



OPTICAL SCIENCES

THE UNIVERSITY OF ARIZONA
TUCSON, ARIZONA

TECHNICAL REPORT NO. 17

PRELIMINARY DESIGN FOR A
MULTI-SPECTRAL TRACKING TELESCOPE (MSTT)

P. N. SLATER

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FOREWORD

The following report was originally prepared by P. N. Slater as a progress report on a Multi-Spectral Tracking Telescope for the Apollo Applications Program under NASA contract NSR 03-002-066. Since the work is an outgrowth from investigations supported by other contract funding at the Optical Sciences Laboratory, the report has been adapted as a Technical Report for the information of the other sponsors.

The basic design, following the Meinel-Shack three-mirror arrangement, represents a particularly excellent refinement by R. V. Shack. The extreme compactness of the design is of benefit to this application, and even though the central obscuration is large, the modulation transfer function remains satisfactory for the widely-used reconnaissance films.

--A. B. Meinel



0 1 FT.
APPROXIMATE SCALE

MULTI-SPECTRAL TRACKING TELESCOPE

COWET, 22 FEB 67

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INTRODUCTION AND SUMMARY

This report covers the progress made from December 1, 1966, to March 1, 1967, the seventh quarter of the contract period, on NASA contract NSR 03-002-066.

This report describes only one part of the work carried out during the quarter, namely the optical design of the Multi-Spectral Tracking Telescope (MSTT). Other parts of the project that have received attention during this period, but which are not to be described here, are as follows:

(1) The work of cataloging and reporting the results of ALOTS (Automatic Lightweight Optical Tracking System) photography was completed and a report was written entitled "Summary Report on Photography Obtained With ALOTS in Support of the Earth Resources Aircraft Program." Copies were distributed to those directly concerned. The film obtained from ALOTS photography will be deposited at the Data Bank NASA/MSC Houston, as will additional copies of the report.

(2) Tolerance analyses are being computed for the MSTT optical design. The effect on image quality of errors due to defocusing, and component tilt and decentering are being considered in detail.

(3) Experiments have been initiated to test the feasibility of obtaining high-resolution aerial photographs using a Questar telescope-camera mounted in a Fairchild-Hiller Heli-Porter aircraft.

(4) The feasibility of including a Questar telescope-camera in an early Apollo mission is being urgently investigated. A recommendation on this subject will await the results of forthcoming aircraft experiments (3, above) and further information on the results of Questar photography from the Gemini V mission.

(5) The need for an astronaut to assist in the operation of an Earth orbital MSTT experiment is being investigated. The definition and evaluation of the role of the astronaut, and the consideration of the trade-offs between the degree of astronaut participation and the complexity of support equipment, make this a difficult problem. Several groups which have to some extent considered this problem previously are being consulted.

(6) A proposal was submitted to NASA/MSC on January 9 entitled "System Study of Multi-Spectral Tracking Telescope (MSTT) for Remote Sensing of the Earth from Earth Orbit." Approval of this proposal will allow the University of Arizona (working in conjunction with NASA/MSC), to let and monitor a subcontract for such a system study.

OPTICAL DESIGN OF THE MULTI-SPECTRAL TRACKING TELESCOPE (MSTT)

In setting a design goal for the MSTT, it was decided that considerable emphasis should be placed on designing as fast a system as possible to reduce the problem of compensating for image motion. The optical system was to be all-reflecting, and predesign work suggested that, to meet all the performance requirements, it should be designed to operate at F/5 (T/7) or F/6 (T/8.4) with a static angular resolution of 0.8 arc seconds over a 1.5° total field of view. This, then, was the goal for the optical design study.

Happily, this design goal has been not only met but surpassed by a substantial margin. The high performance potential of the final design resulted from modifications to a new and unconventional three-mirror design first investigated by R. V. Shack and A. B. Meinel.* Briefly, the system is diffraction-limited with an angular resolution of 0.2 arc seconds over its entire 1.75° field. This high performance has come as a surprise to those concerned with the program, as it far exceeds that of presently known systems of similar size.

