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(NASA-CR-150774) THREE-MIRROR SPACE TELESCOPE, VOLUME 2 Final Report (TAI Corp., Huntsville, Ala.) 23 p HC A02/MF A01 CSCL 03A

N78-31016

Unclas G3/89 28559

THREE-MIRROR SPACE TELESCOPE

FINAL REPORT, VOL. II

By

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Prepared For

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
MARSHALL SPACE FLIGHT CENTER, ALABAMA

Contract NAS8-32829

July 1978

SUMMARY

This volume summarizes the results of a complete redesign and re-optimization of the anastigmatic three-mirror telescope that was first introduced in NASA TMX-73326 "STARSAT - A SPACE ASTRONOMY FACILITY." The purpose of this task was to improve the optical system and increase its versatility.

First, a more compact system was obtained by decreasing the primary focal ratio from 2.2 to 2.0. Secondly, a high performance Rowland spectrograph that uses only a total of three reflections and does not interfere with the imaging process, was successfully incorporated into the telescope so that it could be a permanent part of the system. Finally, the usefulness of this telescope concept as a high resolution coronagraph is being demonstrated.

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1. INTRODUCTION

The performance of ground-based telescopes is principally limited by the Earth's atmosphere. The turbulent atmosphere not only limits the resolution to approximately 1 arcsec, but also absorbs large portions of the electromagnetic spectrum. The capability to place a telescope into space and perform extraterrestrial observations without interference from the atmosphere provides new opportunities for major advancements in the field of observational astronomy. The design of new instruments with the capability to utilize all the advantages of an extraterrestrial station is a desirable as well as demanding task.

The Ritchey-Chretien, an improved version of the classical Cassegrain Telescope, is today's most popular telescope. This two-mirror system, however, provides only a high resolution field of a few arcmin and has a curved image surface. To widen and flatten the field, the Ritchey-Chretien telescope is normally used in combination with refractive correctors, the transmission of which is essentially limited to the visible portion of the spectrum. The transmission range of a reflective surface and of a refractive corrector, both optimized for ultraviolet transmission, are shown in comparison with the atmospheric window in the vicinity of the visible spetrum in Figure 1.1. Considering the fact that one major reason for puting astronomical telescopes outside the atmosphere is to expand the obervable range of the electromagnetic spectrum, it becomes evident that an all-reflective space telescope is highly desirable. Exceeding the performance of a two-mirror telescope necessarily means increasing the number of sur-

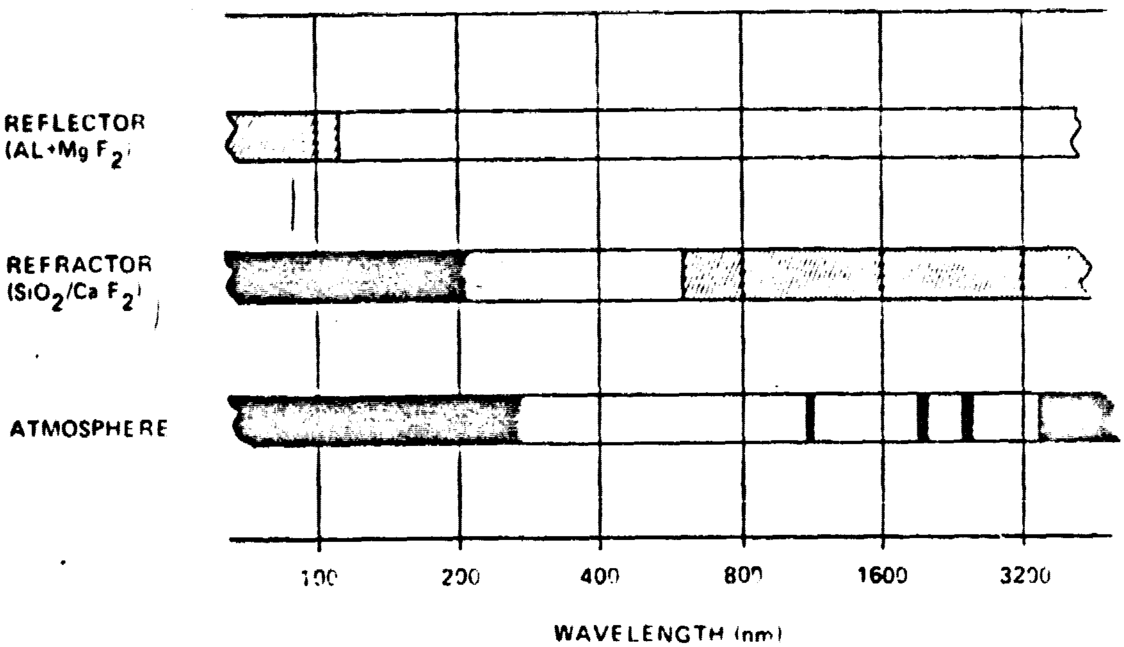


Fig. 1.1: Transmission Comparison

faces, although the addition of surfaces means a loss in transmission, particularly in the extreme ultraviolet. Todays coating techniques make it tolerable at least down to a wavelength of 110 nm according to measurements made by Itek (1) (see Fig. 1.2)

