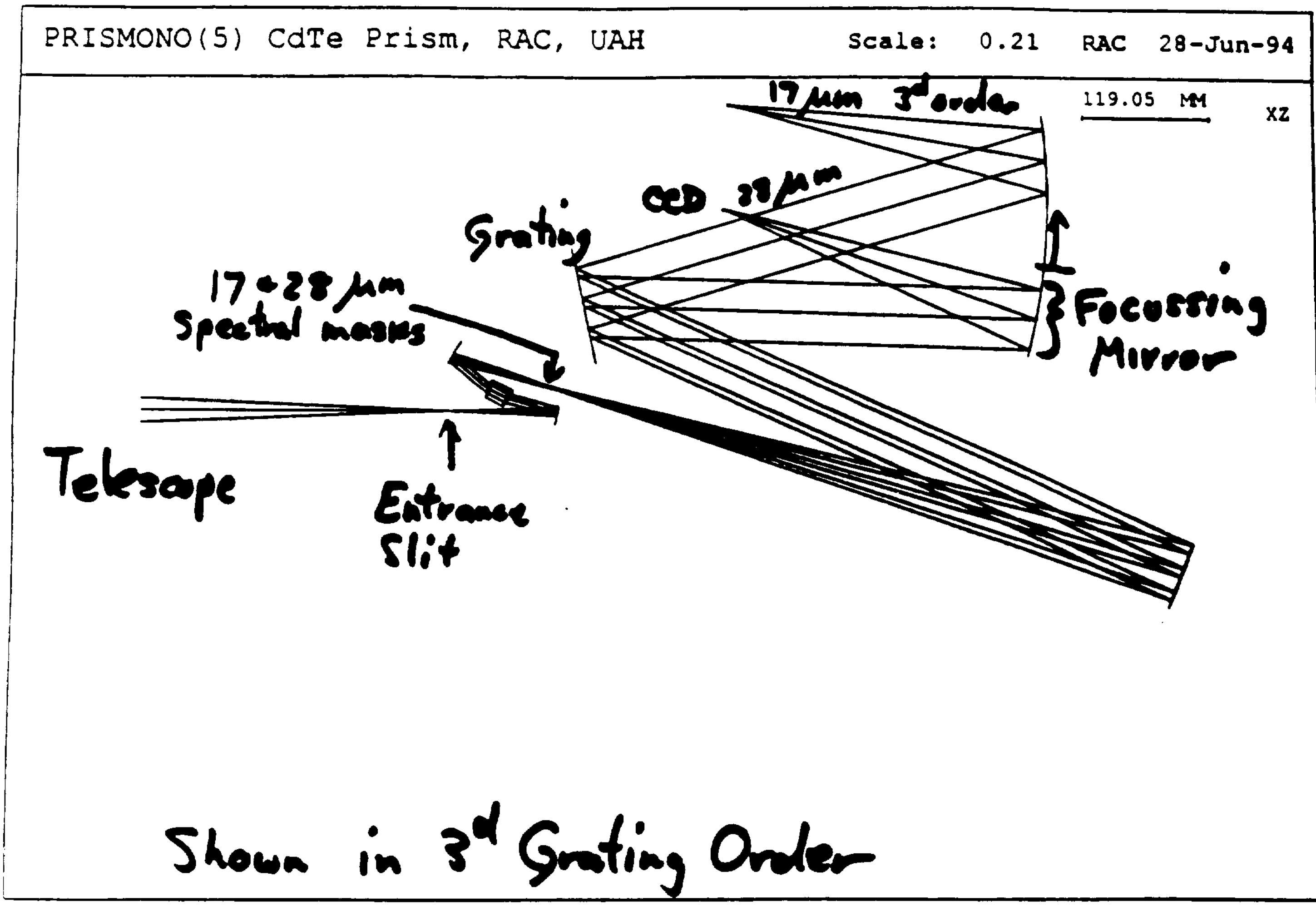
Lagrange Invariant = 60 cm * 1 degree /4 = 15 cm * degree = 26.1 mm * rad
= 62.8 mm 0.83 rad / 2 = 26.1 mm * rad.

A preliminary design has been produced with approximately 1/3 this Lagrange invariant and 1/9 the throughput. This is the design presented in this section.

Figure 1 shows the layout of the conceptual design with light coming from the telescope, through the prism spectrometer, then the grating spectrograph and imaging

Figure 1

Prism Spectrometer and Czerny Turner Spectrograph



Package 70 cm x 40 cm x 10 cm

onto the focal plane array. This design utilizes the coincidence that the ratios of the wavelengths for the two bands 28/17 is approximately 5 to 3. Therefore a diffraction grating will direct the third order of the 28 micron light into nearly the same direction as the fifth order of the 17 micron light. Further, a grating blazed for 28 microns and third order is also blazed for 17 microns and fifth order. Therefore, a high resolution grating spectrometer can be simultaneously used for the two wavebands, and the two spectra placed side-by-side on a single detector array. Such a grating spectrometer requires good suppression of all wavelengths outside these two wavebands which might overlap our spectra at other orders or might scatter into our spectra.

Interference filters might be designed which provided the two required bands, but the most efficient method is a prism spectrometer with two exit slits. Thus the two desired wavebands can be cut out of a low resolution spectra, and all other wavelengths efficiently discarded. Further, prisms are very efficient because prisms only have one order and they can be antireflection coated. The general disadvantage of prisms in spectroscopy is their low angular dispersion. In this design we want the 17 and 28 micron bands to enter the grating spectrograph close together, so the prism works fine. By adjusting the separation between the 17 and 28 micron bands with the prism spectrometers linear dispersion, the separations of the spectra at the detector are adjusted.

Figure 2 is a close-up of the prism spectrometer. Light from the telescope focuses at the slit which sets the field of view of the instrument. This light is collimated by an off-axis parabolic mirror onto a CdTe prism which disperses the light. The prism angle is 40 degrees. Another off-axis parabolic mirror focuses the light onto a low resolution spectrum which contains two slits, one which passes the 17 micron band, the other for the 28 micron band.

CdTe has been analyzed in the Optimator refractive index data base program and has good transmission at both 17 and 28 microns and is a very suitable prism material.

