THE JOHNS HOPKINS UNIVERSITY

DEPARTMENT OF PHYSICS

SPECIAL REPORT

NASA/MSC Contract NAS 9-11528

Task I. Principal Investigator Services

EXIT SLIT MIRRORS FOR THE EBERT SPECTROMETER

Submitted by

Wm. G. Fastie
Principal Investigator

March 16, 1972

Baltimore, Maryland 21218

THE JOHNS HOPKINS UNIVERSITY
DEPARTMENT OF PHYSICS
HOMEWOOD CAMPUS
BALTIMORE, MARYLAND 21218

March 15, 1972

To: Distribution

From: Wm. G. Fastie, Principal Investigator

Subject: Special Report, Exit Slit Mirrors for the Ebert Spectrometer. NASA/MSC Contract NAS 9-11528. Task I - Principal Investigator Services.

We submit herewith a manuscript describing analytical work which was performed under Task I of the subject contract as part of the Technical Supporting Studies Plan. This manuscript has been submitted to Applied Optics for publication.

Wm. G. Fastie
Principal Investigator

WGF:ec

Distribution:

11 Copies NASA/MSC, L. McFadin
1 Copy " " , M. Krisberg
1 " " " , E. Jones
1 " " " , N. Hardee
1 " " " , E. Smith
1 " " " , H. Harvey
1 " ONRRR/JHU, W. B. Girkin
1 " APL/JHU, T. Wyatt
1 " APL/JHU NASARR, D. Beeman
1 " JHU, A. P. Ashton
1 " NASA, G. F. Esenwein, Jr.
1 " NASA/GSFC, J. Diggins
1 " File

To Remove, Tear Along This Line

EXIT SLIT MIRRORS FOR
THE EBERT SPECTROMETER

by

Wm. G. Fastie

Department of Physics
The Johns Hopkins University
Baltimore, Maryland 21218

Submitted to Applied Optics

ABSTRACT

The use of a very long straight entrance slit in an Ebert grating spectrometer with two plane mirrors at the shorter exit slit to increase the energy density is described. This system has been employed in a far ultraviolet rocket spectrometer to provide higher sensitivity than has been achieved previously. The imaging properties and required slit and mirror adjustments are presented. Experimental results are included.

I. INTRODUCTION

The use of very long circularly curved slits in an Ebert spectrometer to increase the spectral signal without loss of resolution is well established.[1,2,3] Condensing optics, optical pyramids, and image slicers[4] are widely used to concentrate the energy from a long exit slit onto small detectors. Space limitations and low optical efficiency have precluded the use of these devices for far ultraviolet rocket spectroscopy, and it has been the practice to use the largest available detectors at the exit slit, which limits the effective length of the slits to less than 25 mm. We have recently designed an exit slit mirror system which permits the use of a much longer entrance slit and provides almost three times as large an output signal. Analysis of this system and experimental performance data are described herein.