System parameters

Some of the system parameters are as follows:

- (1) All-reflecting, basic three-mirror system with a fourth folding mirror. Image formed by one concave asphere, one plane asphere, and one convex asphere.
- (2) Full aperture 25 inches (axial aperture 24 inches).
- (3) Effective focal length 96 inches.
- (4) Obscuration ratio 62% (about 38% of light lost due to central obscuration).

*"A three-mirror flat-field photographic objective" (abstr.), J. Opt. Soc. Am. 56(4):545, 1966.

- (5) Overall barrel length 55 inches.
- (6) Six image planes situated around telescope barrel.
- (7) Stepped plane mirror at 45° to axis directs the image sequentially onto the six image planes.
- (8) Each film plane has a 400-foot capacity for 70 mm film.
- (9) Each film plane can contain a different film/filter combination, and one or more can be used as the entrance ports for compact spectrometers and/or radiometers.
- (10) The mirrors can be coated efficiently to reflect radiation from the near UV (0.3 micron) to the middle IR (30 microns). (This range can be extended substantially if necessary.)
- (11) The location of the image planes around the barrel and toward the front of the barrel simplifies the problem of film recovery during extra-vehicular activity.

Optical performance

The optical performance of the MSTT design can be summarized as follows:

- (1) Focal ratio: $F/4$
- (2) Speed: $T/5.6$
- (3) Diffraction-limited imagery over the entire 1.75° field for wavelengths greater than 1000 A. At 5000 A the angular resolution of the telescope optics alone is 0.2 arc sec.
- (4) Flat field.
- (5) Zero chromatic aberration and chromatic focal shift.
- (6) In the order of 100 lines/mm imagery should be obtainable of low-contrast scenes (1.6:1) over the entire 70 mm image format of high-resolving-power film.

(7) Distortion about 1.2 arc sec or 0.04% at edge of field.

(8) Vignetting causes negligible reduction in flux at full field.

Effects of central obscuration

The central obscuration of about 15 inches in diameter (62% of overall area) contributes largely to reducing the speed of the system to T/5.6. The obscuration is, of course, inherent in the design, and its size is mainly a consequence of the large image clearance (required to fold the image to outside the barrel), the required field size, the problem of baffling stray light from entering the image plane (at the same time keeping the barrel short), and the desirability of minimizing vignetting.

The central obscuration does reduce the frequency response (compared to an identical diffraction-limited system without obscuration) at high spatial frequencies. In fact, the comparison curves (Fig. 1) show that, in terms of frequency response, the system operates approximately like a diffraction-limited F/9 system with no obscuration. This seems to be the only penalty paid in using this design. But it must be pointed out that no other all-reflecting system has been designed which approaches the performance of this one even when operating at a speed of F/9.

The central obscuration does have some advantages. For example, although this is a compact diffraction-limited F/4 system operating with a speed of T/5.6, the tolerance on depth of focus is relaxed to about that of an F/12 system. This means that mechanical-structural deformations are more tolerable than would be the case if the image were formed by a diffraction-limited solid F/4 cone. Other advantages of the obscuration are that it allows space for the motorized stepping mirror and it reduces the barrel length required for baffling stray light.

Performance-degrading factors

It should be noted that the performance figures listed above are derived from computer calculations. Several factors inherent in construction and operation of the actual instrument will serve to degrade this theoretical performance. These are as follows:

- (1) Fabrication and alignment of the system.
- (2) Introduction of support spiders for the secondary mirror and mirror motor.
- (3) Atmospheric turbulence.
- (4) Vibration during operation.
- (5) Structural and component thermal deformation.
- (6) Inadequate image motion compensation.