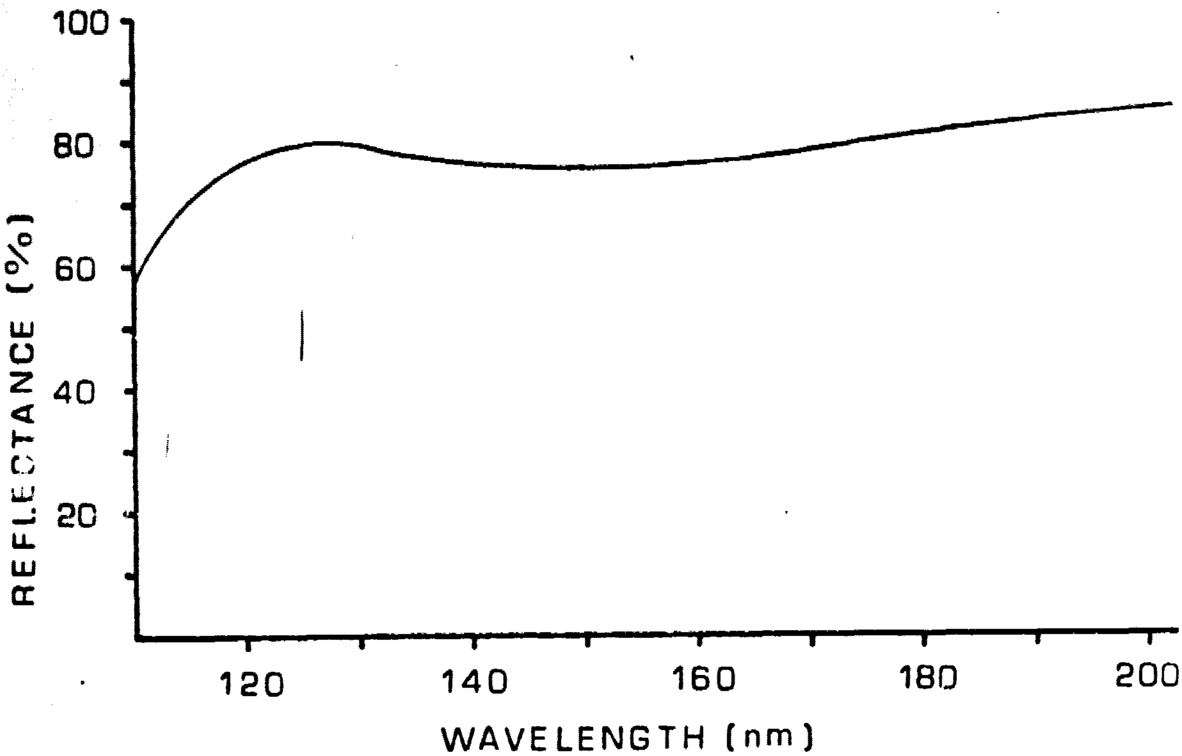


Fig. 1.2: UV-Reflectance of Aluminum overcoated with 200Å of MgF_2.

Several three-mirror telescopes have been proposed in the past (2-8), none of which provides a practical and useful solution. Examples of the most typical configurations are shown in Figure 1.3. The main shortcomings of the types a, b, and c are the inacessibility of the image plane, the large central obscuration, and the practically invariable fast focal ratio forced by the configuration. A special class of tilted- component tele-