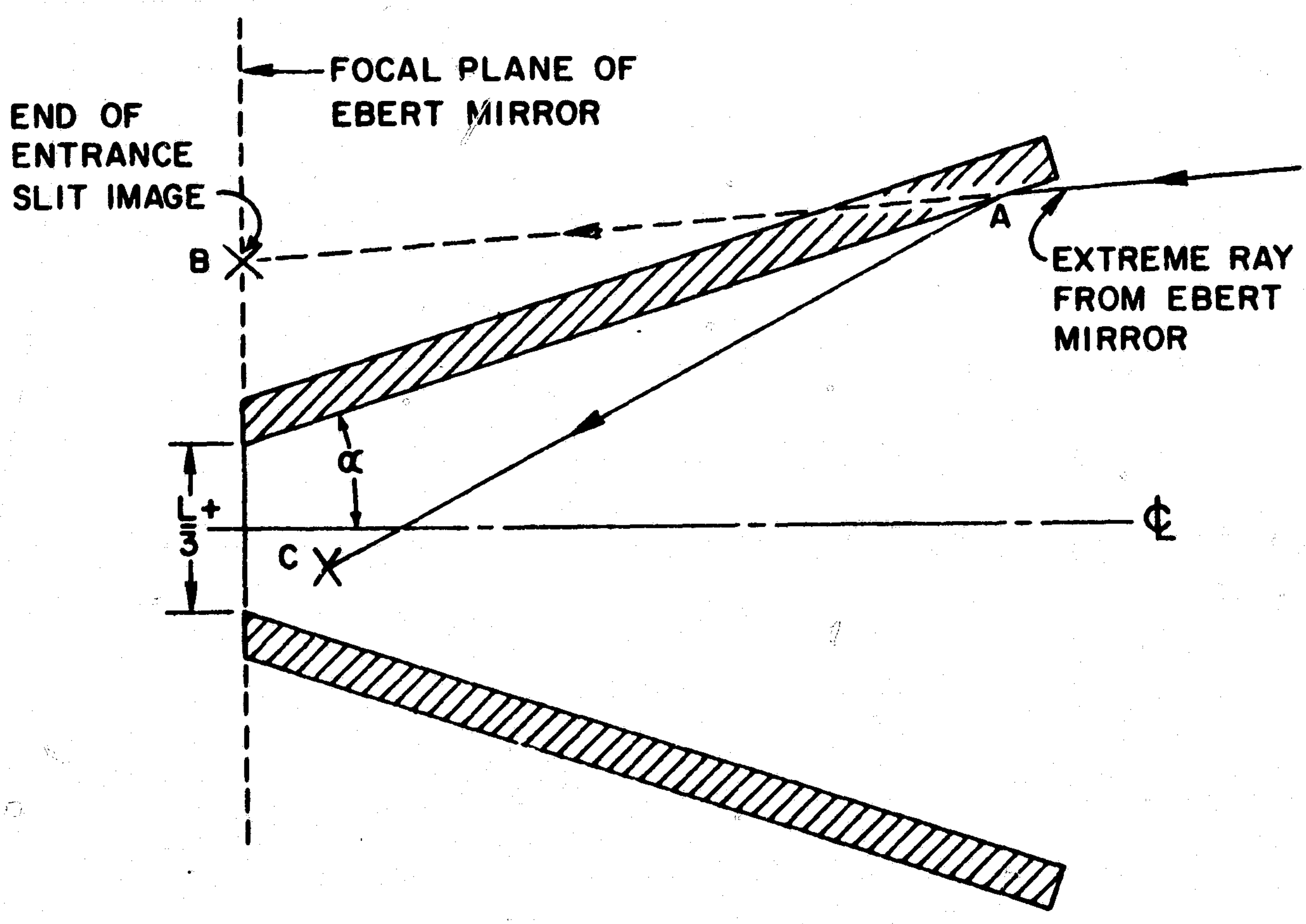

Fig. 1 Side View of Exit Slit Mirrors Showing Defocused End of Slit Image. Point B in Focal Plane Reflects to Point C Inside Focal Plane.

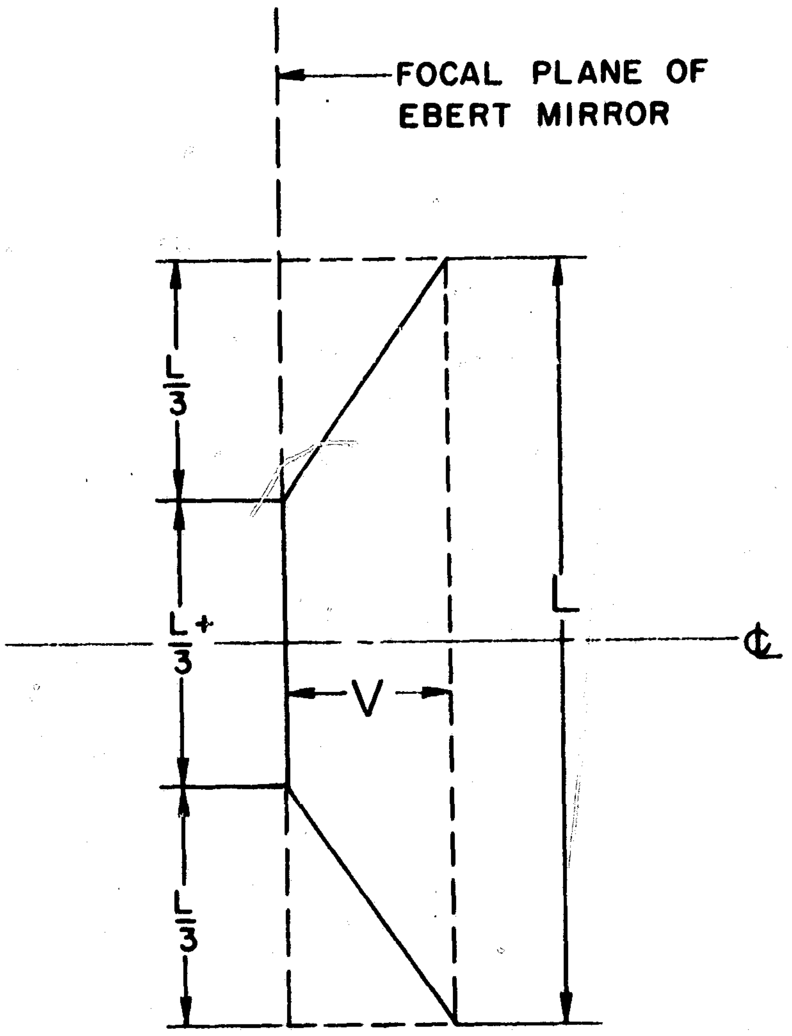

Fig. 2 Side View of Entrance Slit With Ends of Slit Inside of Focal Plane.