Taking into account all these factors plus the film response, a reasonable estimate is that this system in orbit should yield an angular resolution in the order of 1 arc second. For low-contrast objects, the ground resolution should therefore be of the order of 1 meter from an orbital altitude of 200 km when the image is recorded on high-resolving-power black-and-white film. For relatively high-contrast objects, particularly those with clear demarcations, such as some types of vehicles and buildings and other man-made objects, the resolution may be as high as 1/2 to 1/4 meter. With lower resolution film, such as color film or fast black-and-white film used with a filter, the ground resolution will be worse but should still be adequate to resolve clearly a medium-sized family residence.

Of the six image-degrading factors listed above, the one causing the most concern at present is No. 6, the problem of inadequate image motion compensation. It was because of this problem that every effort was made in the optical design to produce a system that would be as fast as possible.

The final design, which operates at T/5.6, has significantly surpassed our earlier expectations and will allow for exposure times in the order of 1/250 second on slow, high-resolving-power, black-and-white film (SO-226). The advantages of a short exposure time are that it relaxes the tolerance on the accuracy of image motion compensation and it reduces any image blurring effects due to low frequency vibrations.* It turns out that, in gimbaling a telescope of the size under consideration to accurately track a ground target, the problem is not primarily one of realizing the telescope slew rate with sufficient accuracy but one of minimizing low-frequency vibration in the gimbal drives. The latter could be termed "servo jitter." With a system of the mass and inertia of the one considered here, the servo jitter falls mainly in the frequency range 0 to 100 cps and can be of quite large amplitude. Beyond this frequency range, however, the jitter damps out fairly rapidly. Thus there is a very real advantage in using a T/5.6 design compared to, say, a T/10 design.

Illustrations

Figs. 1 through 4 on the following pages are largely self-explanatory. Some additional comments, however, should be made with reference to Fig. 2. Each off-axis spot diagram contains 10⁴ spots. Thus it can be seen immediately that the heavy nucleus of spots in each diagram is contained within a circle of about 1 micron diameter, even in the worst case (53' off axis). The areas of low spot density in each diagram can be ignored in comparing the spot diagram size to the reference circles on the left of the figure.

*R. V. Shack, "The influence of image motion and shutter operation on the photographic transfer function," Appl. Optics 3(10):1171-1181, 1964.