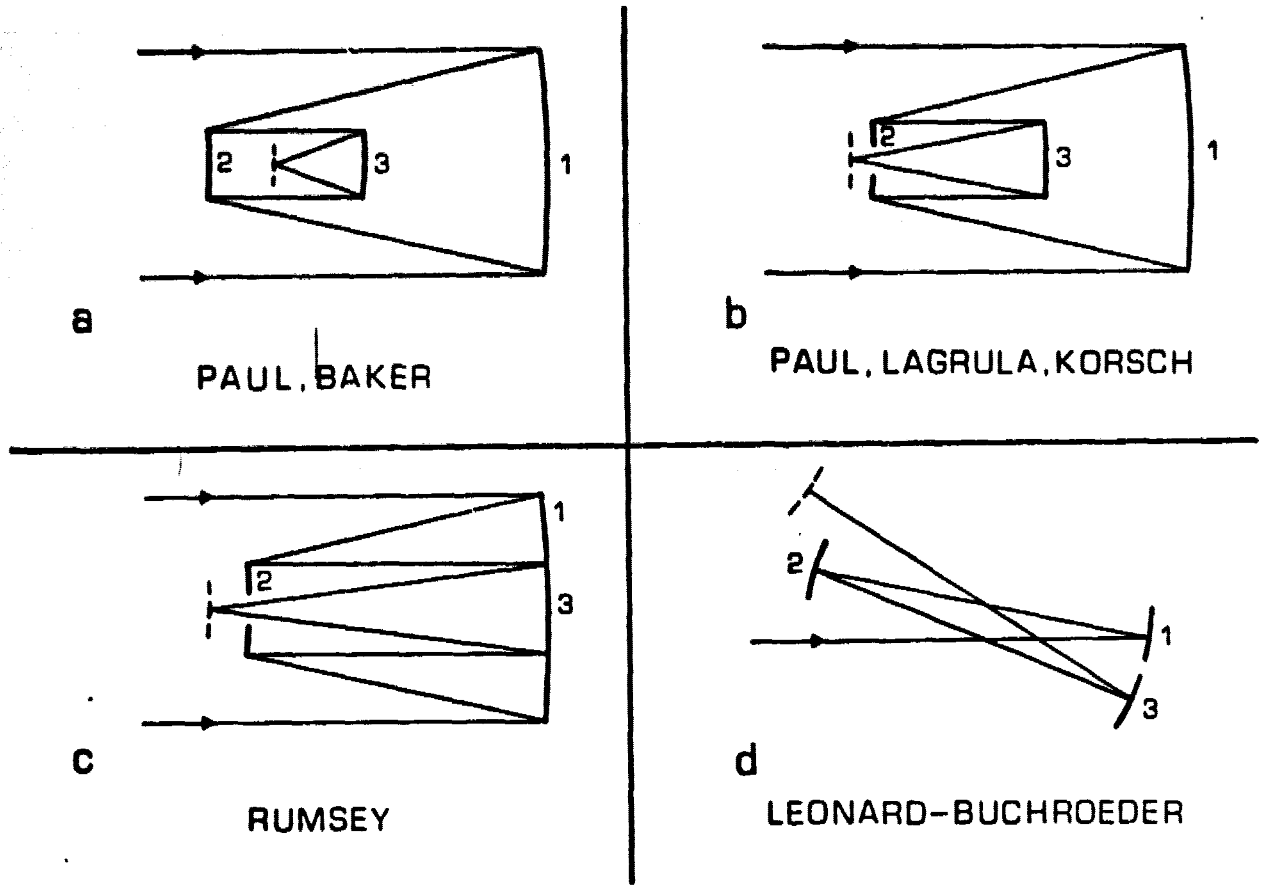


Fig. 1.3: Example of previous Three-Mirror Telescope Designs

scopes is summarized in a report by Buchroeder (9); Figure 3d is one example. Apart from the fact that the largely asymmetric configurations are not very attractive, none of the designs meets the requirements of a high performance space telescope.

2. DESIGN

While any practical two-mirror telescope configuration can only be corrected for maximally two aberrations, usually spherical aberration and coma, the three-mirror telescope presented here is corrected for four aberrations: spherical aberration, coma, astigmatism, and field curvature. The primary/secondary configuration resembles the Cassegrain, forming a real image closely behind the primary (Fig. 2.1. This secondary image is