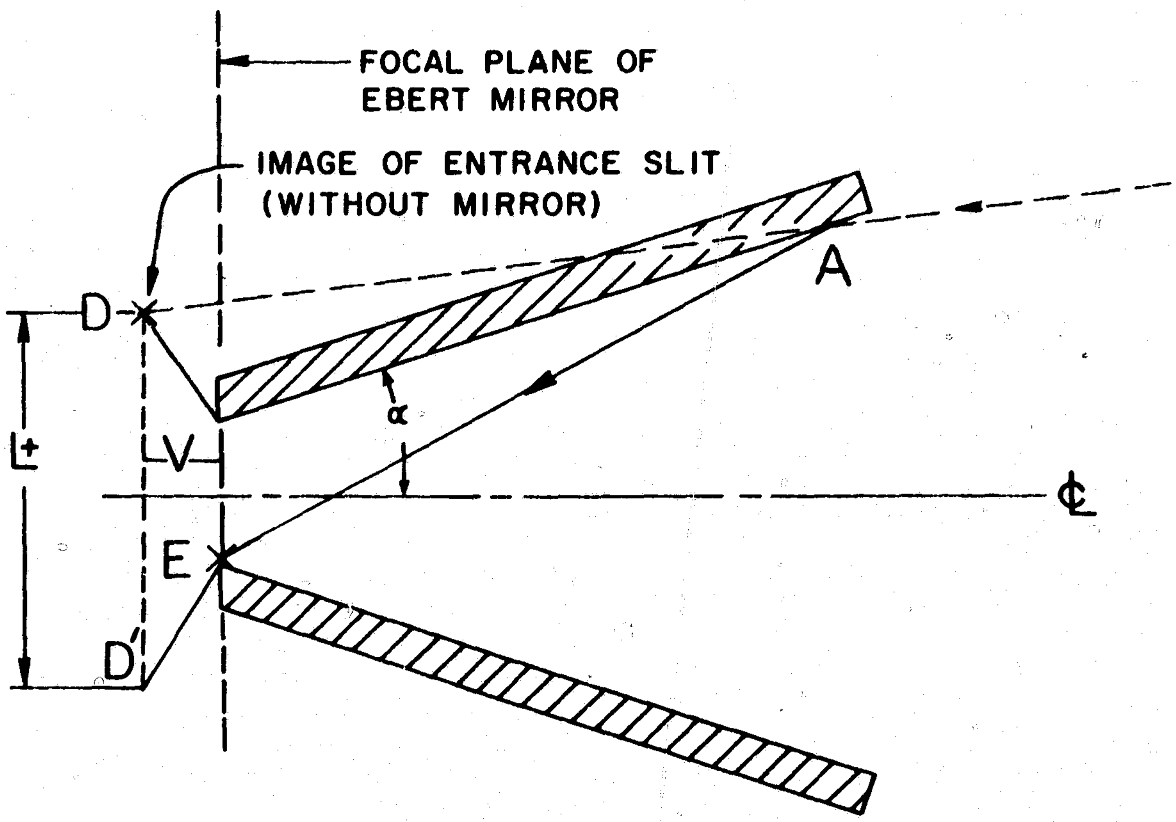

Fig. 3 Side View of Slit Mirrors Showing Reflected Slit Image E in Focal Plane.

II. DESCRIPTION OF EXIT SLIT MIRRORS

The exit slit mirrors, as shown in a side view in Fig. 1 are placed with one end adjacent to the exit slit plane, and positioned at the angle α so that the other end of the mirrors will intercept the extreme rays from the Ebert mirror. The separation between the slit mirrors at the focal plane is slightly greater than 1/3 the slit length. The image of the slit end at point B is at point C, such that the distance AB = AC. Thus the slit mirrors produce an out of focus image of the ends of the slit image.