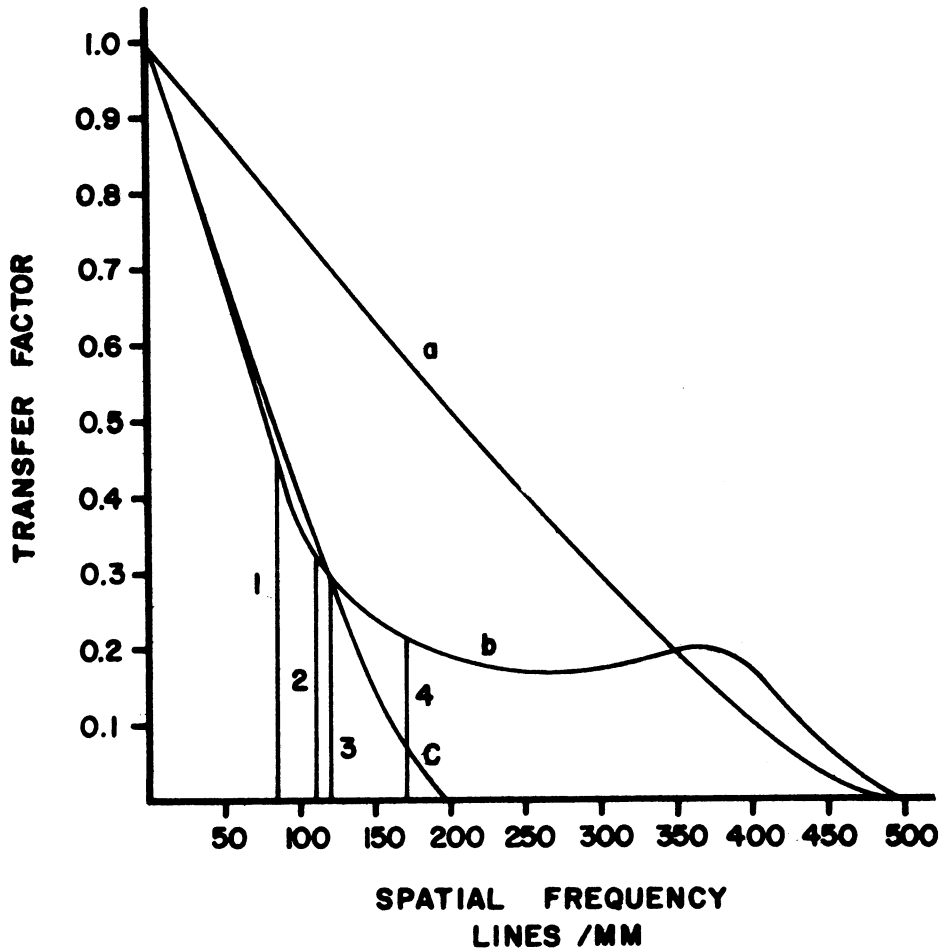


FIGURE 1: FREQUENCY RESPONSE CURVES

- (a) F/4 DIFFRACTION LIMITED SYSTEM WITH NO OBSCURATION
- (b) F/4 DIFFRACTION LIMITED SYSTEM WITH 60% OBSCURATION (THE MSTT DESIGN)
- (c) F/9 DIFFRACTION LIMITED SYSTEM WITH NO OBSCURATION (MATCHES CURVE (b) OVER MOST OF THE SPATIAL FREQUENCIES OF INTEREST)
- (1) CUT-OFF FREQUENCY FOR SO-226 WITH OBJECT CONTRAST OF 1.6:1
- (2) CUT-OFF FREQUENCY FOR SO-243 WITH OBJECT CONTRAST OF 1.6:1
- (3) CUT-OFF FREQUENCY FOR SO-226 WITH OBJECT CONTRAST OF 4:1
- (4) CUT-OFF FREQUENCY FOR SO-243 WITH OBJECT CONTRAST OF 4:1