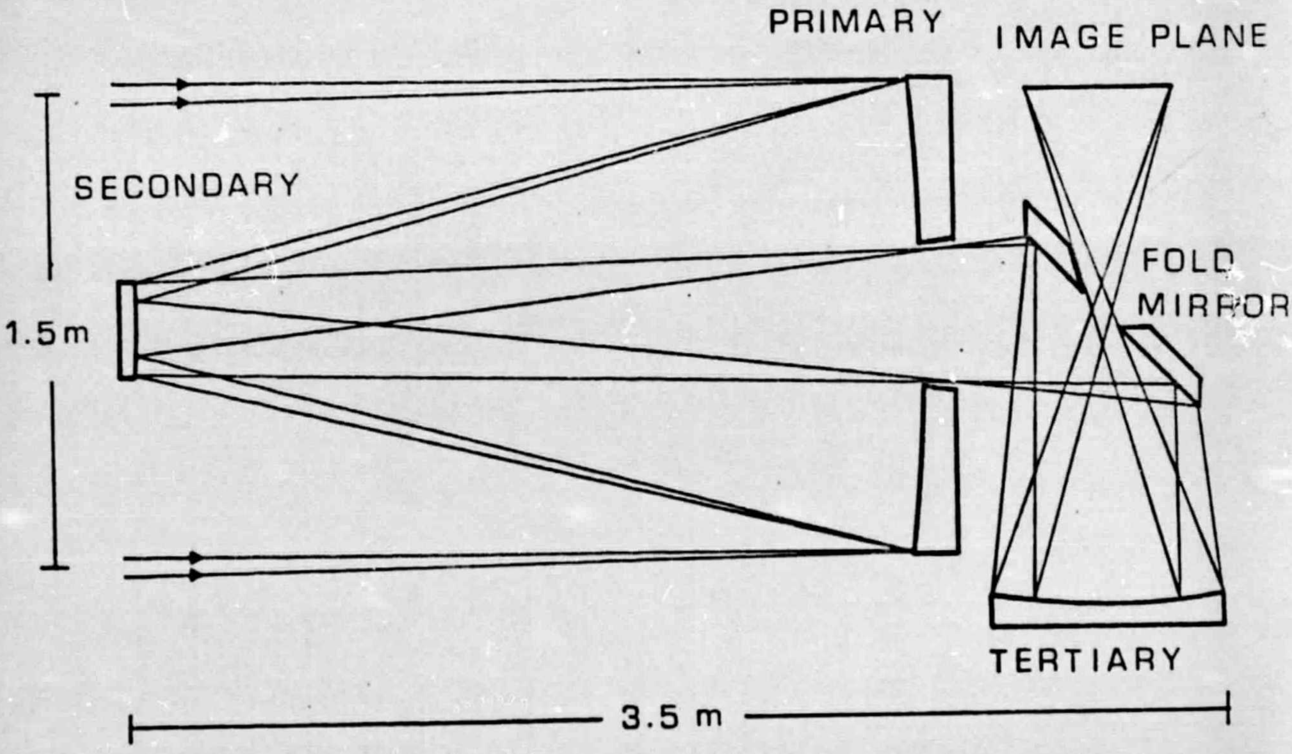


Fig. 2.1: The Three-Mirror Telescope Configuration

then reimaged by a tertiary mirror at approximately unit magnification. To gain accessibility of the final image plane, a perforated fold mirror is placed diagonally between primary and tertiary. The design parameters are summarized in Table 1.1. The difference to the designs introduced in refs. 10 and 11 is in the faster primary mirror allowing an even more compact design. An isometric view of the concept is shown in Fig. 2.2.