This defect can be corrected by making the entrance slit in three sections as shown in a side view in Fig. 2. The upper and lower third of the entrance slit is angled in toward the Ebert mirror so that the ends of the entrance slit image at D (Fig. 3) falls a distance outside the focal plane but the reflected image at E is in the focal plane, that is the distance AD equals AE. It should be noted that the distance V between the ends of the entrance slit image (L+, Fig. 3) is greater than the distance between the ends of the entrance slit (L, Fig. 2) because of magnification, which amounts to $\frac{F + V}{F - V}$ where F is the focal length of the Ebert mirror.

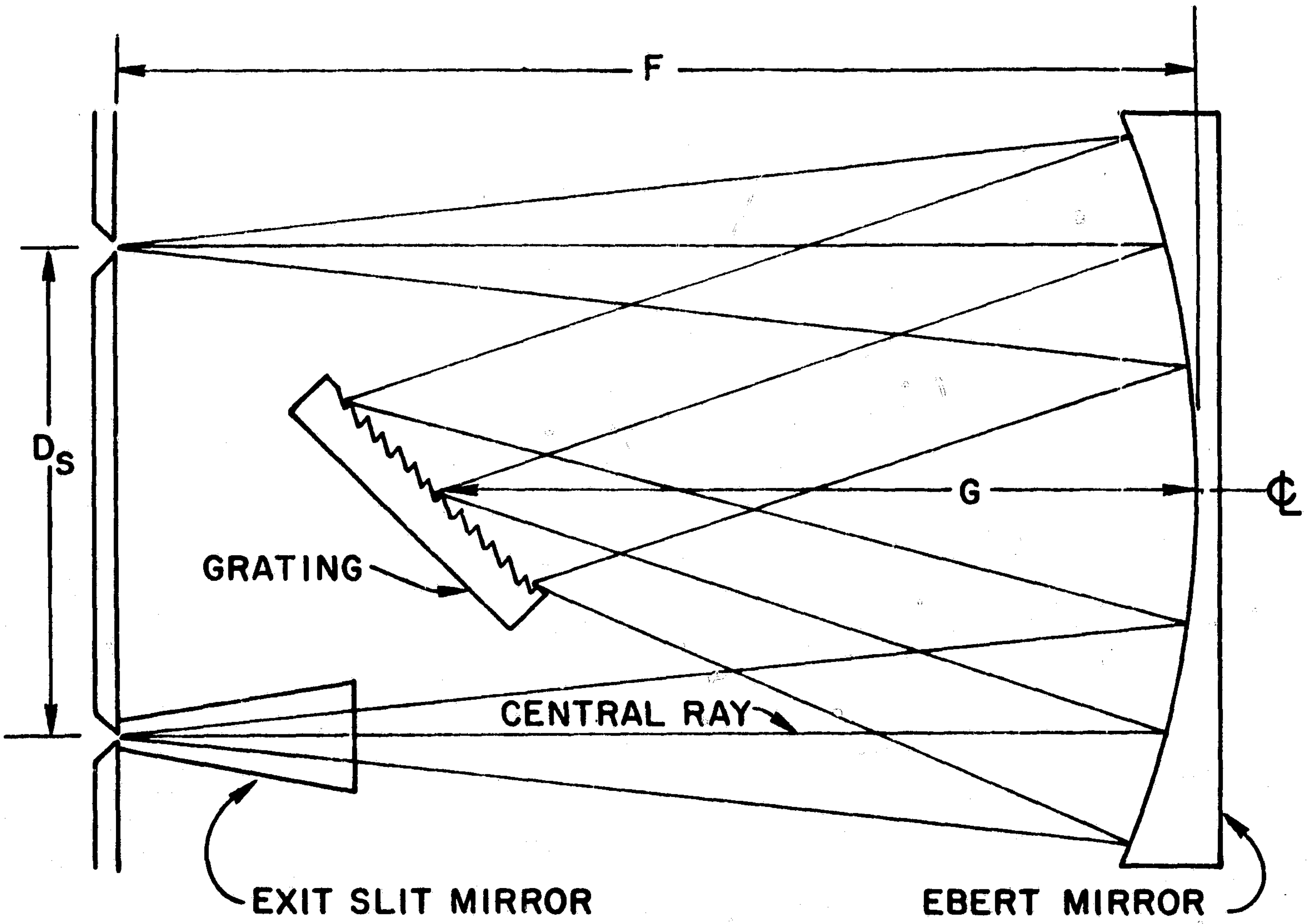

Fig. 4 Plan View of Ebert Spectrometer Showing Location of Truncated Exit Slit Mirrors.