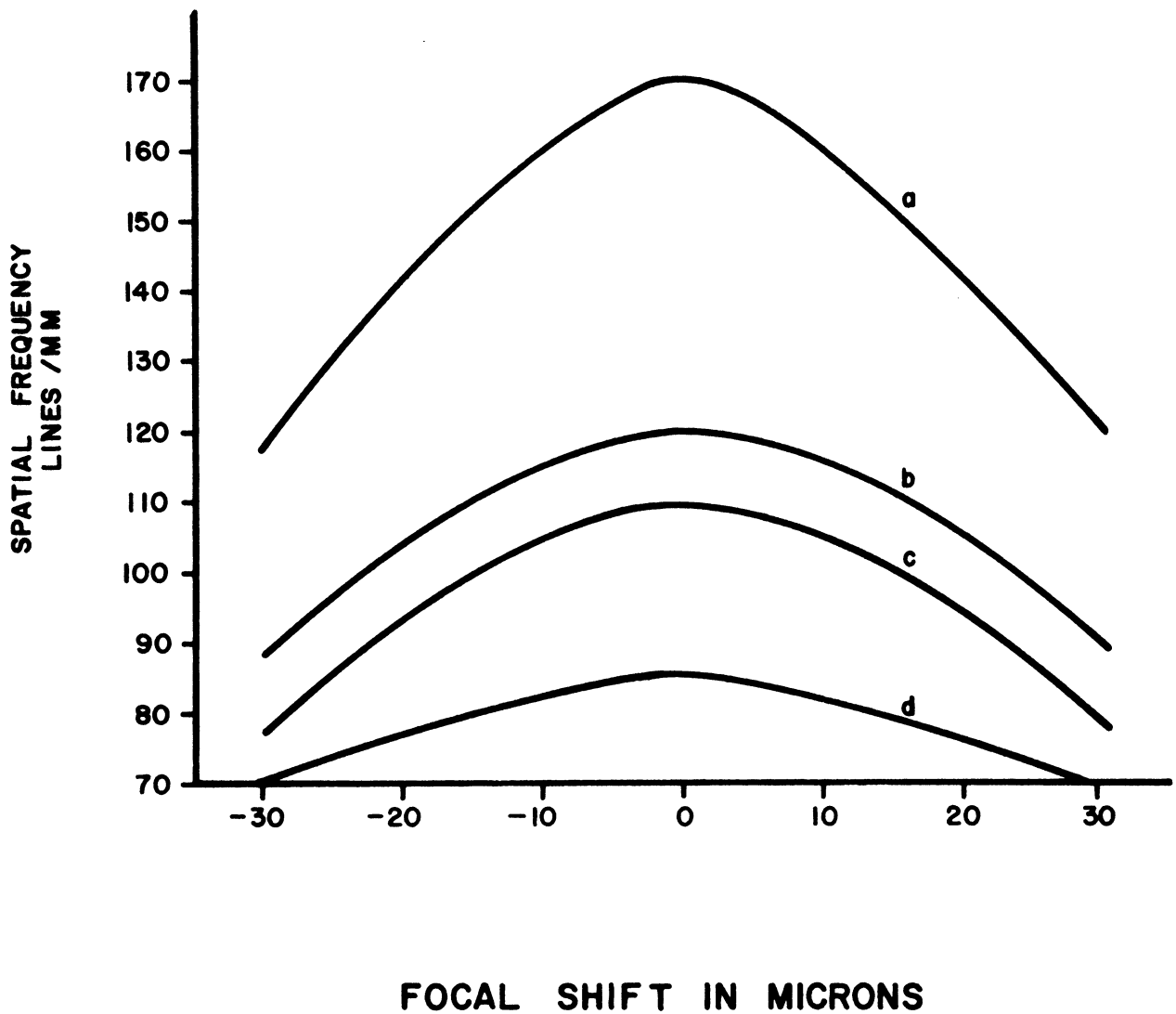


FIGURE 2: EFFECT OF FOCAL SHIFT ON SPATIAL FREQUENCY OF RECORDED IMAGE FOR TWO FILM TYPES AND OBJECT CONTRASTS

- (a) FILM: SO-243. OBJECT CONTRAST 4:1
- (b) FILM: SO-226. OBJECT CONTRAST 4:1
- (c) FILM: SO-243. OBJECT CONTRAST 1.6:1
- (d) FILM: SO-226. OBJECT CONTRAST 1.6:1

N.B. A SPATIAL FREQUENCY OF 85 LINES/MM ON A FILM PLANE IN THE MSTT CORRESPONDS TO A GROUND RESOLUTION OF ABOUT 1 METER FROM AN ALTITUDE OF 200km.