Figure 2

Prism Spectrometer
40° CdTe Prism

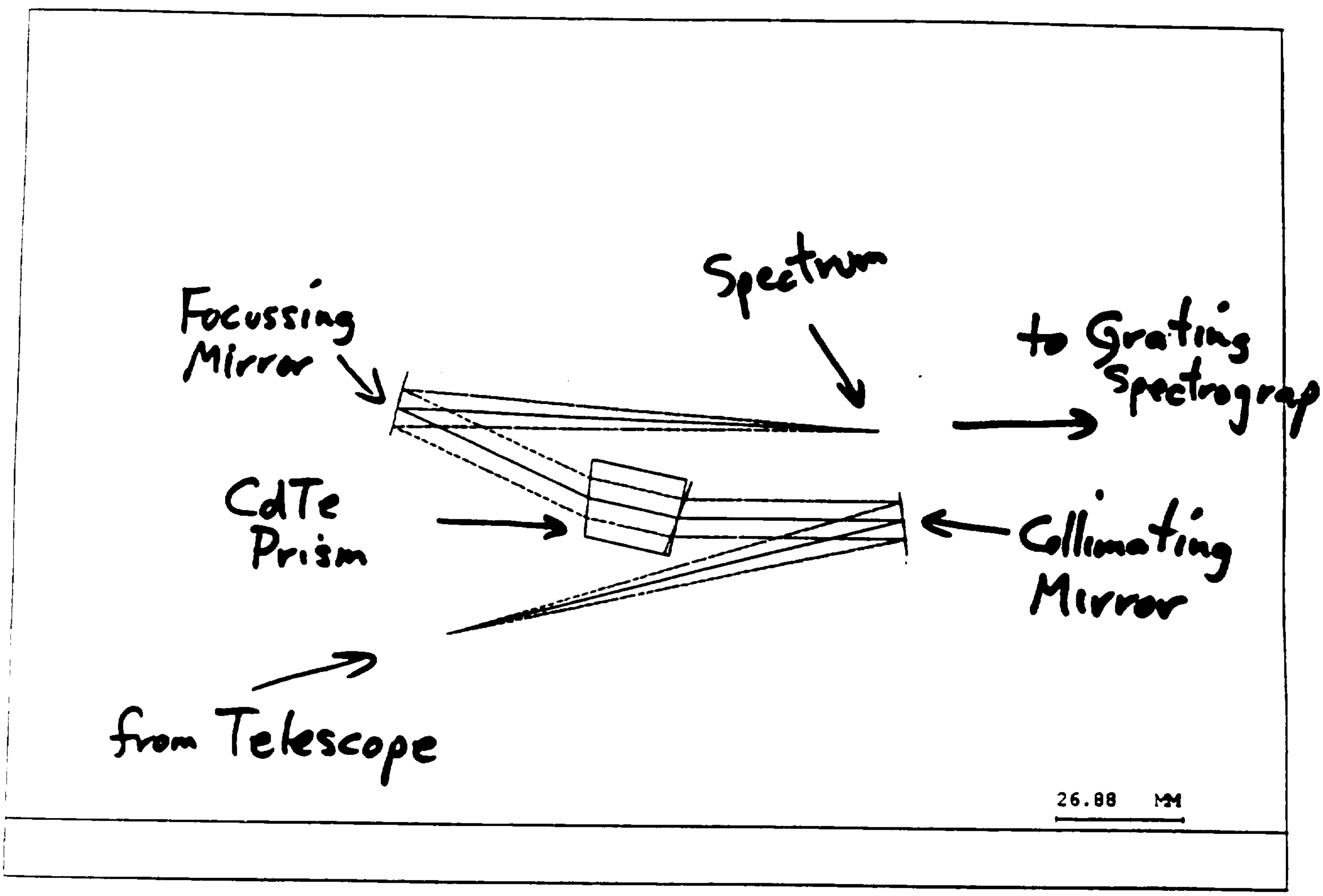


Figure 2a

Prism Spectrometer

21:17:58

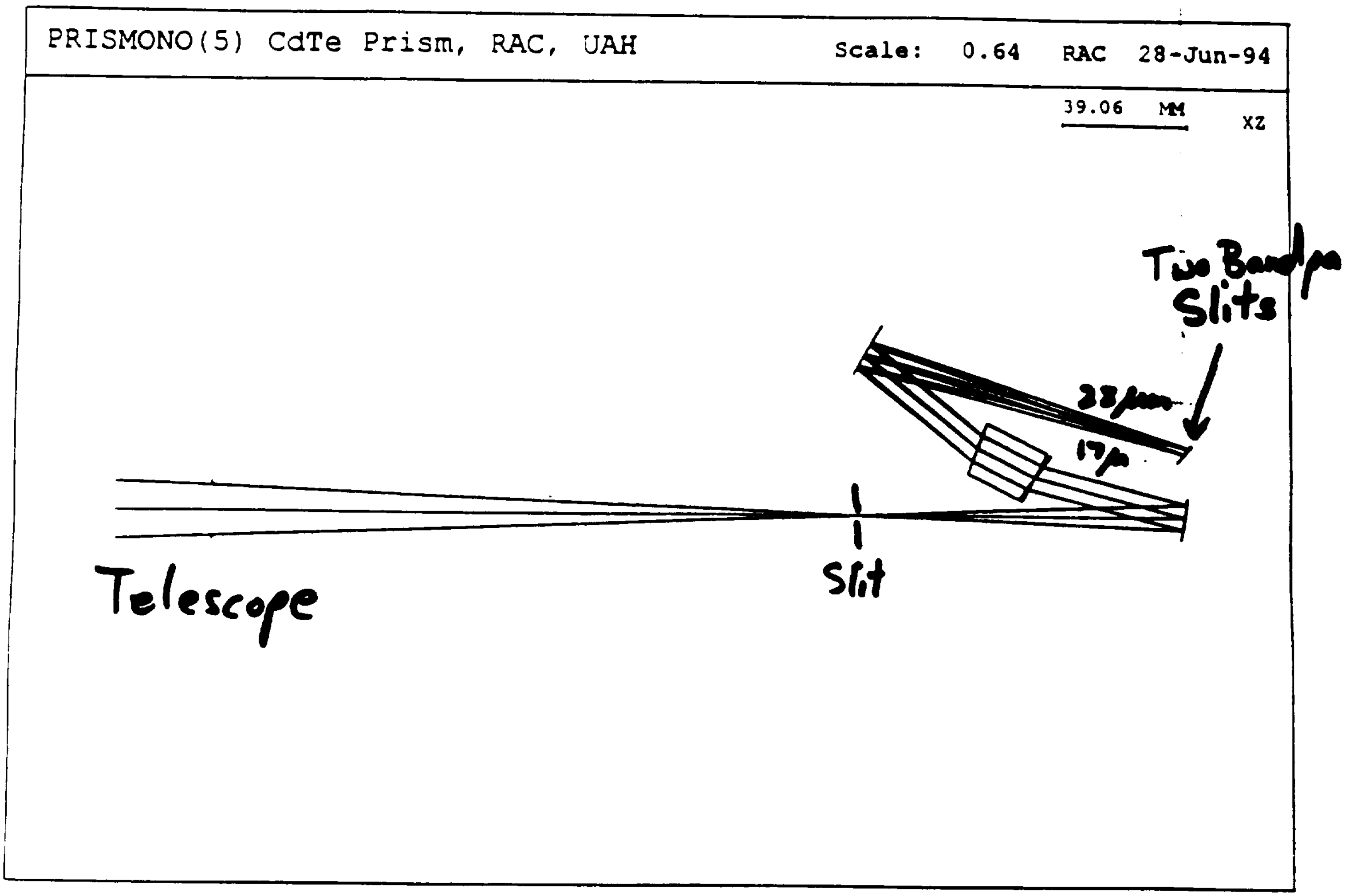
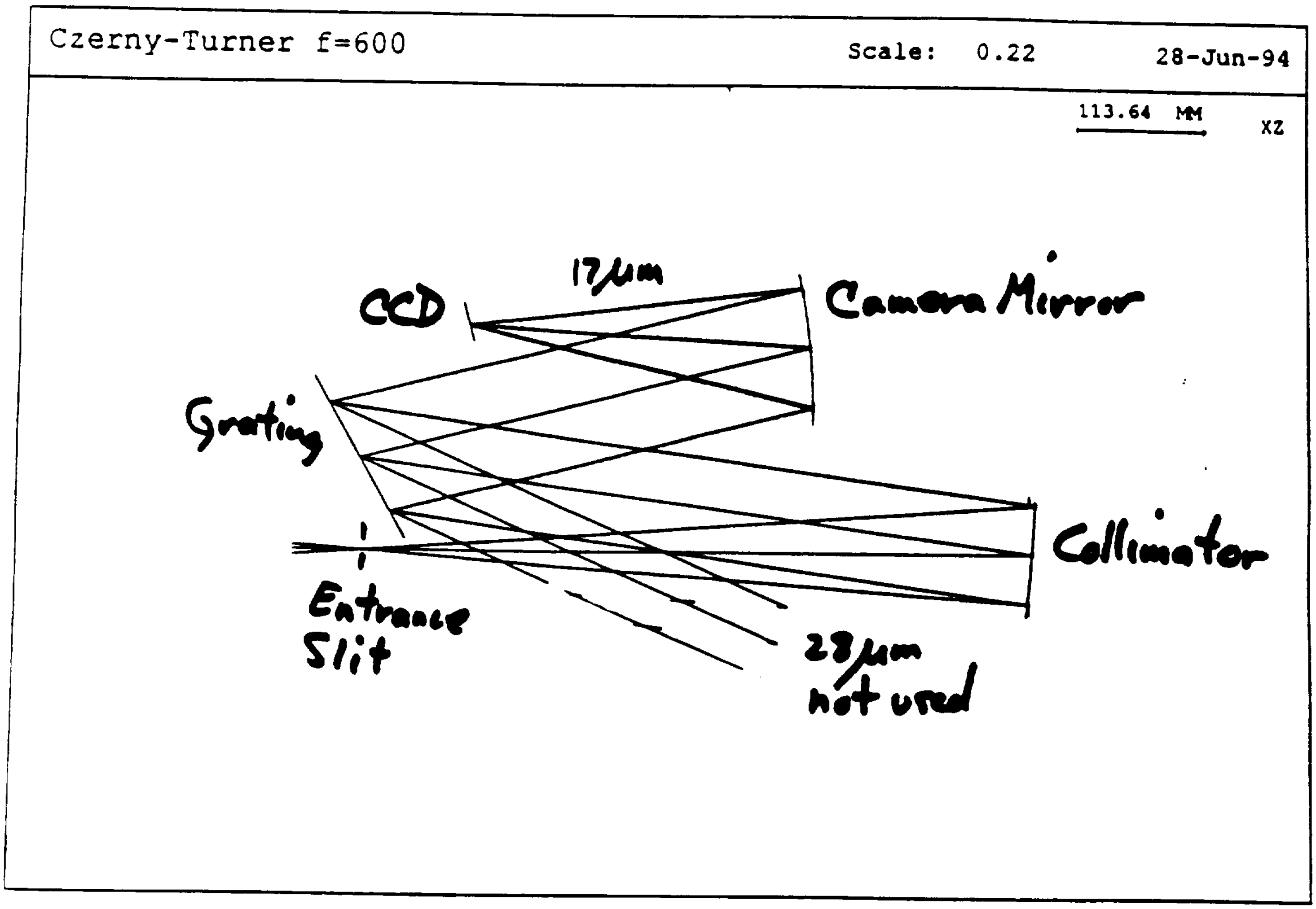


Figure 3

Czerny Turner Spectrograph

Camera Mirror focal length = $\frac{1}{2}$ Collimator

20:38:59



Shown in -5^{th} Diffraction Order

Grating Law $\sin\alpha + \sin\beta = \frac{m\lambda}{d}$

$(m\lambda) = (3 \cdot 28) = 84$
$(m\lambda) = (5 \cdot 17) = 85$

} Can put two spectra side by side

Figure 3 shows the grating spectrometer operating in fifth order. Light from the two slits is collimated at an off-axis parabola and illuminates the diffraction grating. This figure shows the fifth orders of the two wavelengths. The 17 microns beam illuminates a camera mirror (another off-axis parabola) and focuses at the CCD. The 28 micron fifth order beam exits toward the bottom and would be blocked by a baffle. The 28 micron fifth order beam would be a weak beam with only a few percent of the light. The 17 micron fifth order beam would contain greater than 75% of the 17 micron energy.

Figure 4 shows the grating spectrometer operating in third order. Now the 28 micron third order beam, which contains greater than 75% of the 28 micron light, is focussed by the camera mirror onto the CCD. The 17 micron third order beam, which contains a few percent, exits the top of the figure and will be blocked by a baffle.

The image quality of this system is diffraction limited. Figures 5 and 6 show the spot diagrams for 17 and 28 microns. The scale of a 75 micron pixel is shown in the lower right hand corner. The ray aberrations are shown in Figures 7 and 8 .

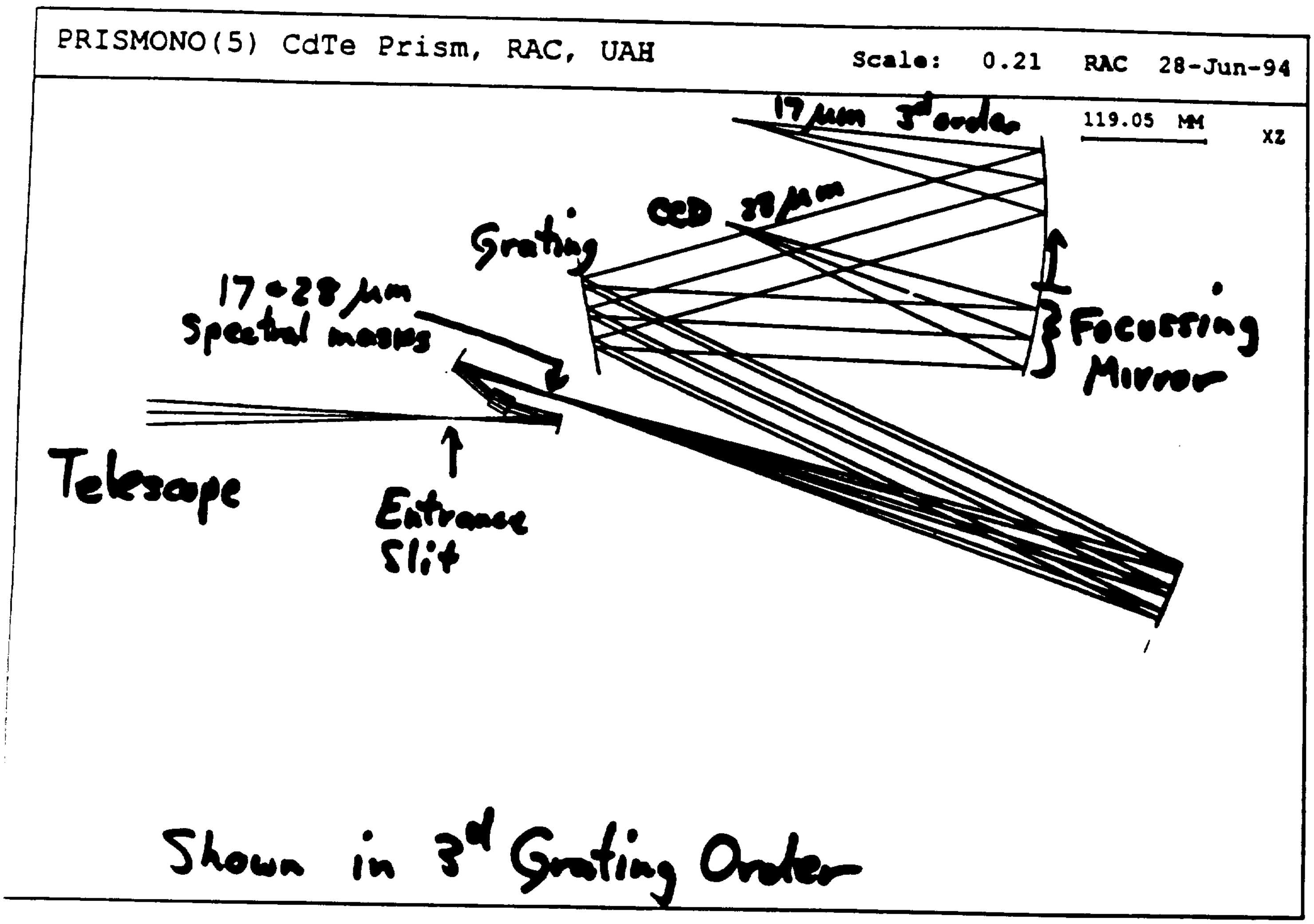
6 Issues in Increasing the Throughput

The last section shows the optical design concept for PRISM but that design is operating at one third the image height and one third the numerical aperture of the PRISM specifications. Increasing the field of view and the numerical apertures both by a factor of three is a significant task which will involve considerably more optical design sffort than was budgeted in this contract. In the Low Throughput Design, off-axis parabolas suffice for all the collimators. As the throughput increases, two mirror or three mirror designs are required to control the aberrations over the pupil and field of view. In the prism spectrometer, increasing the throughput is simpler because the numerical aperture can be kept smaller and the size of this subsystem increased. In the grating spectrometer, increasing the throughput is more challenging because an f/0.85 beam is required at the detector due to pixel size. This puts stringent requirements on the spectrograph camera system (the elements between the grating and the focal plane)