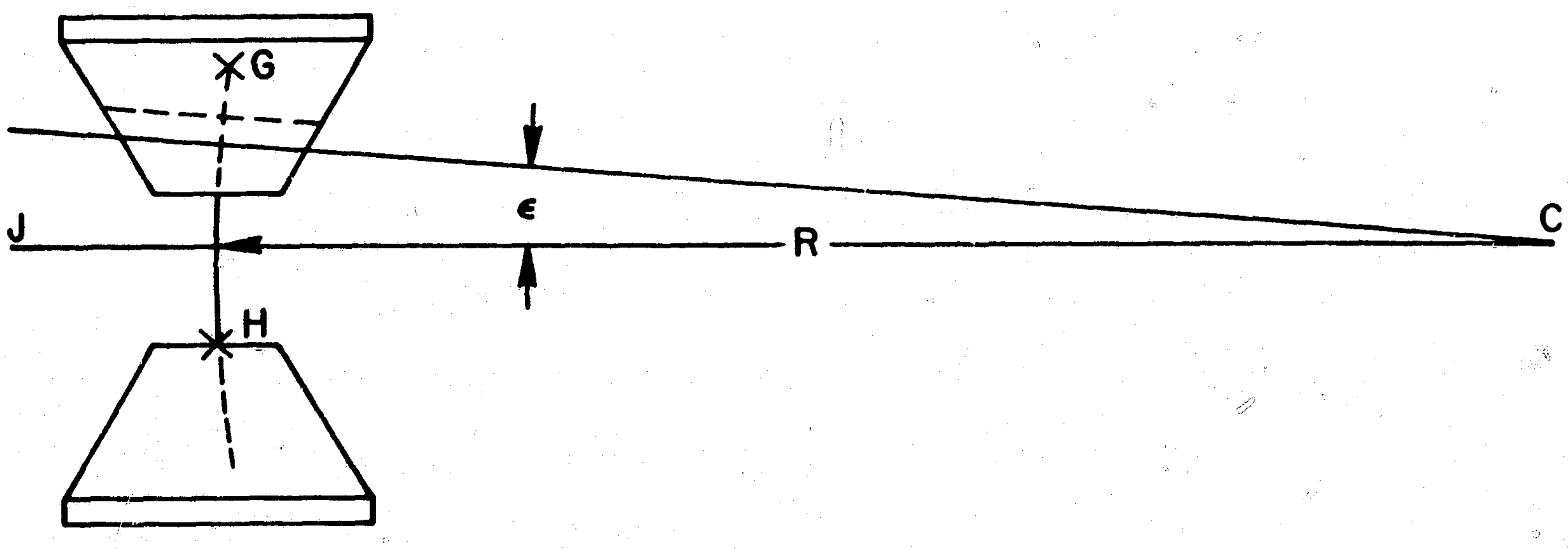

Fig. 5 End-on View of Exit Slit Mirrors Showing Tilt to Correct for Spectral Curvature.

The exit slit mirrors can be truncated as shown in Fig. 4, which is a plan view of the Ebert system, and their center line in this plane should be coincident with the central ray which angles outward slightly if the grating is placed inside the focal plane.

Whether the entrance slit is straight or circularly curved (in the focal plane) the entrance slit image will be circularly curved, but the exit slit mirrors can be tilted as shown in Fig. 5 where R is the radius of curvature of the entrance slit image and the line JC is in the focal plane and passes through the plane of the exit mirror. The line JC is perpendicular to the line GH which ensures that the end of the slit image at G will fall on the exit slit at H. If the slits are curved on the Ebert circle, R will be the radius of curvature of the Ebert circle. If the entrance slit is straight, the entrance slit image will be curved away from the entrance slit if the grating faces the entrance slit half of the system (as shown in Fig. 4) and toward the entrance slit if the grating faces the exit slit section. The spectral curvature of the entrance slit image depends upon the grating constant and can be calculated from Minkowski's formula

$$\Delta \lambda = \frac{\lambda L^2}{8 F^2} \qquad (1)$$

where L is the slit length

λ the wavelength

$\Delta\lambda$ the wavelength error

F the focal length

The sagitta of the curved image is given by

$$S\,(mm) = \frac{\Delta\lambda}{R_D} \tag{2}$$

where R_D is the reciprocal dispersion in A/mm.

The radius of curvature R is given by the sagittal formula

$$R = \frac{L^2}{8S} \tag{3}$$

combining (1), (2) and (3)

$$R_{(mm)} = \frac{R_D(\text{A/mm})}{\lambda\,(\text{A})} \quad F^2(mm) \tag{4}$$

III. THE EBERT CIRCLE

The conditions under which diffraction limited resolution can be achieved in an Ebert grating spectrometer with slits curved along the Ebert circle were described two decades ago.[2] In general, at f/10, where spherical aberration is negligible, theoretical resolution is achievable with slit to focal length ratios as large as 0.25.