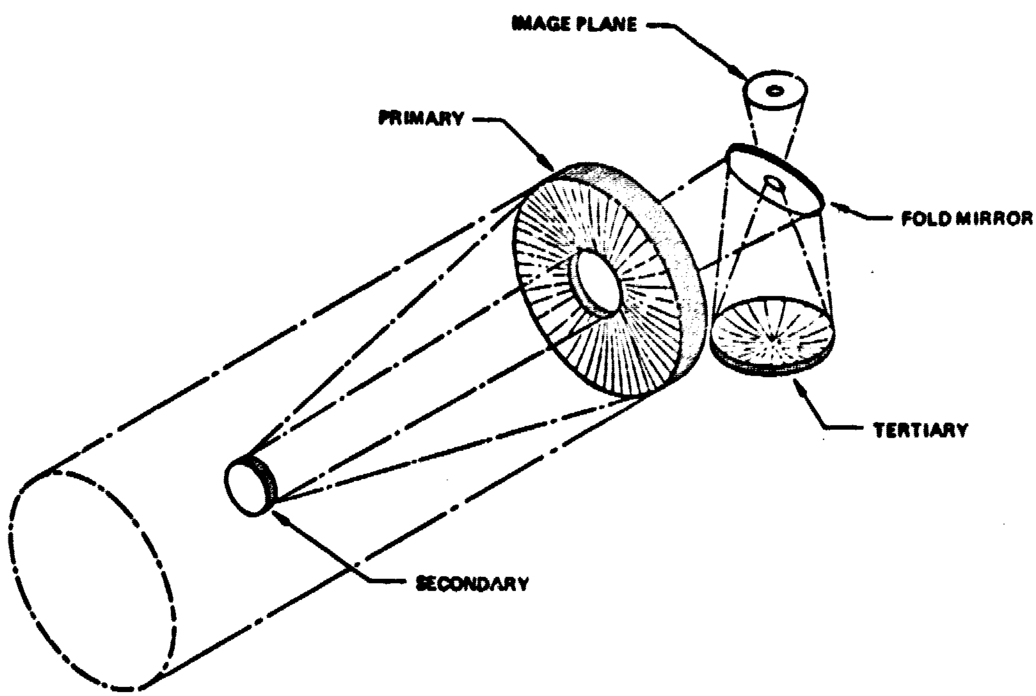


Fig. 2.2: Isometric View of the Three-Mirror Design Concept

TABLE 1.1: Telescope Parameters

Clear Aperture	150 cm
Primary F-No.	2
System F-No.	12
System Focal Length	1800 cm
Secondary Diameter	31.8 cm
Tertiary Diameter	74.8 cm
Exit Pupil Diamter	9.8 cm
Secondary Image Diameter	21.07 cm
Final Image Diameter	48.16 cm
Primary Radius	600.0000 cm
Secondary Radius	121.1212 cm
Tertiary Radius	149.8381 cm
Primary Deformation	-0.972080362
Secondary Deformation	-1.858186567
Tertiary Deformation	-0.549638336
Distance:	
Primary-Secondary	250.9124 cm
Secondary-Tertiary	400.0000 cm
Tertiary-Exit Pupil	91.0000 cm
Exit Pupil-Image Plane	69.0000 cm

3. ANALYSIS

3.1 Performance

This telescope provides a flat image field of 1.5° in diameter with a geometric rms spot size not larger than 0.05 arcsec anywhere in the field. Only a central portion of ± 15 arcmin is partially vignetted (fig. 3.1).

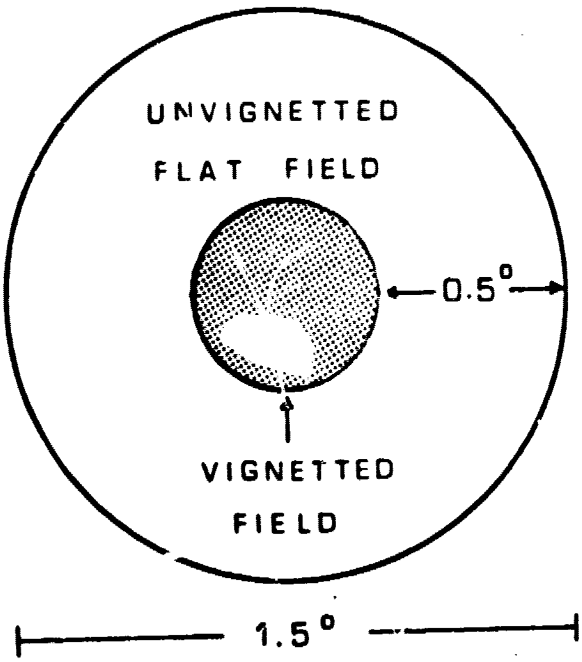


Fig. 3.1: Field of the Three-Mirror Telescope

The performance of the three-mirror telescope is demonstrated in Fig. 3.2 where it is compared to the performance of a Ritchey-Chretien telescope. The geometric spot size, i.e. the diameter of the smallest circle surrounding all rays traced through the system, is plotted as a function of the field angle. The superior performance of the three-mirror telescope is not only reflected in the significantly smaller spot size, but also in the fact that it was determined in a flat field while the best performance of the Ritchey-Chretien is on a curved surface.