Prism Spectrometer and Czerny Turner Spectrograph

Figure 4

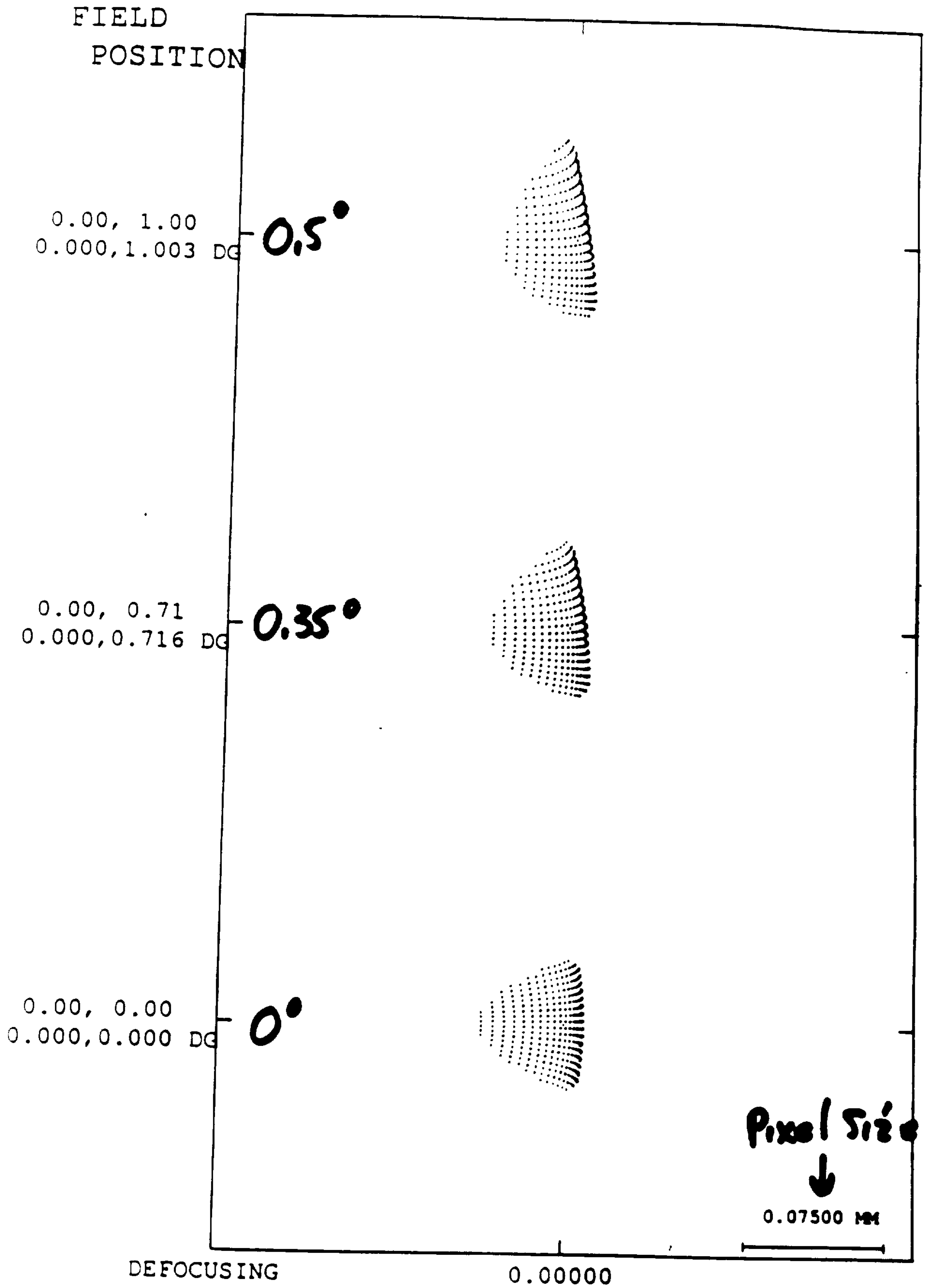
21:27:14



Package 70 cm x 40 cm x 10 cm

Image Quality 17 μm

Figure 5

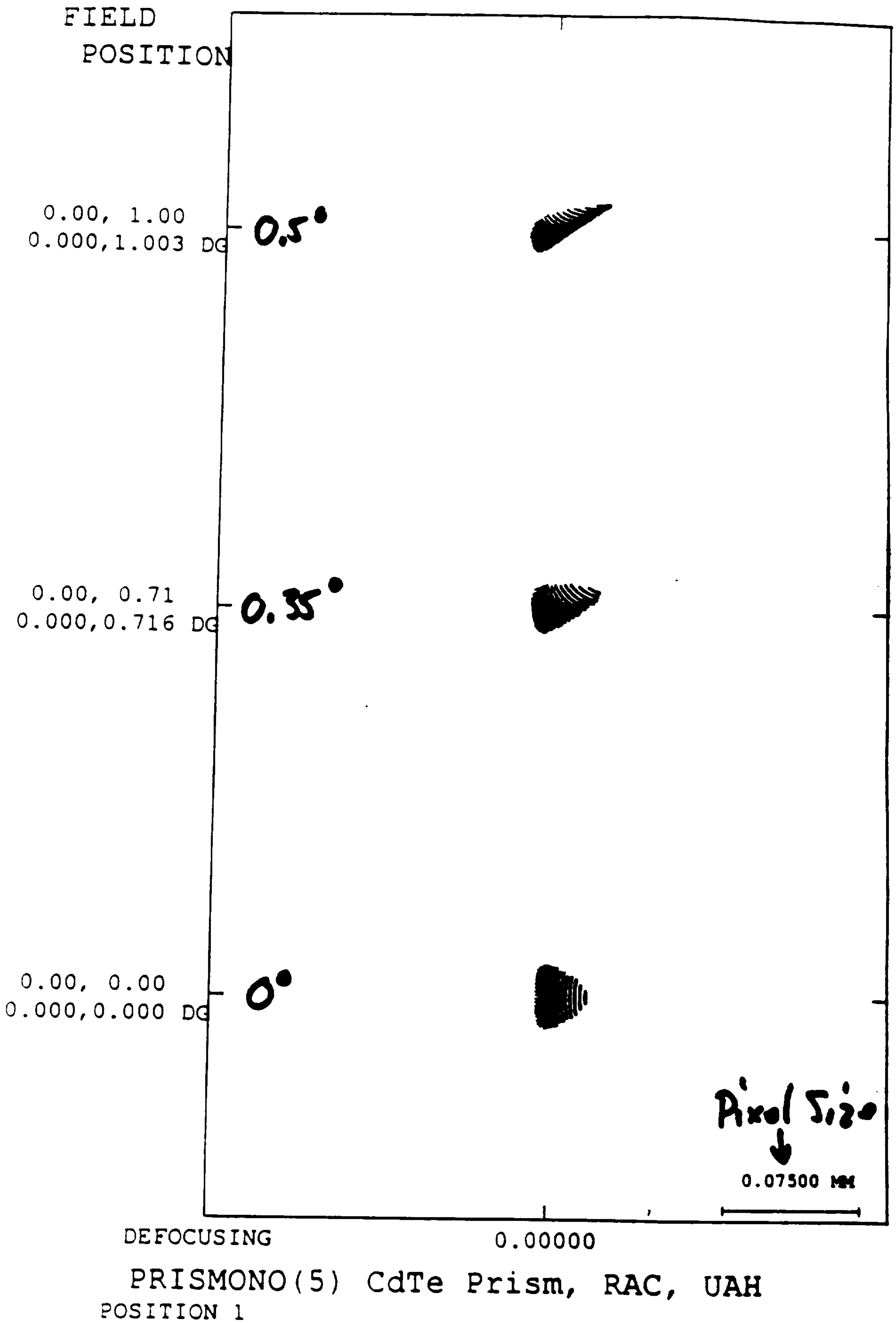


PRISMONO(5) CdTe Prism, RAC, UAH

POSITION 2

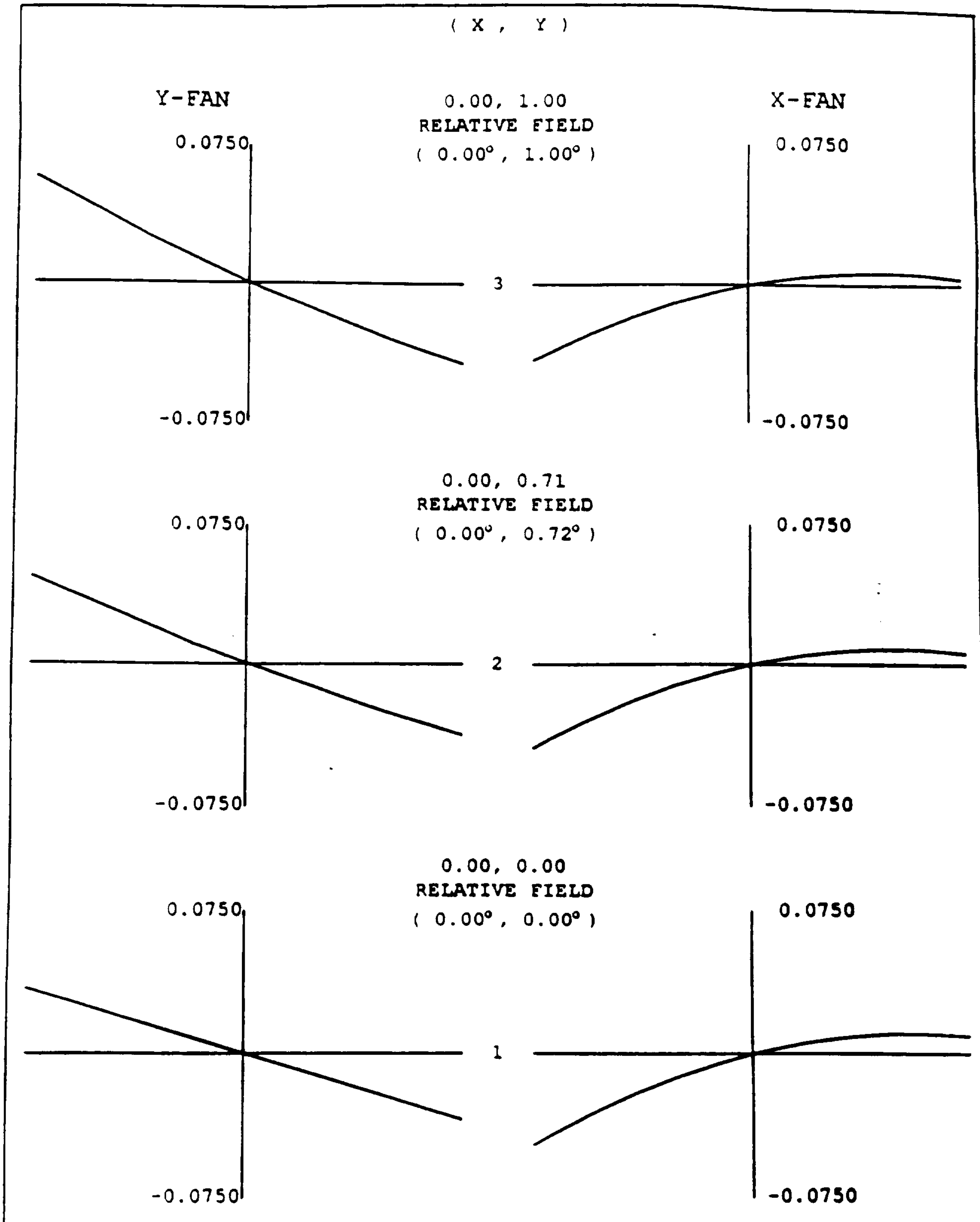
Image Quality 28 μm

Figure 6



17 μm

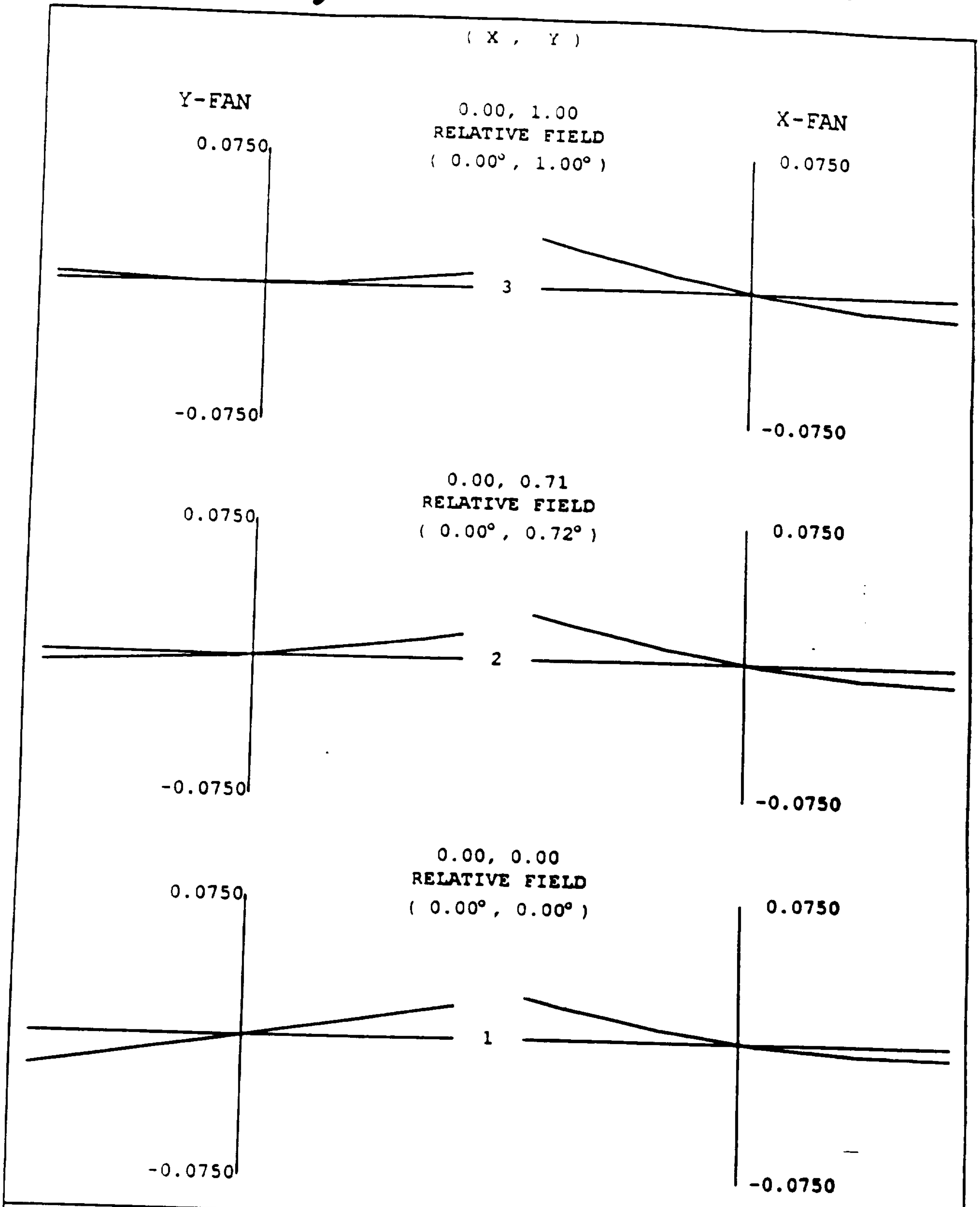
Figure 7



PRISMONO(5) CdTe Prism, RAC, UAH RAY ABERRATIONS (MILLIMETERS)	17000.0
RAC POSITION 2 28-Jun-94	

28 μm

Figure 8



PRISMONO(5) CdTe Pri
sm, RAC, UAH

RAY ABERRATIONS (MILLIMETERS)

RAC POSITION 1 28-Jun-94

28000.0

making it the most difficult subsystem to design. The grating spectrometer collimator has the same numerical aperture as the prism spectrometer subsystem, and thus is easier to design.

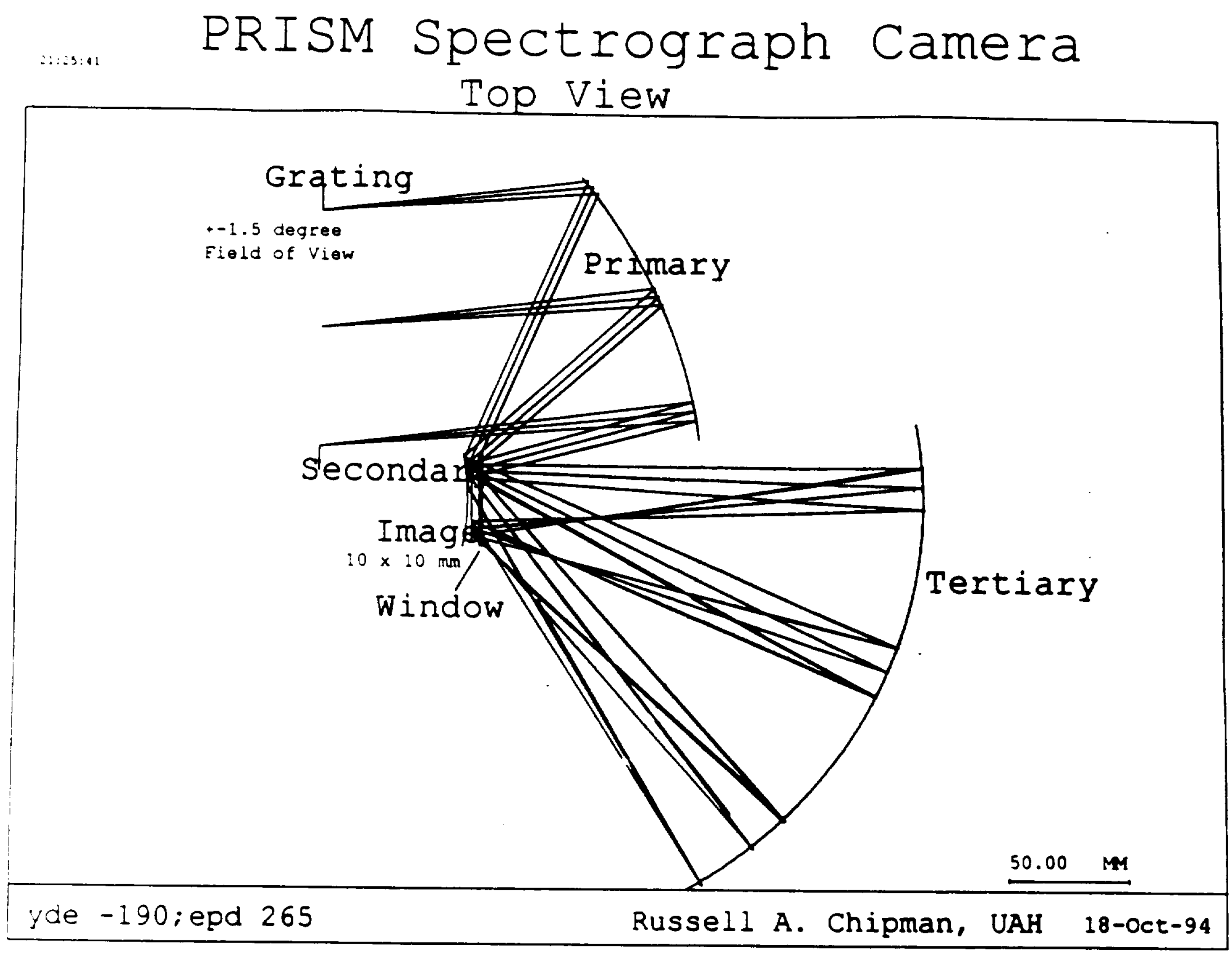
Since the spectrograph camera is the most difficult component to design, I spent the balance of the time budgeted for this contract on this component. With this design in hand, we can be confident that an acceptable design can be developed for the rest of the system.

The smaller the spectrograph camera, the shorter its focal length and the larger its field of view. It is the field of view which determines the complexity required to balance the aberrations. The spectrograph camera will meet its aberration requirements with a single off-axis mirror of 6 meters (!) in diameter, clearly impossible but encouraging none the less. A two mirror system needs to be a meter and a half in diameter, still much to big for our 60 cm packaging target. A three mirror design has been produced which corrects the aberrations within the packaging target.

7 Spectrograph Camera Design

A spectrograph camera has been designed which meets the PRISM system specifications operating at f/1 with a well corrected image field of up to 73 mm. Figure 9 is a top view layout showing the three aspheric mirror design. At the top left is the collimated beams diffracting from the grating with a $\pm 1.5°$ extent. The primary mirror brings the beams to an intermediate focus near the secondary mirror which is above the image plane. The secondary and the image are both near the center of curvature of the large tertiary mirror, the largest of the three mirrors , which re-images the intermediate image onto the CCD at f/1.0. The secondary mirror acts as a field corrector. All three mirrors are high order rotationally symmetric aspheres, and all share a common axis making the system an off-axis piece of a rotationally symmetric system. These mirrors could be diamond turned on the UAH or MSFC diamond turning machines.