It would appear that the use of the exit slit mirrors described above will not decrease the spectral resolution when curved slits are used, but will provide increased energy density at the detector.

There are many practical applications of the exit slit mirror system for which straight slits are desirable, including adaptation to existing systems, and applications where the more precise adjustments required for curved slits are impractical. In the specific application for which the exit slit mirror system was designed only moderate resolution was required and it was desirable to use an external baffle to exclude scattered light from a linear horizon, which could be done most effectively with a straight-edged baffle and with a straight entrance slit.

IV. EFFECT OF ASTIGMATISM

When straight slits are used there are two sources of errors, astigmatism and entrance slit image curvature which varies with wavelength.

The length of a point image in the Ebert spectrometer can be derived with the use of Coddington's formulas

$$\frac{1}{F\cos\phi} = \frac{1}{O_D^V} + \frac{1}{I_D^V} \qquad (5)$$

and

$$\frac{\cos\phi}{F} = \frac{1}{O_D^H} + \frac{1}{I_D^H} \qquad (6)$$

where ϕ is the off axis angle of the spherical mirror

O_D and I_D are the various image and object distances.

Placing O_D^V = F cos ϕ, the distance ΔF between the vertical and horizontal images can be derived from Eqs. (5) and (6) and is

$$\Delta F = 2F\phi^2 \tag{7}$$

and the length of the image is

$$\Delta L = \frac{2F\phi^2}{f} \tag{8}$$

where f is the f number, defined here as the ratio of the focal length of the width of the grating (Wg) which is assumed to be square.

At the center of the slit, the astigmatism causes no loss of resolution because the line image of the center point of the entrance slit is parallel to the exit slit. However, at the end of the slit the line image is canted with respect to the exit slit as shown in Fig. 6. The projected width Δ W of the line image in a direction perpendicular to the exit slit is

$$\Delta W = \Delta \frac{LxL}{D_s} \tag{9}$$

where D_s is the distance between the entrance and exit slits.

The off axis angle ϕ for the central ray is given by (see Fig. 4)

$$\phi = \frac{D_s}{2F} - \frac{D_s G}{4F^2} \tag{10}$$

For the usual value G = .8F

$$\phi = \frac{.3D_s}{F} \tag{11}$$

Combining (8), (9), and (11)