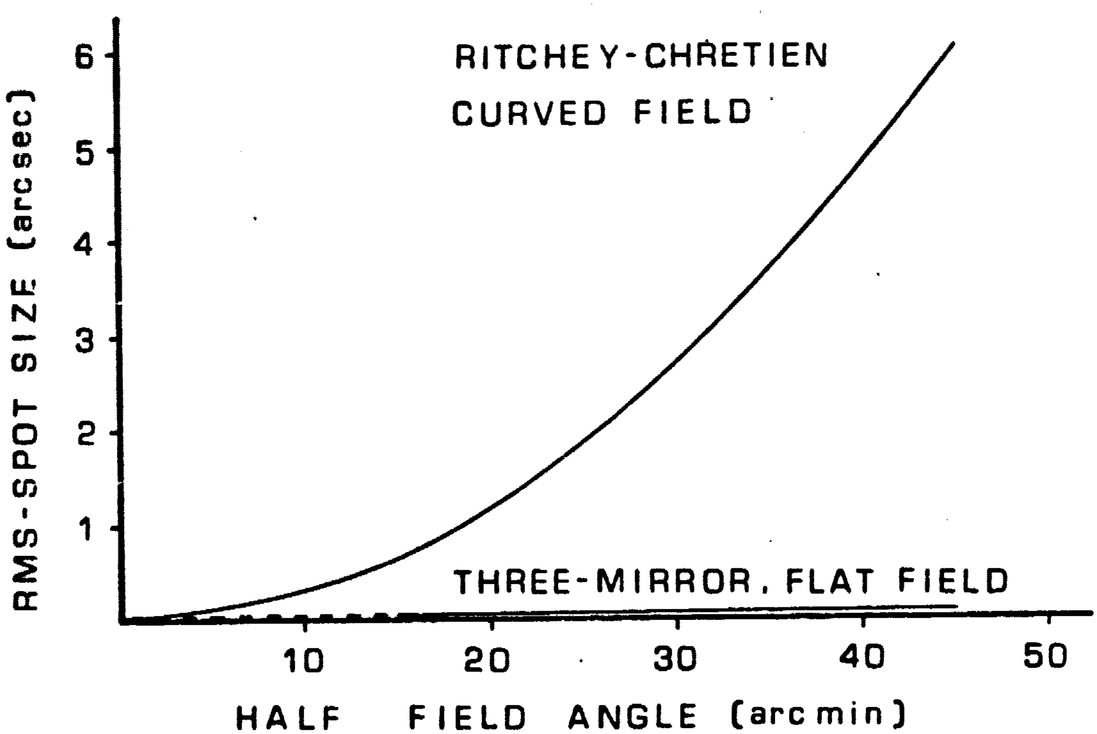


Fig. 3.2: Performance Comparison with the Ritchey-Chretien

3.2 Misalignment Sensitivities

Although it is common practice to determine the misalignment sensitivities of an optical system relative to the well-focused point image on-axis, this method is mostly unrealistic because a real detector is generally located in some compromise focal plane causing the sensitivities to vary markedly as a function of the field position. The misalignment sensitivities of the secondary and tertiary mirrors given in Table 1.2 are the maximum rms-spot increases in the best compromise flat focal plane over the entire 1.5° field, and therefore, considerably more conservative than usual. One outstanding result is the relative insensitivity of the tertiary compared to the secondary mirror.

TABLE 1.2: Misalignment Sensitivities

	INCREASE OF GEOMETRIC SPOT DIAMETER PER UNIT MISALIGNMENT
<u>SECONDARY</u>	
DESPACE	0.0160μrad/μm
DECENTER	0.0015μrad/μm
TILT	0.0120μrad/μrad
<u>TERTIARY</u>	
DESPACE	0.0100μrad/μm
DECENTER	0.0009μrad/μm
TILT	0.0032μrad/μrad

3.3 Straylight Suppression

To protect the secondary image in a Cassegrain telescope effectively from stray light requires a very complex and elaborate baffling system. One major advantage of the three-mirror telescope is the natural baffling property of this configuration. The final image plane is already well protected from stray light without adding an extra baffling system. Main reasons for this effect are the folded out image plane and the exit pupil behind the tertiary forming a bottleneck in the optical train.

A preliminary analysis made by Martin Marietta (12) indicates that the straylight suppression capability of this three-mirror telescope exceeds that of a typical Cassegrain configuration by several orders of magnitude.

4. INCORPORATION OF A ROWLAND SPECTROGRAPH

It is possible to incorporate a high-resolution ultra-violet Rowland Spectrograph into the three-mirror configuration that uses no more than a total of three reflections including the grating (see Fig. 4.1). The primary-secondary system forms a 26μm star image in the plane of the baffled slit located in the back of the hole of the primary mirror. The spectrum