Figure 9



21:25:41
PRISM Spectrograph Camera
Top View
Grating
+-1.5 degree
Field of View
Primary
Secondary
Image
10 x 10 mm
Window
Tertiary
50.00 MM
yde -190;epd 265
Russell A. Chipman, UAH 18-Oct-94

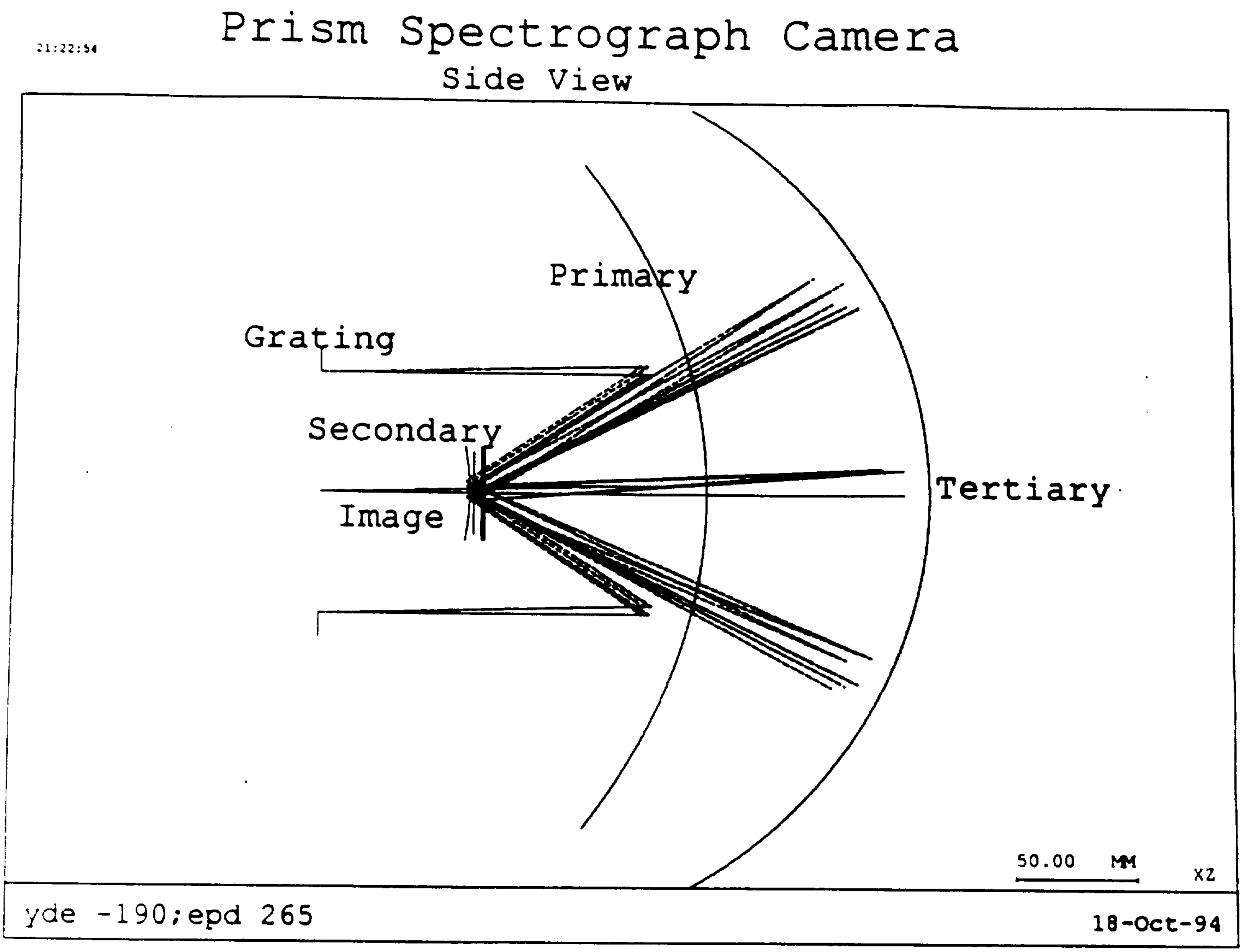
Figure 10 is a top view of the spectrograph camera. Figure 11 is a magnified view from the top showing the secondary (above) and the CCD with a window in front of it. Figure 12 magnifies the side view of the secondary and the image.

Because of its complexity this system required 70 hours of computer time to optimize. The starting design was a f/2 system with a larger field of view. The system was repeatedly optimized as the f/number was steadily lowered. Large numbers of rays were needed to control the aspherics, and it took large numbers of optimization cycles at each step to find the minima in the 40 dimensional optimization space. After each increase in the throughput, human intervention was required to keep the mirrors out of each others way and to keep the system physically realizable, through the addition of more and more constraints.

The optical performance of this spectrograph camera is excellent. Figure 13 shows the modulation transfer function at the center, top, bottom, and two corners of the CCD. The system is very close to the diffraction limit over the entire image. Figure 14 shows the spot diagrams compared to the pixel size. Figure 15 shows the crossections through the wavefront aberration function on a scale of $\pm\lambda/8$ revealing very small amounts of high order aberrations, especially at the edges of the pupil.

The tolerances for this system have not been calculated but will be very tight because of the large numerical aperture and the higher order aspherics. The design could probably be pushed to still lower f/numbers if the size could increase. The tolerances would get very difficult. Similarly, the system will become much easier to build if the f/number is increased. Figure 16 shows one of the intermediate designs for f/1.5 with the commensurately larger spacings between the elements and the various beams.

Figure 10



21:22:54
Prism Spectrograph Camera
Side View
Primary
Grating
Secondary
Image
Tertiary
50.00 MM
XZ
yde -190;epd 265
18-Oct-94