$$\Delta W = \frac{.18\ L\ D_s}{f\ F} \tag{12}$$

and the spectral width at the end of the slit

$$d\lambda = \Delta W R_D = \frac{.18\ L\ D_s R_D}{f F} \tag{13}$$

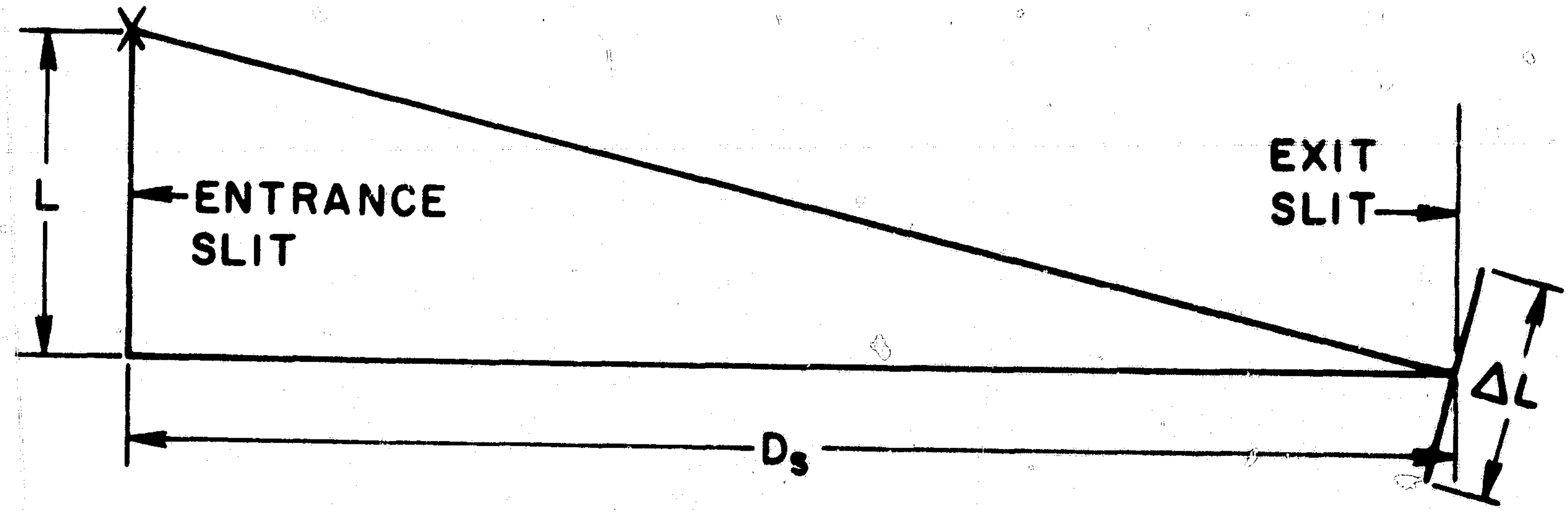

Fig. 6 Diagram of Slit Plane Showing Astigmatic Image of Length ΔL at End of Slit Image.

where as before R_D is the reciprocal dispersion in A/mm.

Equation 13 demonstrates that the astigmatism error increases linearly with slit width, whereas spectral curvature error (Eq. 1) increases as the square of the slit length. However, the technique of tilting the slit mirrors (described in Section II) reduces the spectral curvature error at a chosen wavelength by a factor of 9 but cannot reduce the astigmatism error. Therefore Eq. (13) describes the limit of spectral resolution which can be achieved with straight slits at a chosen wavelength. It should be recognized that Eqs. (1) through (13) contain simplified approximations which do not produce significant errors or affect the conclusions.

At another wavelength λ_e spectral curvature will produce additional wavelength error $\delta\lambda$, which from Eq. (1) will be

$$\delta\lambda = (\lambda_e - \lambda) \frac{(L^2)}{8F^2} \tag{14}$$

where λ is the wavelength for which the slit mirrors were adjusted to correct for spectral curvature.

Thus the parameters L, D_s, R_D, f and F can be chosen for a given application to minimize the total wavelength error in the spectral image when straight slits are employed.

V. EXPERIMENTAL RESULTS

We have built and flown in a rocket a scanning Ebert grating spectrometer employing exit slit mirrors. The instrument was a pre-prototype of a spectrometer which will orbit the moon in the Apollo 17 command module to measure the composition temperature and density of the atomic lunar atmosphere, using resonance reradiation of solar far ultraviolet emissions in the range 1200 to 1700A as the method of detection.

The instrument employed the optical parameters shown in Table I.

Table I

Focal length (F)	500 mm
Entrance slit length (L)	57 mm
Exit slit length	22 mm
Distance between slits (D_s)	160 mm
f Ratio (F/W_g)	5
Central wavelength (λ)	1450A
Extreme wavelength (λ_e)	1700A, 1200A
Reciprocal dispersion (R_D)	5.5A/mm
Slit Width	2 mm
Spectral Slit Width	10 A