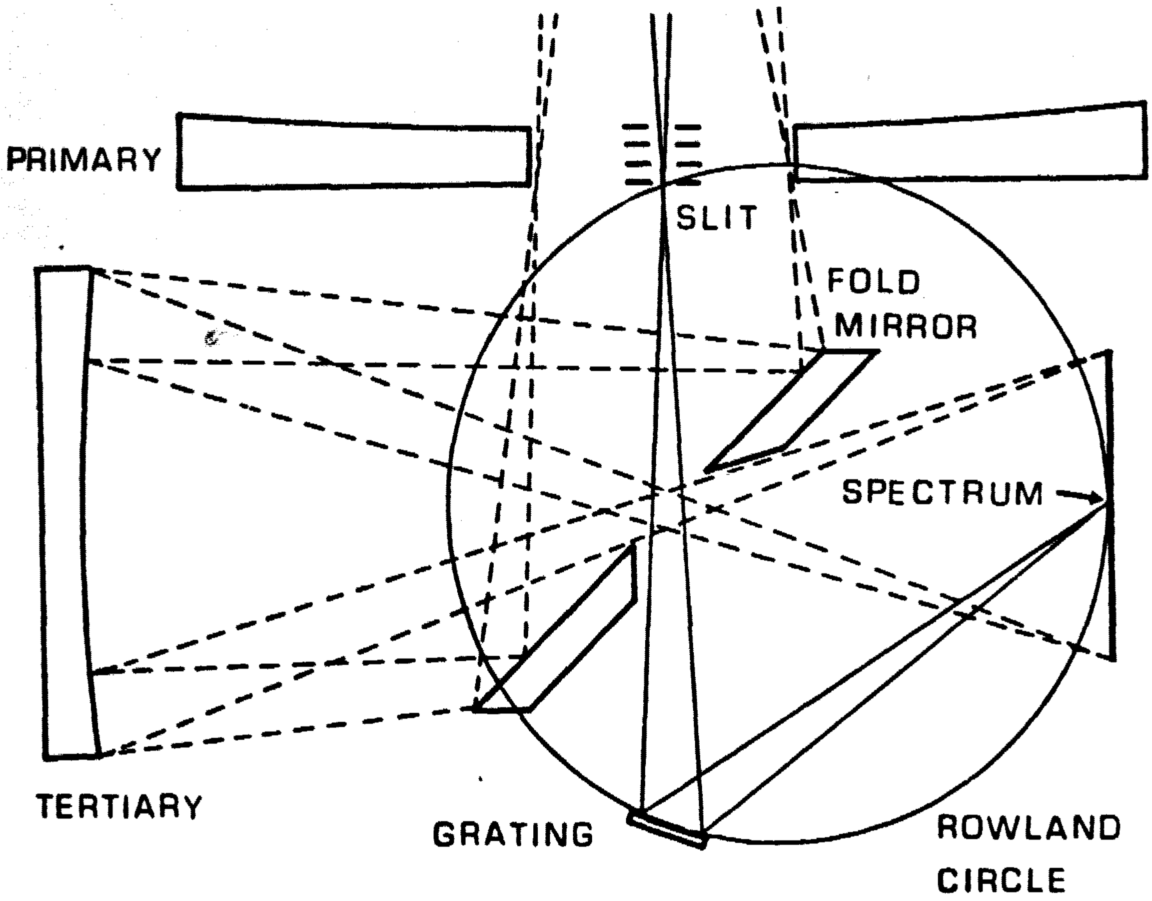


Fig. 4.1: Rowland Spectrograph Incorporated into the Three-Mirror Telescope Configuration

is then reflected by the concave (conventional or holographic) grating into the vignetted and therefore unused central portion of the final image field.

To estimate the spectral resolution,

$$R = \lambda/d\lambda$$

that can be achieved with this Rowland spectrograph configuration we use the grating equation,

$$k\ n\ \lambda = \sin\alpha - \sin\beta$$

where k = order of the spectrum,

n = number of grooves per unit length,

λ = wavelength,

α and β are the angles of incidence and deflection as shown in Fig. 4.2.

The first derivative of the grating equation yields the angular dispersion,

$$\frac{d\beta}{d\lambda} = \frac{kn}{\cos\beta} ,$$

and the linear dispersion is obtained by multiplying the angular dispersion by the distance, s, from the grating to its spectrum,

$$\frac{dL}{d\lambda} = s.\ \frac{d\beta}{d\lambda} = \frac{kns}{\cos}$$

If dL is regarded a resolution element of the spectrum, then dL must be comparable with the image of a star in the plane of the spectrum. The radius of the star image (a measure of the limiting resolution) in the spectrometer slit is 13 μm. A subsequent reduction due to the concave grating by a factor 0.85 results in a spot radius of 11 μm in the plane of the spectrum.