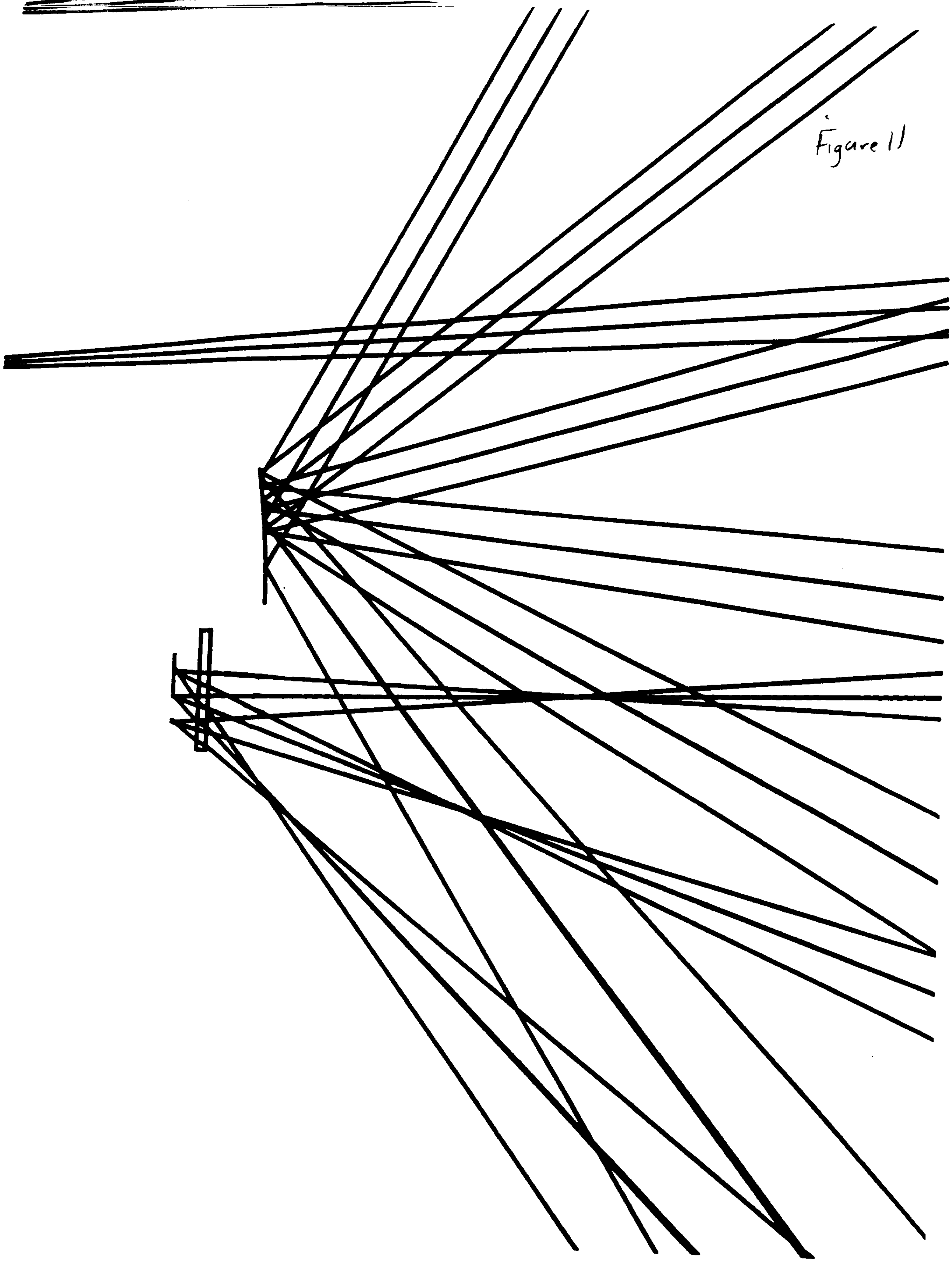


Figure 11

Figure 12

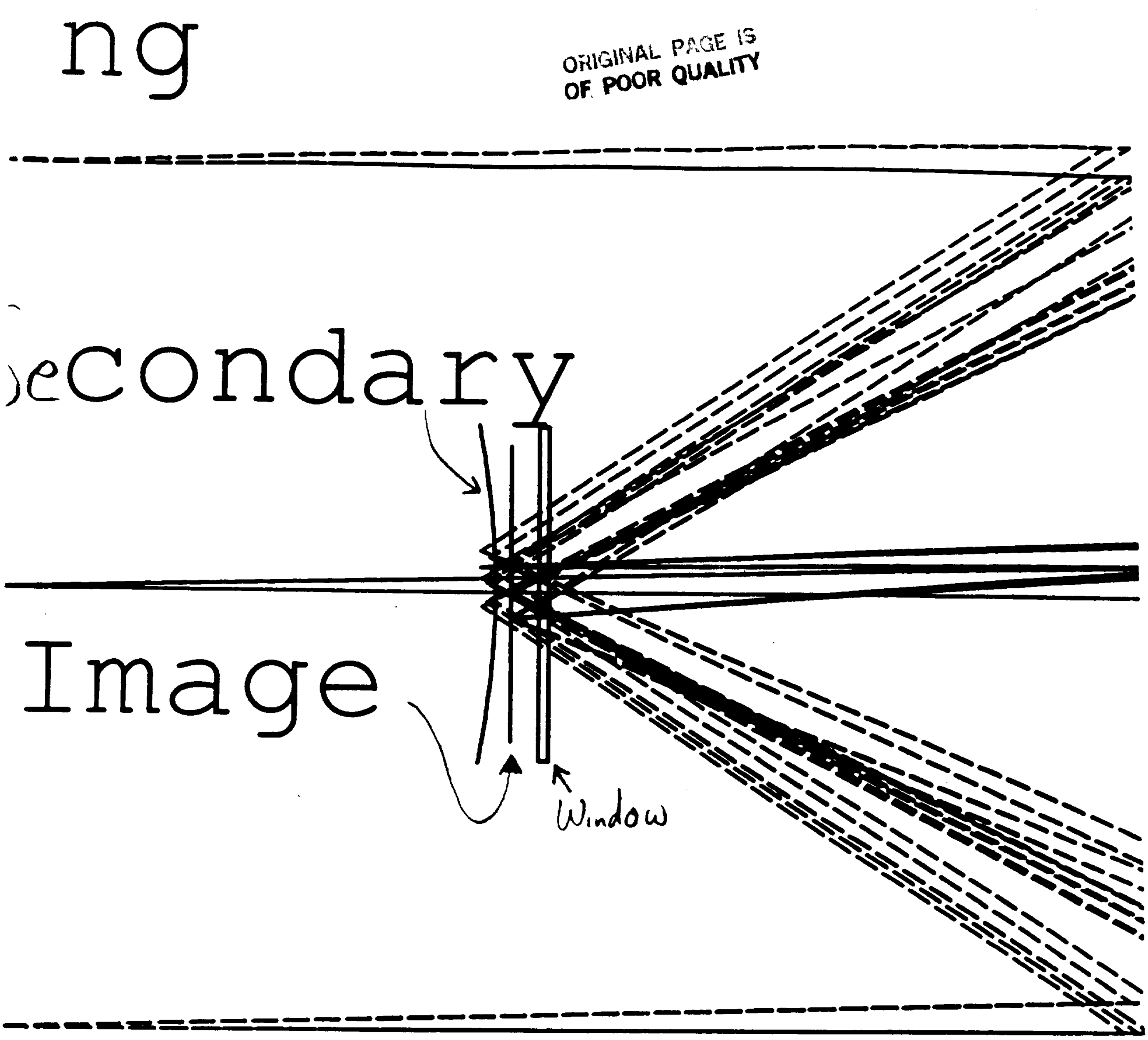
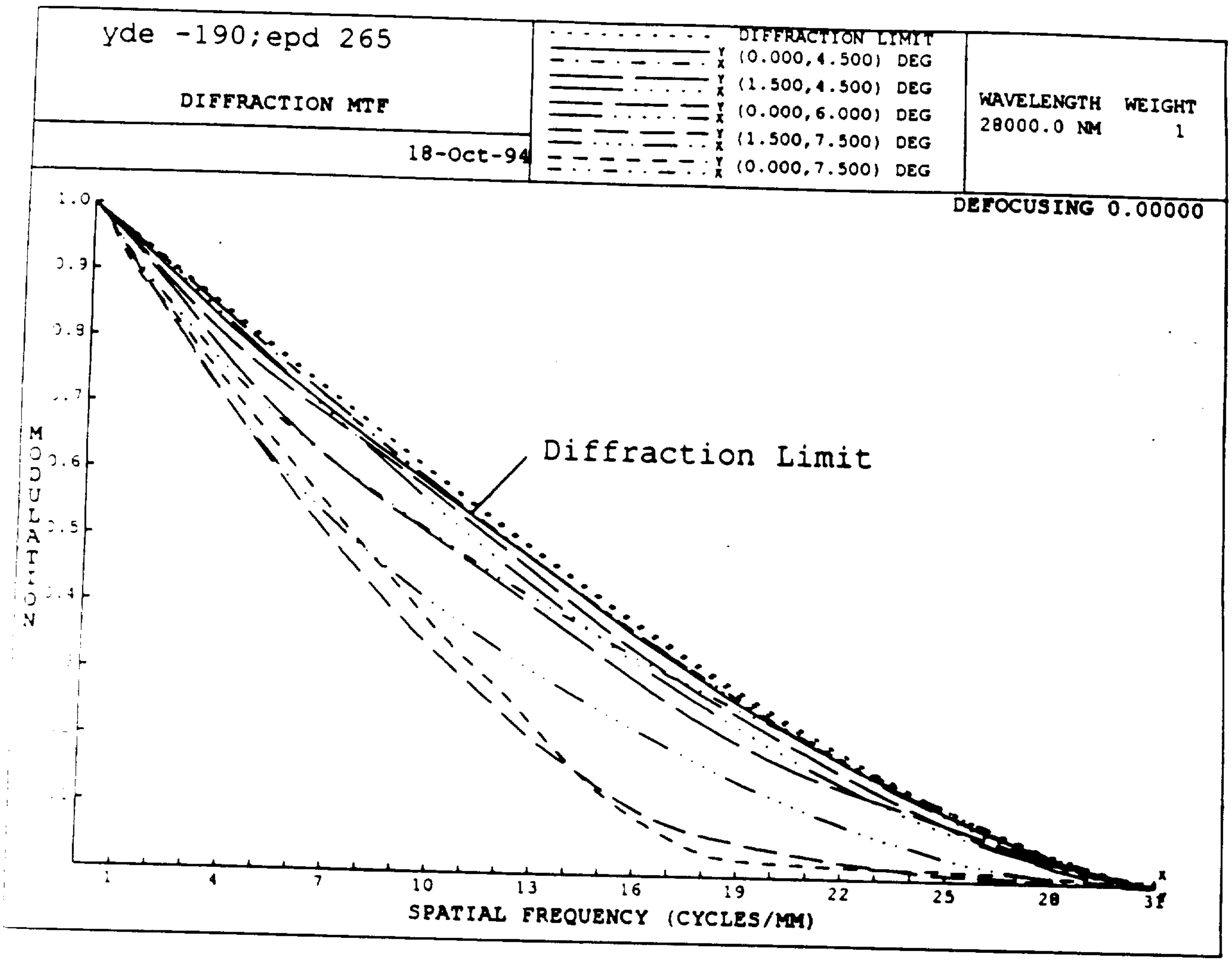


Figure 13

PRISM Spectrograph Camera



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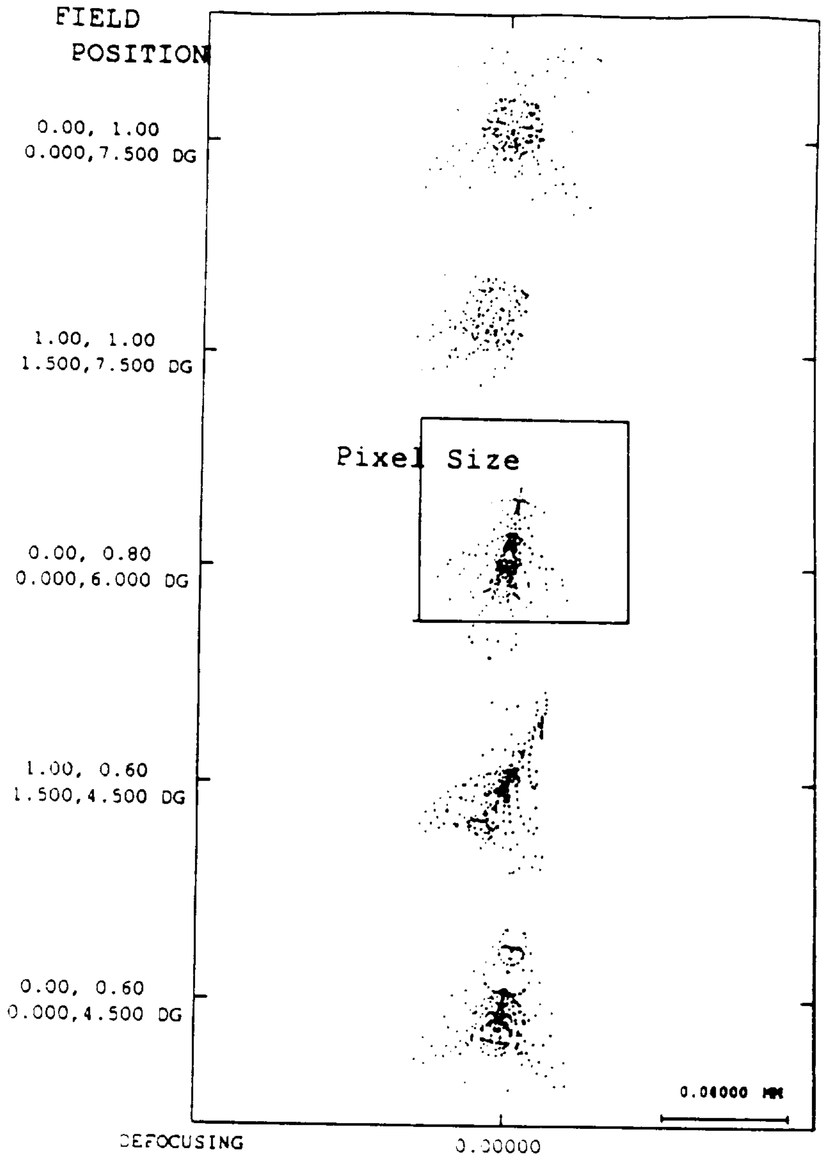
PRISM Spectrograph Camera

