1up

NASA TECHNICAL NOTE

NASA TN D-7627

NASA TN D-7627

A SYSTEMATIC STUDY OF FOCAL RATIOS AND EFFECTS OF OPTICAL MISALIGNMENT FOR LST

by Charles L. Wyman

George C. Marshall Space Flight Center
Marshall Space Flight Center, Ala. 35812

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • MAY 1974

TECHNICAL REPORT STANDARD TITLE PAGE

1. REPORT NO. NASA TN D-7627	2. GOVERNMENT ACCESSION NO.	3. RECIPIENT'S CATALOG NO.
4. TITLE AND SUBTITLE A Systematic Study of Focal Ratios and Effects of Optical Misalignment for LST		5. REPORT DATE May 1974 6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) Charles L. Wyman*		8. PERFORMING ORGANIZATION REPORT # M222
9. PERFORMING ORGANIZATION NAME AND ADDRESS George C. Marshall Space Flight Center Marshall Space Flight Center, Alabama 35812		10. WORK UNIT NO. 11. CONTRACT OR GRANT NO.
12. SPONSORING AGENCY NAME AND ADDRESS National Aeronautics and Space Administration Washington, D.C. 20546		13. TYPE OF REPORT & PERIOD COVERED Technical Note 14. SPONSORING AGENCY CODE

15. SUPPLEMENTARY NOTES

Prepared by Astrionics Laboratory, Science and Engineering

*This report represents research by author Charles L. Wyman to be applied toward fulfilling the Ph.D. dissertation requirements at the University of Alabama, University, Al.

16. ABSTRACT

Possible LST geometries are studied to determine performance and the effects of misalignments. The results are displayed parametrically as a function of Relative Back Focal Distance (RBFD). As RBFD increases, a larger high resolution field is obtained, and misalignment effects become less severe.

17. KEY WORDS	18. DISTRIBUTION STATEMENT CAT. 14

19. SECURITY CLASSIF. (of this report) Unclassified	20. SECURITY CLASSIF. (of this page) Unclassified	21. NO. OF PAGES 14	22. PRICE $3.00

MSFC - Form 3292 (Rev December 1972)

For sale by National Technical Information Service, Springfield, Virginia 22151

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

DEFINITION OF SYMBOLS

Symbol	Definition
b	Back focal distance
d	Intravertex distance
D_1	Primary mirror diameter
F/#	System focal ratio
$F_p/\#$	Primary focal ratio
m_2	Secondary magnification
d_i	Linear image diameter
λ	Wavelength (325 nanometers)
θ	Angular image diameter
θ_R	Angular resolution
w	Working distance

Nonstandard Abbreviations

RBFD = b/D_1	Relative Back Focal Distance

A SYSTEMATIC STUDY OF FOCAL RATIOS AND EFFECTS OF OPTICAL MISALIGNMENT FOR LST

INTRODUCTION

The Large Space Telescope (LST) is to be a Ritchey-Chretien telescope with a 3-meter-diameter primary mirror. The resolution of the LST is expected to exceed that of ground-based telescopes by nearly an order of magnitude, approaching diffraction-limited performance in the visible ultraviolet region of the spectrum.[1]

The LST must have a sufficiently large high resolution field to accommodate multiple scientific instruments and must have a sufficiently large total field to accommodate an offset star tracking guidance system. The system focal ratio must either be compatible with direct operation of science instruments and the offset guidance system, or be amenable to relaying to higher focal ratios. In fact, some instruments will operate at the system focal plane and others will utilize relay optics.

The primary constraints on the design of the optics for the LST are volumetric. The telescope is to be launched by the Space Shuttle, and the Optical Telescope Assembly (OTA), Scientific Instruments (SI), and the Support System Module (SSM) must fit within the Shuttle cargo bay. Another constraint is that the primary mirror must be located such that it will be supported by the load bearing rib structure of the Shuttle cargo bay. These ribs are spaced approximately 1.5 meters apart.

The purpose of this study is to systematically investigate various possible combinations of primary mirror and system focal ratios, along with the effects of optical misalignments. The results of these investigations are displayed parametrically as a function of the Relative Back Focal Distance (RBFD). The RBFD is defined as the ratio of the back focal distance, b, to the primary mirror diameter, D_1. RBFD has been found to be a key parameter for describing performance and misalignment effects of telescopes. Telescope geometries are sought that are compatible with the science instruments and offset guidance system. Several geometries are possible within the Shuttle volumetric and structural constraints.

The groundwork for the systematic study is set with a brief discussion of telescope resolution and a description of Ritchey-Chretien telescopes.