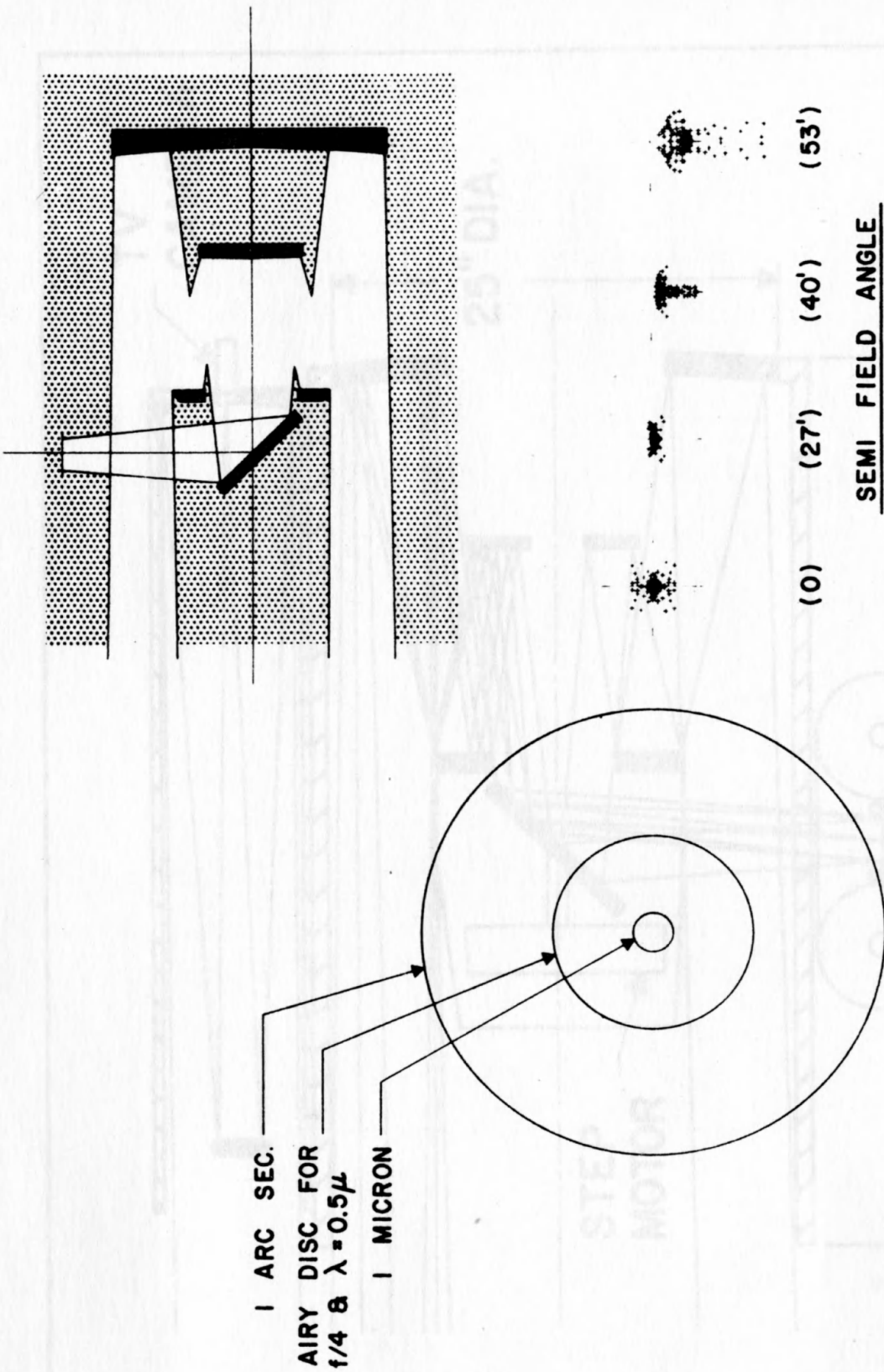


FIGURE 3: OPTICAL LAYOUT AND VARIATION OF SPOT
 DIAGRAM SIZE WITH FIELD ANGLE.