Figure 14



yde -190;epd 265

PRISM Spectrograph Camera, f/1.35
Wavefront Crossections

Figure 15

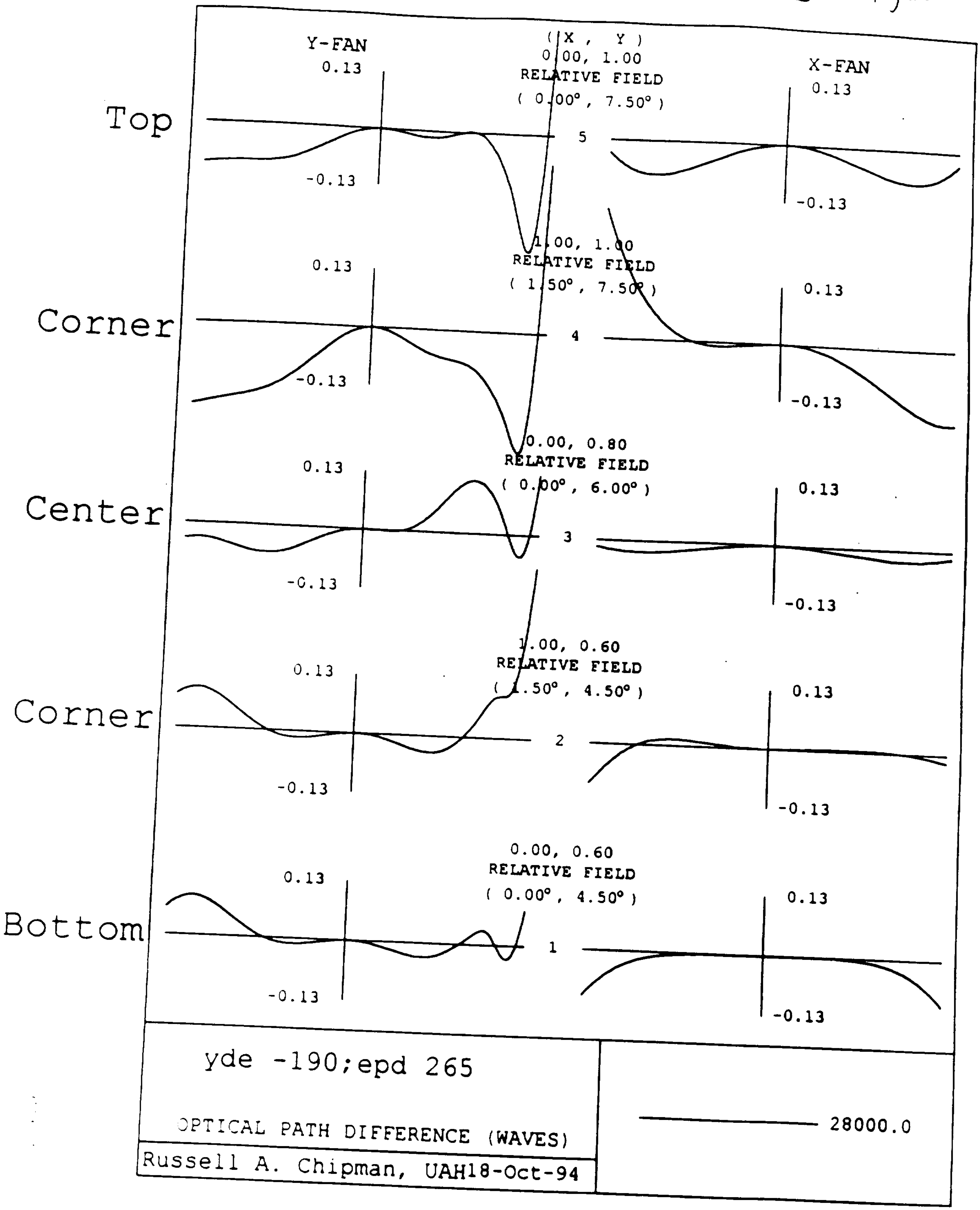
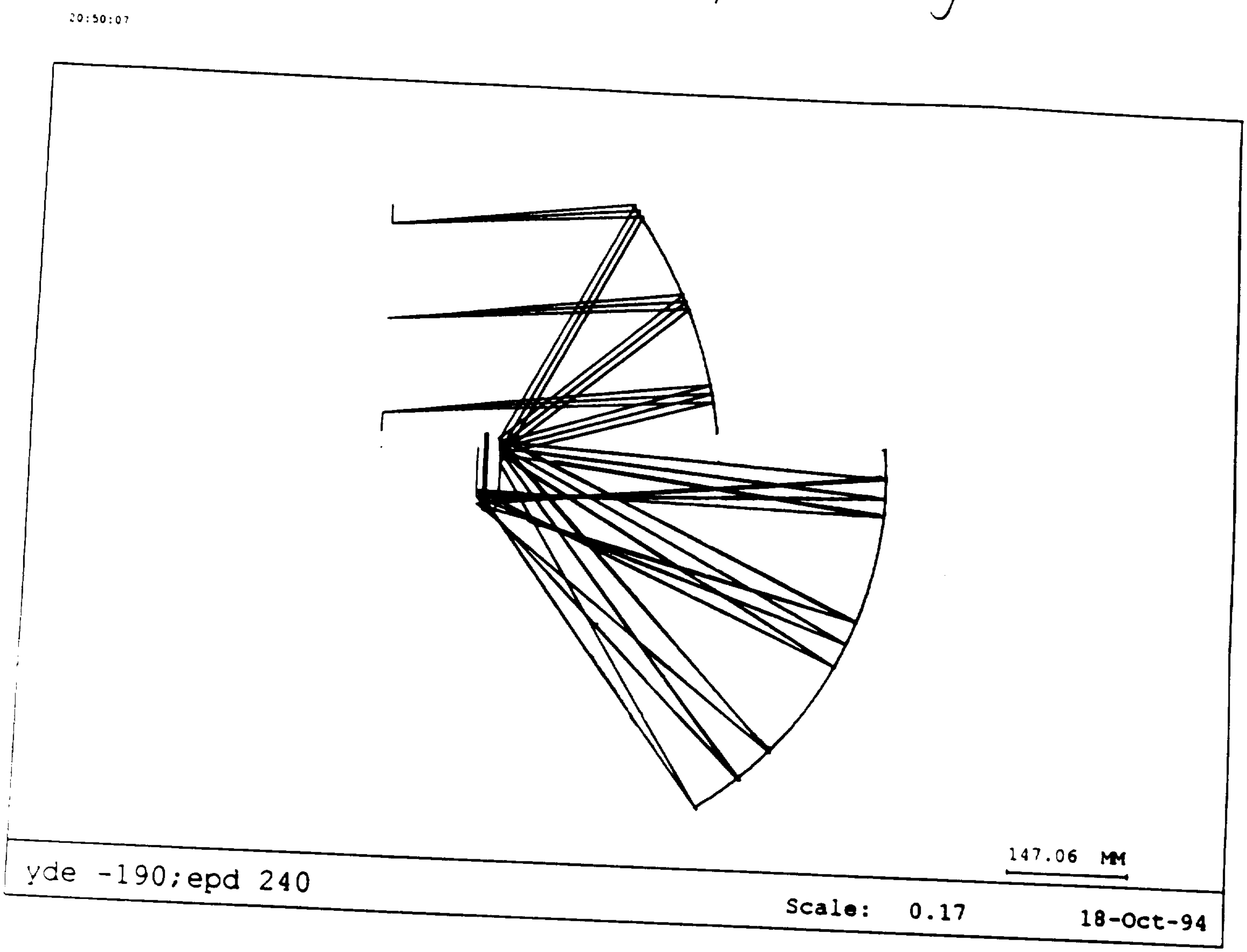


Figure 16

Alternative f/1.5 Design



8 Appendix A

The following is the listing for the CODE V file for the Prism Spectrometer - Grating Spectrograph Lower Throughput Design.

From file PRISMONO.TXT

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          RDY          THI    RMD     GLA       CCY  THC  GLC
> OBJ:      INFINITY    -200.000000                   100  100
 STO:       INFINITY    200.000000                    100  100
  2:        INFINITY    100.000000                    100  100
   XDE:  0.000000  YDE:  0.000000  ZDE:  0.000000
   XDC:    100     YDC:    100     ZDC:    100
   ADE:  0.000000  BDE:  15.000000  CDE:  0.000000
   ADC:    100     BDC:    100     CDC:    100

  3:    -200.00000    -50.000000  REFL                100  100
   ASP:
   K :  -1.000000  KC :    100
   IC :   YES     CUF:  0.000000  CCF:   100
   A :0.000000E+00  B :0.000000E+00  C :0.000000E+00  D :0.000000E+00
   AC :    100     BC :    100     CC :    100     DC :    100

  4:     INFINITY     0.000000    CDTE_SPECIAL    100  100
   XDE:  26.330500  YDE:  0.000000  ZDE:  0.000000
   XDC:    100     YDC:    100     ZDC:    100
   ADE:  0.000000  BDE:  20.000000  CDE:  0.000000
   ADC:    100     BDC:    100     CDC:    100
```

```
5:   INFINITY    -20.000000   CDTE_SPECIAL   100  100
 XDE:  0.000000  YDE:  0.000000  ZDE:  0.000000
 XDC:   100     YDC:   100     ZDC:   100
 ADE:  0.000000  BDE:  -7.624850  CDE:  0.000000
 ADC:   100     BDC:   100     CDC:   100

6:   INFINITY     0.000000                  100  100
 XDE:  0.000000  YDE:  0.000000  ZDE:  0.000000
 XDC:   100     YDC:   100     ZDC:   100
 ADE:  0.000000  BDE:  -7.624850  CDE:  0.000000
 ADC:   100     BDC:   100     CDC:   100

7:   INFINITY    -50.000000                  100  100
 XDE:  0.000000  YDE:  0.000000  ZDE:  0.000000
 XDC:   100     YDC:   100     ZDC:   100
 ADE:  0.000000  BDE:  20.000000  CDE:  0.000000
 ADC:   100     BDC:   100     CDC:   100

8:   200.00000   100.000000 REFL            100  100
 ASP:
 K :  -1.000000  KC :   100
 IC :   YES    CUF:  0.000000  CCF:   100
 A :0.000000E+00  B :0.000000E+00  C :0.000000E+00  D :0.000000E+00
 AC :   100     BC :   100     CC :   100     DC :   100
 XDE:  40.000000  YDE:  0.000000  ZDE:  0.000000
 XDC:   100     YDC:   100     ZDC:   100
 ADE:  0.000000  BDE:  0.000000  CDE:  0.000000
 ADC:   100     BDC:   100     CDC:   100

9:   INFINITY     0.000000                  100  100
 XDE:  0.000000  YDE:  0.000000  ZDE:  0.000000
```

XDC: 100 YDC: 100 ZDC: 100
ADE: 0.000000 BDE: -22.629550 CDE: 0.000000
ADC: 100 BDC: 100 CDC: 100

10: INFINITY 0.000000 100 100
11: INFINITY 0.000000 100 100
12: INFINITY 600.000000 100 100
XDE: 0.000000 YDE: 0.000000 ZDE: 0.000000
XDC: 100 YDC: 100 ZDC: 100
ADE: 0.000000 BDE: 8.000000 CDE: 0.000000
ADC: 100 BDC: 100 CDC: 100

13: -1200.00000 0.000000 REFL 100 100
ASP:
K : -1.000000 KC : 100
IC : YES CUF: 0.000000 CCF: 100
A :0.000000E+00 B :0.000000E+00 C :0.000000E+00 D :0.000000E+00
AC : 100 BC : 100 CC : 100 DC : 100

14: INFINITY 0.000000 100 100
RET S10

15: INFINITY 0.000000 AIR 100 100
XDE: 84.736800 YDE: 0.000000 ZDE: 0.000000
XDC: 100 YDC: 100 ZDC: 100
ADE: 0.000000 BDE: 0.000000 CDE: 0.000000
ADC: 100 BDC: 100 CDC: 100

16: INFINITY 0.000000 REFL AIR 100 100
GRT:
K : 0.000000 KC : 100 IC : YES
A :0.000000E+00 B :0.000000E+00 C :0.000000E+00 D :0.000000E+00
AC : 100 BC : 100 CC : 100 DC : 100

```
  GRO:   -3    GRS:  0.100000
  GRX:  1.000000  GRY:  0.000000  GRZ:  0.000000
  XDE:  0.000000  YDE:  0.000000  ZDE:  0.000000  DAR
  XDC:   100     YDC:   100     ZDC:   100
  ADE:  0.000000  BDE: -29.000000  CDE:  0.000000
  ADC:   100     BDC:   100     CDC:   100

 17:     INFINITY     0.000000                 100  100
 18:     INFINITY   400.000000                 100  100
  XDE: 100.000000  YDE:  0.000000  ZDE:  0.000000
  XDC:   100     YDC:   100     ZDC:   100
  ADE:  0.000000  BDE: -15.000000  CDE:  0.000000
  ADC:   100     BDC:   100     CDC:   100

 19:   -600.00000    0.000000 REFL              100  100
  ASP:
  K :  -1.000000  KC :   100
  IC :  YES    CUF:  0.000000  CCF:   100
  A :0.000000E+00  B :0.000000E+00  C :0.000000E+00  D :0.000000E+00
  AC :   100    BC :   100    CC :   100    DC :   100

 20:     INFINITY  -300.000000                 100  100
IMG:     INFINITY     0.013503                 100    0
  XDE:  0.000000  YDE:  0.000000  ZDE:  0.000000  DAR
  XDC:   100     YDC:   100     ZDC:   100
  ADE:  0.000000  BDE:  19.287757  CDE:  0.000000
  ADC:   100     BDC:    0     CDC:   100


SPECIFICATION DATA
 EPD     16.17251
 DIM        MM
 WL     28000.00  17000.00
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REF	1	
WTW	1	1
INI	RAC	
XOB	0.00000	
YOB	0.00000	
VUX	0.00000	
VLX	0.00000	
VUY	0.00000	
VLY	0.00000	

REFRACTIVE INDICES

GLASS CODE	28000.00	17000.00
CDTE_SPECIAL	2.577622	2.649840

No solves defined in system

ZOOM DATA

	POS 1	POS 2
REF	1	2
GRO S16	-3.00000	-5.00000

* GENERATED BY A SOLVE - VALUE WILL CHANGE TO SATISFY THE SOLVE

This is a decentered system. If elements with power are decentered or tilted, the first order properties are probably inadequate in describing the system characteristics.