RESOLUTION OF A TELESCOPE

The limiting resolution of a telescope is determined by diffraction resulting from the finite-sized aperture of the telescope [1]. The effect of diffraction is that a point

1. LST Project Guidelines and Requirements Document, George C. Marshall Space Flight Center, September 21, 1973.

source in space is imaged in the focal plane as a finite-sized intensity pattern. For monochromatic light this pattern is characterized by a central bright region surrounded by bright and dark rings. For a telescope without a central obscuration the central bright region has a linear diameter of

$$d_i = 2.44\ \lambda\ F \text{ micrometers} \quad ,$$

where λ is the wavelength in micrometers and F is the system focal ratio. Notice that this linear dimension is independent of the telescope diameter. On the other hand, the angular diameter that the linear dimension represents is,

$$\theta = 2.44\ \frac{\lambda}{D_1} \text{ microradians} \quad ,$$

where λ is again in micrometers and D_1 is the diameter of the telescope's primary mirror in meters. By Rayleigh's criteria, a telescope can resolve two point sources with an angular spacing of

$$\theta_R = \frac{1.22\ \lambda}{D_1} \text{ microradians}$$

For an LST with a 3-meter aperture this is approximately 132 nanoradians (0.027 arc seconds), for a wavelength of 325 nanometers.

Several factors can cause the resolution to be degraded from the theoretical limit:

1. Residual errors in the optical surfaces.

2. Image motion due to disturbances in the telescope, or noise in the pointing control system.

3. Geometric aberrations.

4. Optical misalignments.

Residual errors in the optical surfaces result in a deformation in the wave front as it passes through the optics. Reduction of these errors is clearly in the manufacturing of the surfaces and in the maintenance of the surface figure during operation. Image motion results in a long-term smearing of the image and tends to reduce the high spatial frequency response of the telescope. Reduction of this error is clearly a problem in sensing and controlling. These two errors will not be discussed further in this report.

Wave-front deformations are the result of the last two errors. It is traditional in optics to measure or specify these errors in terms of rms wave-front errors at some reference wavelength. The LST guidelines specify the HeCd laser line of 325-nanometers wavelength as the reference wavelength.

Geometric aberrations will be discussed in conjunction with the description of the Ritchey-Chretien telescope. Misalignment effects are discussed in conjunction with the systematic studies.

THE RITCHEY-CHRETIEN TELESCOPE

Imaging systems in general are limited by image defects known as geometric aberrations [1]. Selected aberrations can be reduced or even eliminated, but, in general, the more aberrations one wants to eliminate the more optical surfaces that are necessary.

The most serious aberrations are a set called Primary or Seidel aberrations. There are five such aberrations and they are called spherical aberration, coma, astigmatism, field curvature, and distortion. The latter two do not cause wave-front errors (hence, the images are not smeared) and, therefore, are not considered serious in astronomical instruments.

Of the other three errors, spherical aberration causes the greatest smearing of images, and coma causes substantial asymmetric smearing of off-axis image points. Astigmatism causes a lesser effect, and is characterized by two image planes with points being imaged into lines in each of the two planes. The line images are at right angles in these two planes, and in between a symmetrically smeared image exists.

It has been theoretically demonstrated that, in general, one Seidel aberration can be eliminated for each optical surface used [2,3]. For a two-mirror telescope, such as the LST, highest performance results when spherical aberration and coma are eliminated. A system that has these two aberrations eliminated is called an aplanatic optical system. The Ritchey-Chretien [4]telescope is the aplanatic version of the Cassegrain telescope.

The standard Cassegrain telescope has a parabolic primary mirror and a hyperbolic secondary. It is free of spherical aberration, but has both coma and astigmatism. The Ritchey-Chretien telescope has primary and secondary mirrors that are both hyperbolic and are free of primary spherical aberration and coma. The high resolution field that results is substantially larger than for the regular Cassegrain telescope. The size of the useful field in the Ritchey-Chretien telescope is ultimately determined by the amount of astigmatism that can be tolerated. The wave-front error caused by astigmatism increases as the square of the field angle.

The Ritchey-Chretien telescope can take any of the forms shown in Figure 1. All three of these forms are analyzed in the systematic study. In the figure, D_1 is the primary mirror diameter, b is the back focal distance, d is the intravertex distance, and w is designated as the working distance. We have defined the ratio of the back focal distance to the primary mirror diameter, b/D_1, to be the Relative Back Focal Distance. RBFD has been shown to be an important parameter relating to telescope performance.[2]

A SYSTEMATIC STUDY OF THE RITCHEY-CHRETIEN TELESCOPE

We shall call the primary mirror focal ratio F_p, and the system focal ratio F. The secondary mirror magnification is m_2 and relates to the focal ratios as $F = - m_2 F_p$, where m_2 is taken to be negative. Several dozen possible Ritchey-Chretien geometries were designed and analyzed using a two stage computer program [3]. Primary focal ratios were varied from $F_p/1.5$ to $F_p/5$. System focal ratios covered the range of F/8 to F/30. The secondary magnification m_2 was varied from 1.6 to 20.