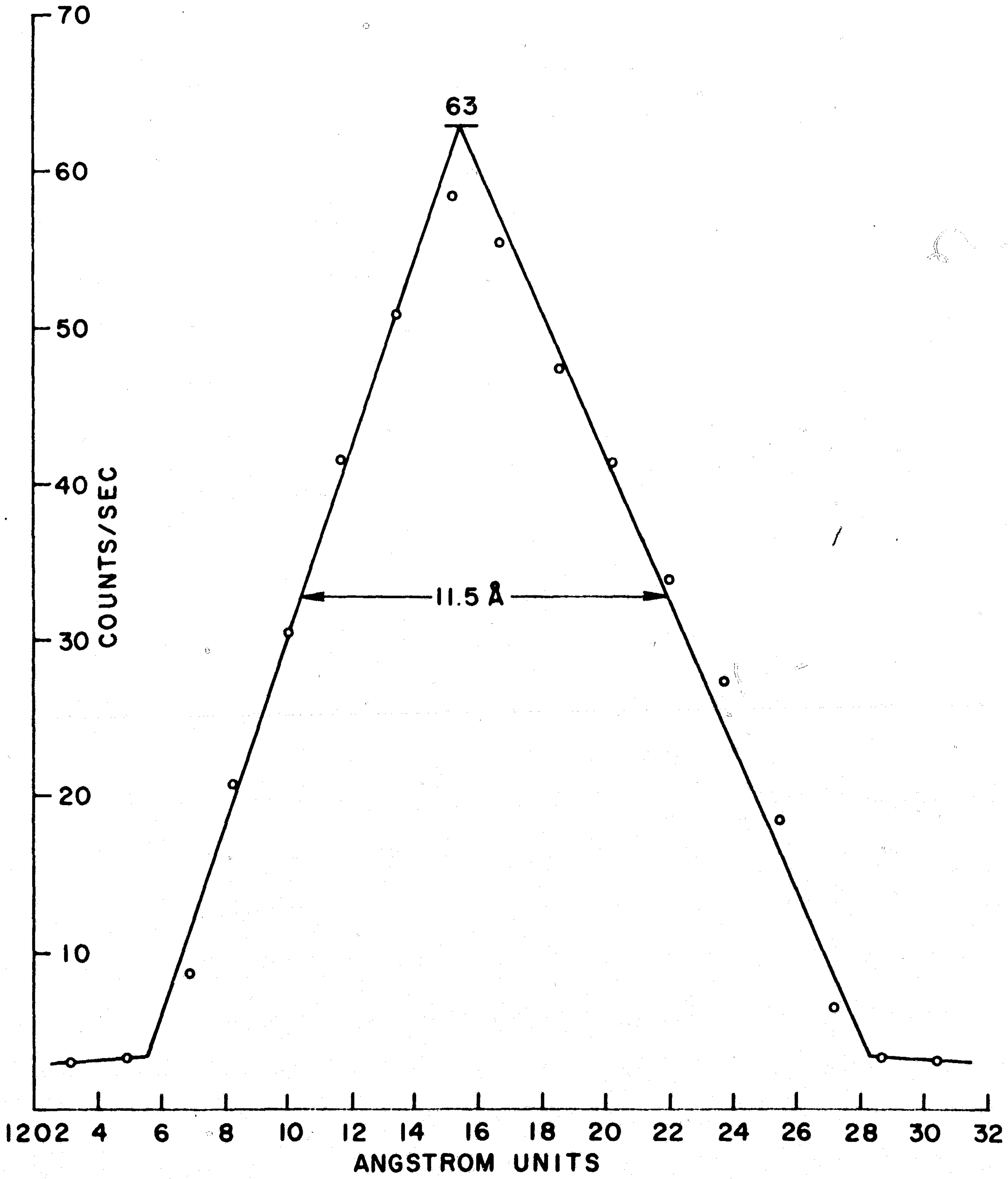

Fig. 7 Plot of Flight Spectral Data Showing 11.5 Å Half Width. Physical Slit Widths were 10 Å.

Based on these parameters and Eqs. (13) and (14) we would expect the following spectral resolution

at the center of the slit		10 A (slit width)
from Eq. 13	$d\lambda$ =	3.55 A
from Eq. 14	$\delta\lambda$ =	0.4 A

Based on these calculations the average observed spectral resolution would be expected to be about 12 A.

Figure 7 shows the spectrum of the day airglow emission at Ly α (1216A) which was recorded with the preprototype spectrometer during the rocket flight. The inflight observed half width of the Ly α line was about 11.5 A, providing confirmation of the above optical analysis.

The measured optical efficiency of the exit slit system was about 80%, based on measured reflectivities of about 70% at the grazing angles at which the mirrors were employed and on the fact that no exit slit mirror reflection was required for the central section of the entrance slit image. The mirrors were bare aluminum, oxydized in air.[5]

The preflight measured and inflight observed overall sensitivity of the spectrometer also confirmed that the exit slit mirrors were effective. The sensitivity was 30 photoelectrons per second per Rayleigh (a Rayleigh is a brightness unit of $\frac{10^6}{4\pi}$ photons/sec/cm^2/steradian). This sensitivity was two to three times greater than we had achieved in earlier rocket experiments.

VI. ACKNOWLEDGEMENTS

The analytical work described herein was supported by NASA Contract NAS 9-11528.

The rocket experiment described herein was supported by a grant between the National Aeronautics and Space Administration and The Johns Hopkins University (NGR 21-001-001). Dr. John Osantowski (see Ref. 5) of the Goddard Space Flight Center provided advice and analyses with respect to mirror coatings. Mr. Milton Nemec, JHU Department of Physics shop foreman, designed and constructed most of the preprototype instrument.

REFERENCES

1. Wm. G. Fastie, J. Opt. Soc. Am. 42, 641 (1952).
2. Wm. G. Fastie, J. Opt. Soc. Am. 42, 647 (1952).
3. H. M. Crosswhite and Wm. G. Fastie, J. Opt. Soc. Am. 46, 110 (1956).
4. William Benesch and John Strong, J. Opt. Soc. Am. 41, 252 (1951).
5. W. R. Hunter, J. F. Osantowski and G. Hass, Appl. Opt. 10, 540 (1971).