	POS 1	POS 2
INFINITE CONJUGATES		
EFL	55.8889	55.7572
BFL	-272.0555	-272.1214
FFL	311.7779	311.5143

```
  FNO       -3.4558   -3.4477
AT USED CONJUGATES
  RED       -0.5000   -0.5000
  FNO        6.1884    6.1884
  OBJ DIS  -200.0000 -200.0000
  TT        180.0135  180.0135
  IMG DIS  -299.9865 -299.9865
  OAL       680.0000  680.0000
  PARAXIAL IMAGE
   HT        0.0000    0.0000
   THI    -300.0000 -300.0000
  ANG        0.0000    0.0000
  ENTRANCE PUPIL
   DIA      16.1725   16.1725
   THI       0.0000    0.0000
  EXIT PUPIL
   DIA       2.8991    2.8947
   THI    -282.0741 -282.1013
  STO DIA   16.1725   16.1725
```

The CODE V sequence file :

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EPD  16.1725067385
DIM  M
WL   28000.0 17000.0
REF  1
WTW  1 1
INI  'RAC'
XOB  0.0
```

```
YOB  0.0
VUX  0.0
VLX  0.0
VUY  0.0
VLY  0.0
SO   0.0 -200.0
S    0.0 200.0
 STO
S    0.0 100.0
 ADE 0.0; BDE 15.0; CDE 0.0
S    -200.0 -50.0 REFL
 ASP
 K  -1.0
 IC  Yes; CUF 0.0
 A  0.0; B 0.0; C 0.0; D 0.0
S    0.0 0.0 CDTE_SPECIAL
 XDE 26.3305; YDE 0.0; ZDE 0.0
 ADE 0.0; BDE 20.0; CDE 0.0
S    0.0 -20.0 CDTE_SPECIAL
 ADE 0.0; BDE -7.62485; CDE 0.0
S    0.0 0.0
 ADE 0.0; BDE -7.62485; CDE 0.0
S    0.0 -50.0
 ADE 0.0; BDE 20.0; CDE 0.0
S    200.0 100.0 REFL
 ASP
 K  -1.0
 IC  Yes; CUF 0.0
 A  0.0; B 0.0; C 0.0; D 0.0
 XDE 40.0; YDE 0.0; ZDE 0.0
S    0.0 0.0
 ADE 0.0; BDE -22.62955; CDE 0.0
S    0.0 0.0
```

```
S    0.0 0.0
S    0.0 600.0
 ADE 0.0; BDE 8.0; CDE 0.0
S    -1200.0 0.0 REFL
 ASP
 K  -1.0
 IC  Yes; CUF 0.0
 A  0.0; B 0.0; C 0.0; D 0.0
S    0.0 0.0
 RET S10
S    0.0 0.0 AIR
 XDE 84.7368; YDE 0.0; ZDE 0.0
S    0.0 0.0 REFL
 GRT
 K  0.0; IC Yes
 A  0.0; B 0.0; C 0.0; D 0.0
 GRO -3; GRS 0.1
 GRX 1.0; GRY 0.0; GRZ 0.0
 DAR
 ADE 0.0; BDE -29.0; CDE 0.0
S    0.0 0.0
S    0.0 400.0
 XDE 100.0; YDE 0.0; ZDE 0.0
 ADE 0.0; BDE -15.0; CDE 0.0
S    -600.0 0.0 REFL
 ASP
 K  -1.0
 IC  Yes; CUF 0.0
 A  0.0; B 0.0; C 0.0; D 0.0
S    0.0 -300.0
SI   0.0 0.0135032998154
 THC 0
 DAR
```

```
 ADE 0.0; BDE 19.2877572891; CDE 0.0; ADC 100; BDC 0; CDC 100
ZOO  2
ZOO  REF 1 2
ZOO  GRO S16 -3.0 -5.0
GO
```

9 Appendix B The Spectrograph Camera Code V Design

Multiple systems were optimized at the same time and this one has somewhat different optical performance than documented in the figures. In particular, the wavefront shapes almost exactly match the documented shapes except that the scales don't match, making it possible that the scales on the published figure got rescaled somehow during printing. Very frustrating to try to track down.

From the file CAMERA59.TXT

```
   yde -190;epd 265

           RDY          THI    RMD    GLA       CCY  THC  GLC
> OBJ:     INFINITY     INFINITY                  100  100
 STO:      INFINITY     0.000000                  100  100
  2:       INFINITY     150.000000                100  100
  3:       INFINITY     271.817520                100  100
  4:       -536.36939   -258.763191  REFL           0    0
   ASP:
   K : -0.665752  KC :   0
   IC :   YES    CUF:  0.000000  CCF:   100
   A :0.180932E-09  B :-.110237E-13  C :0.224689E-18  D :-.255358E-23
   AC :    0    BC :    0    CC :    0    DC :    0
   E :0.148003E-28  F :-.340455E-34  G :0.000000E+00  H :0.000000E+00
   EC :    0    FC :    0    GC :   100    HC :   100
   J :0.000000E+00
   JC :   100
   XDE:  0.000000  YDE: -190.000000  ZDE:   0.000000
   XDC:   100      YDC:   100        ZDC:   100
   ADE:  0.000000  BDE:   0.000000   CDE:  10.000000
   ADC:   100      BDC:   100        CDC:   100
```

```
 5:   -85.42265     3.423390 REFL              0  100
  ASP:
  K : -856.164079  KC :    0
  IC :   YES    CUF:  0.000000  CCF:   100
  A :-.247892E-05  B :0.233571E-08  C :-.119136E-11  D :0.297014E-15
  AC :    0     BC :    0     CC :    0     DC :    0
  E :-.116927E-19  F :-.117969E-22  G :0.306940E-26  H :-.314270E-30
  EC :    0     FC :    0     GC :    0     HC :    0
  J :0.000000E+00
  JC :   100

 6:     INFINITY    -3.423390                   100  100
 7:     INFINITY    498.756522                  100   0
 8:   -490.47335    -480.000000 REFL              0  100
  ASP:
  K :   0.002699  KC :    0
  IC :   YES    CUF:  0.000000  CCF:   100
  A :0.329359E-10  B :0.734977E-15  C :-.914719E-20  D :0.108538E-24
  AC :    0     BC :    0     CC :    0     DC :    0
  E :-.584580E-30  F :0.137799E-35  G :0.000000E+00  H :0.000000E+00
  EC :    0     FC :    0     GC :   100    HC :   100
  J :0.000000E+00
  JC :   100

 9:     INFINITY    -2.686624                   100   0
10:     INFINITY    -3.000000   'sapphire'      100  100
11:     INFINITY    -8.500000                   100  100
12:     INFINITY    0.318770                    100  100
IMG:    INFINITY    -0.277066                   100  100

SPECIFICATION DATA
 EPD    265.00000
 DIM       MM
```

WL	28000.00			
REF	1			
WTW	1			
XAN	0.00000	0.00000	0.00000	-1.50000
YAN	4.50000	6.00000	7.50000	6.00000
VUX	0.00000	0.00000	0.00000	0.00000
VLX	0.00000	0.00000	0.00000	0.00000
VUY	0.00000	0.00000	0.00000	0.00000
VLY	0.00000	0.00000	0.00000	0.00000

APERTURE DATA/EDGE DEFINITIONS

CA

APERTURE data not specified for surface Obj thru 13

PRIVATE CATALOG

PWL	28000.00
'sapphire'	1.400000

REFRACTIVE INDICES

GLASS CODE	28000.00
'sapphire'	1.400000

No solves defined in system

This is a decentered system. If elements with power are decentered or tilted, the first order properties are probably inadequate in describing the system characteristics.

INFINITE CONJUGATES

EFL	349.5074
BFL	-1.0086
FFL	-2497.2628
FNO	-1.3189

IMG DIS 0.0417
OAL 167.6242
PARAXIAL IMAGE
HT 36.7347
ANG 6.0000
ENTRANCE PUPIL
DIA 265.0000
THI 0.0000
EXIT PUPIL
DIA 37.0884
THI 47.9071

The associated sequence file CAMERA59.SEQ

```
RDM;LEN
TITLE 'yde -190;epd 255'
EPD 260.0
DIM M
WL 28000.0
REF 1
WTW 1
INI ''
XAN 0.0 1.5 0.0 1.5 0.0
YAN 4.5 4.5 6.0 7.5 7.5
VUX 0.0 0.0 0.0 0.0 0.0
VLX 0.0 0.0 0.0 0.0 0.0
VUY 0.0 0.0 0.0 0.0 0.0
VLY 0.0 0.0 0.0 0.0 0.0
PRV
 PWL 28000.0
```

```
 'sapphire' 1.4
END
SO   0.0 0.1e14
S    0.0 0.0
 STO
S    0.0 150.0
S    0.0 271.81752
S    -540.296244421 -261.673174548 REFL
 CCY 0; THC 0
 ASP
 K  -0.66674099508; KC 0
 IC  Yes; CUF 0.0
 A  0.182094916553e-9; B -0.109953269977e-13; C 0.223419627155e-18; D&
  -0.253551857637e-23
 AC  0; BC 0; CC 0; DC 0
 E  0.147277833257e-28; F -0.340464306518e-34; G 0.0; H 0.0
 EC  0; FC 0
 J  0.0
 XDE 0.0; YDE -190.0; ZDE 0.0
 ADE 0.0; BDE 0.0; CDE 10.0
S    -99.5756462688 3.42339 REFL
 CCY 0
 ASP
 K  -811.032017616; KC 0
 IC  Yes; CUF 0.0
 A  -0.24162458637e-5; B 0.230642039792e-8; C -0.119500023601e-11; D&
  0.300901683751e-15
 AC  0; BC 0; CC 0; DC 0
 E  -0.116927307797e-19; F -0.117179087688e-22; G 0.292665529832e-26; H&
  -0.295228174211e-30
 EC  0; FC 0; GC 0; HC 0
 J  0.0
S    0.0 -3.42339
```

```
S    0.0 496.608350309
 THC 0
S    -490.707839758 -480.0 REFL
 CCY 0
 ASP
 K  0.00729409086981; KC 0
 IC  Yes; CUF 0.0
 A  0.392720704114e-10; B 0.728374079965e-15; C -0.889958011016e-20; D&
 0.108292006262e-24
 AC  0; BC 0; CC 0; DC 0
 E  -0.589907953606e-30; F 0.142378468199e-35; G 0.0; H 0.0
 EC  0; FC 0
 J  0.0
S    0.0 -4.29472266358
 THC 0
S    0.0 -3.0 'sapphire'
S    0.0 -8.5
S    0.0 0.31877
SI   0.0 -0.277066
GO
```