The performance of each system was analyzed. System performance is measured in terms of available field angle for a given geometric spot size on the focal surface. The spot size is defined as the minimum angular diameter which includes all rays traced through the system. For the LST we assumed a 150-nanoradian spot size. Performance as a function of RBFD is plotted in Figure 2. The results of the systematic study have shown that, to a very good approximation, a single curve represents the performance of all the Ritchey-Chretien geometries investigated. We see that as RBFD increases, the available field angle also increases. The three vertical lines represent the phase A design and two more configurations that could possibly fit in the Shuttle.

Without considering other constraints, we see that we can choose our geometry and focal ratios at will. A driving factor in the choice of the system focal ratio is the desire to have a linear field size sufficient to accommodate all the scientific instruments simultaneously. The linear size is directly proportional to the system focal ratio.

THE EFFECTS OF MISALIGNMENT

In a two-mirror telescope we are concerned with the relative misalignment between the primary and the secondary. A motion of the secondary with respect to the

2. Wyman, C. and Korsch, D.: Paper submitted to Applied Optics.

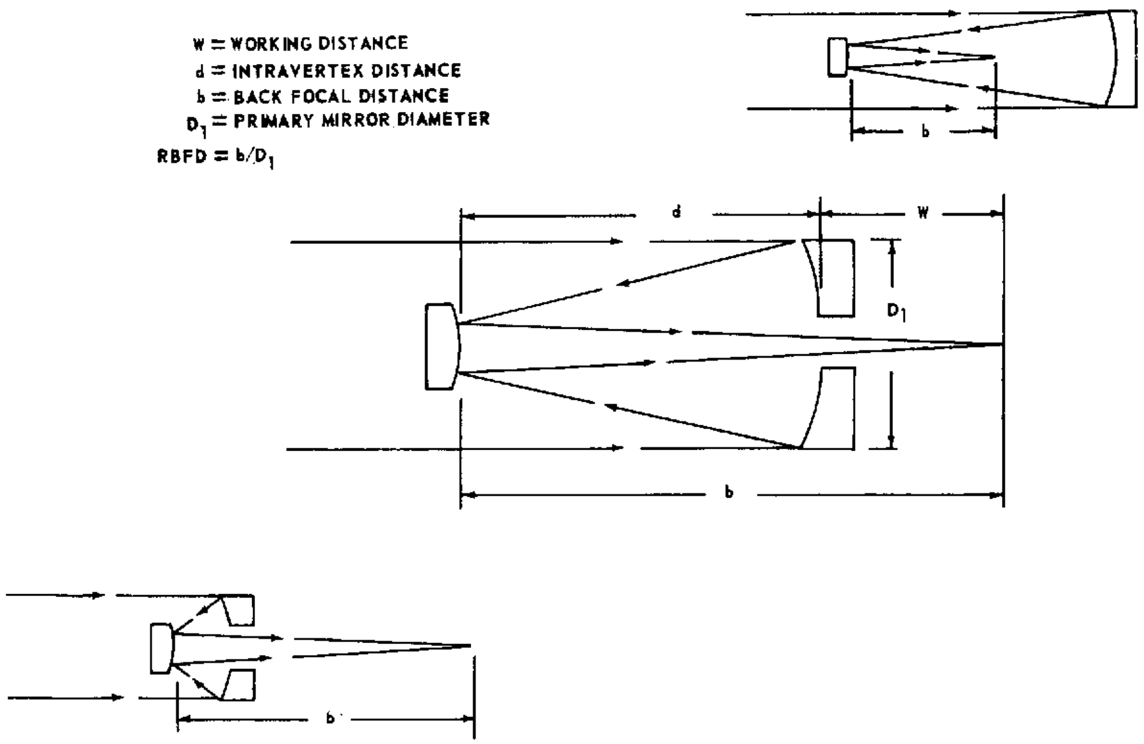

Figure 1. Telescope geometry and definition of RBFD.