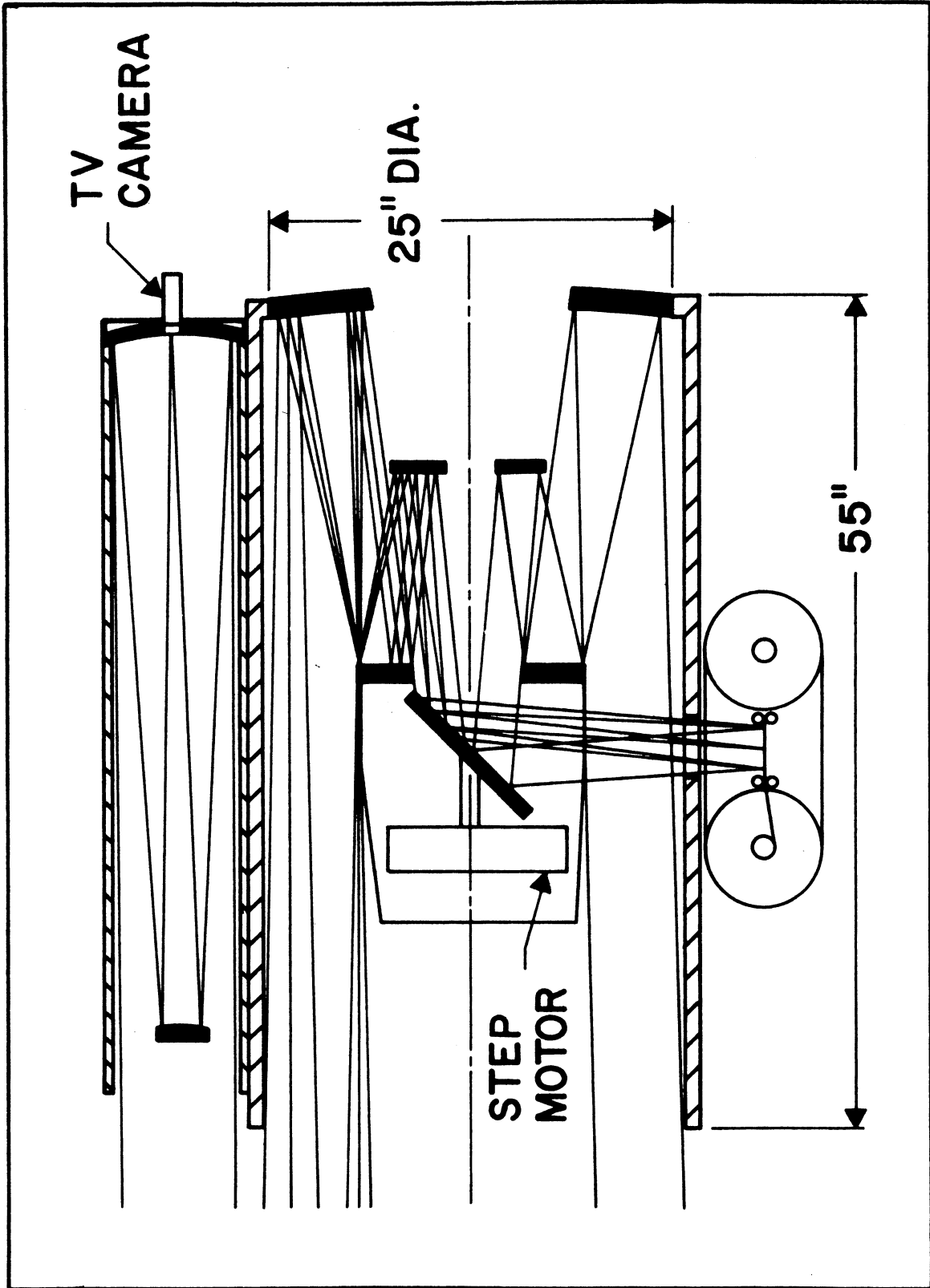


FIGURE 4 OPTICAL PATH THROUGH MULTI-SPECTRAL TRACKING TELESCOPE

FUTURE WORK

The next phase of the work, which is likely to take several months to complete, will be concerned with a detailed tolerance analysis of the system. It will analyze the effect of component tilt and decentering on the performance of the system. As criteria, we will probably determine what combinations of tolerances still provide diffraction-limited imagery. If these tolerances appear to be severe, the next step will be to redetermine the tolerances for a performance 1.5 or 2 times worse than diffraction-limited performance. Lastly, specifications and tolerances will be drawn up for optically testing the figuring of the components, and any required special optical equipment will be designed.

ACKNOWLEDGMENT

The author wishes to thank Dr. R. V. Shack for carrying out the computer design work for the MSTT. His cooperation in this program, together with his valuable contributions to many discussions, is gratefully acknowledged.