Using now dL = 11 μm and the following parameter values that are

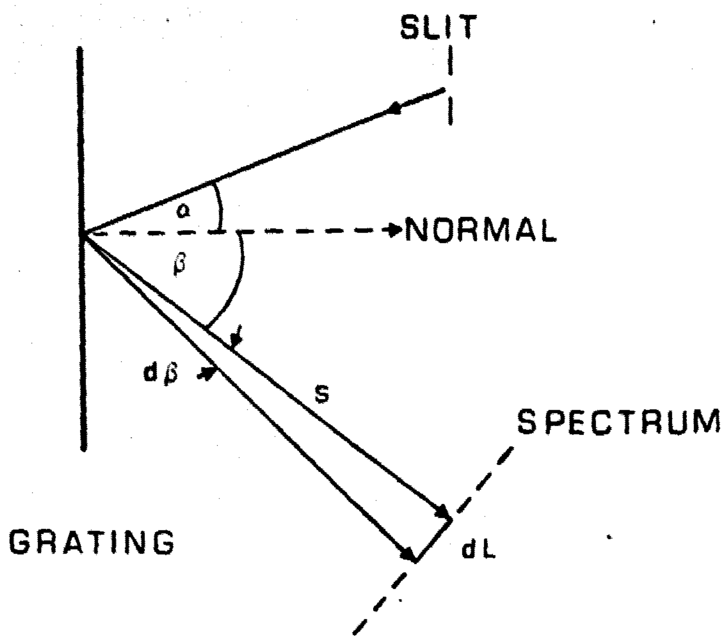


Fig. 4.2: Grating Geometry

largely dictated by the geometry shown in Fig. 4.1

$\beta = 35^0$,

$s = 740$ mm,

$n = 3600$/mm,

and k = 1 (standard value for holographic gratings), one obtains for the minimum resolvable wavelength difference,

$$d\lambda = \qquad d\lambda = \frac{dL \cos\beta}{kns} \simeq 3.4 \cdot 10^{-3} \text{nm},$$

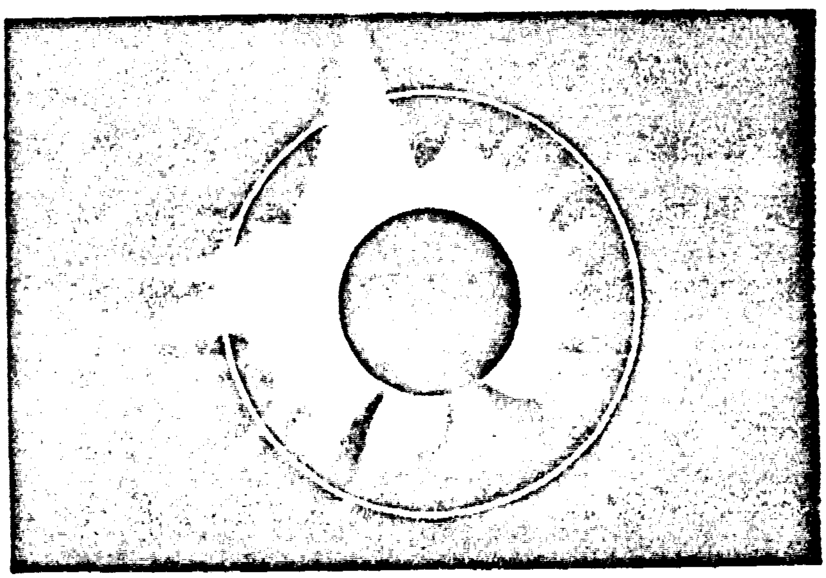
or for the spectral resolution at the wavelength of λ = 110 nm,

$$R = 3 \cdot 10^4.$$

A higher resolution could be achieved by essentially increasing the size of the spectrograph.

5. THE THREE-MIRROR TELESCOPE AS CORONAGRAPH

The annularly shaped image field of the three-mirror telescope seems to lend itself to the application of coronagraphy. The circle on the corona photograph in Figure 5.1 describes the 1.5° field with subsecond resolution provided by the telescope.



5.1: The Three-Mirror Telescope as a Coronagraph. The white circle describes the 1.5° field with subsecond resolution.

In order to get the entire field on a single photograph, the telescope design described earlier must be scaled down. Assuming the use of the readily available 9 in. film format, a suitable scale factor is 2.5, yielding a full field size of 19.26 cm in diameter. The diameter, D, of the entrance aperture is then 60 cm, and the angular width of the Airy-disk, Δ, at a wavelength of 500 nm is

$$\Delta = 2.44\lambda/D = 2\ \mu rad$$

providing a limiting resolution of about 1 μrad or 0.2 arcsec.

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