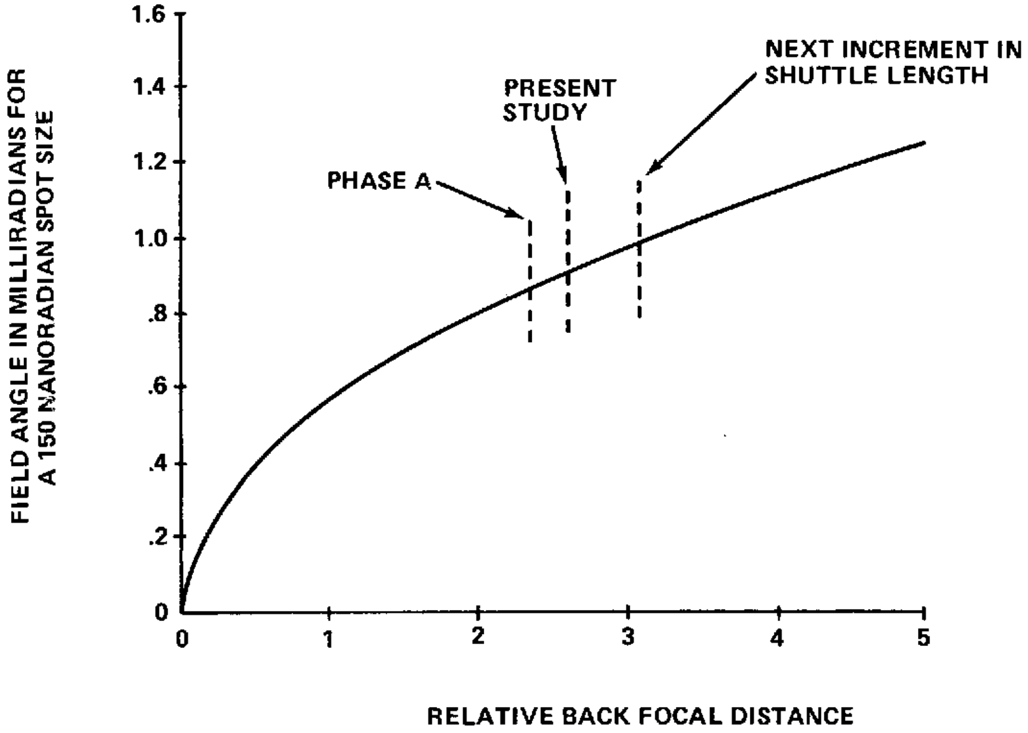

Figure 2. Performance of the Ritchey-Chretien telescope.

primary has the same effect as moving the primary with respect to the secondary. The ray trace program was set up to analyze the effects of secondary movements with respect to the primary.

Lateral movements with respect to the optical axis are called decenter, rotation about an axis tangent to the secondary vertex is called tilt, and a longitudinal movement is called despace. The sensitivity to various misalignments is measured in terms of rms wave-front errors.

It was found that the sensitivity varied with RBFD and with the working distance w. The phase A LST design has an RBFD of 2.4, and a working distance of 192 cm. Figures 3, 4, and 5 display the effects of decenter, tilt, and despace respectively. The curves were generated for a fixed working distance of 150 cm. The effects are shown for a decenter of 10 micrometers, 10-microradians tilt, and a 1-micrometer despace. The effects on the phase A design are noted on each graph. The wave-front errors are for the reference wavelength of 325 nanometers. Focal ratios of F/12, F/20, and F/30 are shown. It is evident that the larger working distance of the phase A design results in a more severe wave-front error. Higher system focal ratios are more sensitive to decenter and despace, but less sensitive to tilt. This is because the primary focal ratio decreases with the increasing system focal ratio for a fixed RBFD and fixed working distance. The effects are substantially reduced for larger values of RBFD.

Figure 6 displays the effect of each misalignment for a system focal ratio of F/24. The phase A F/12 system is also denoted on the graph. F/24 is presently considered desirable from the standpoint of an adequate linear field size and because it represents a reasonable match for a high resolution camera. Again w is fixed at 150 cm.

Figure 7 shows the effect of varying the working distance while holding the RBFD constant at 2.6667. It is evident that the smallest possible working distance is desirable from the standpoint of optical misalignments.

CONCLUSIONS

Focal ratios above F/20 are necessary to obtain a sufficient linear field size to accommodate all the instruments in fixed positions. An F/24 system has been tentatively chosen, based partly on a focal plane layout proposed by MSFC and partly on the recommendations of the LST working group because of a reasonable match with high resolution camera capabilities.

Decenter and despace sensitivities are more severe for higher focal ratios, but can be more than offset by designing for a larger RBFD. Working distance should be held to a minimum.

The presently recommended design is an F/24 with RBFD = 2.6667, b = 800 cm, w = 150 cm, and d = 650 cm. Assuming that this geometry does indeed match the Shuttle, the next increment in length would give an RBFD = 3.1667. This value would substantially reduce misalignment sensitivities, but might cause serious volume constraints on the SSM or the science instruments.

The results shown in this report should be traded against thermal and structural effects to determine if there is an overall net gain to be achieved by lengthening the telescope. Within the constraints of reasonable optical design, the final geometry must be determined jointly with structural and mechanical designers.

George C. Marshall Space Flight Center
National Aeronautics and Space Administration
Marshall Space Flight Center, Alabama, March 4, 1974

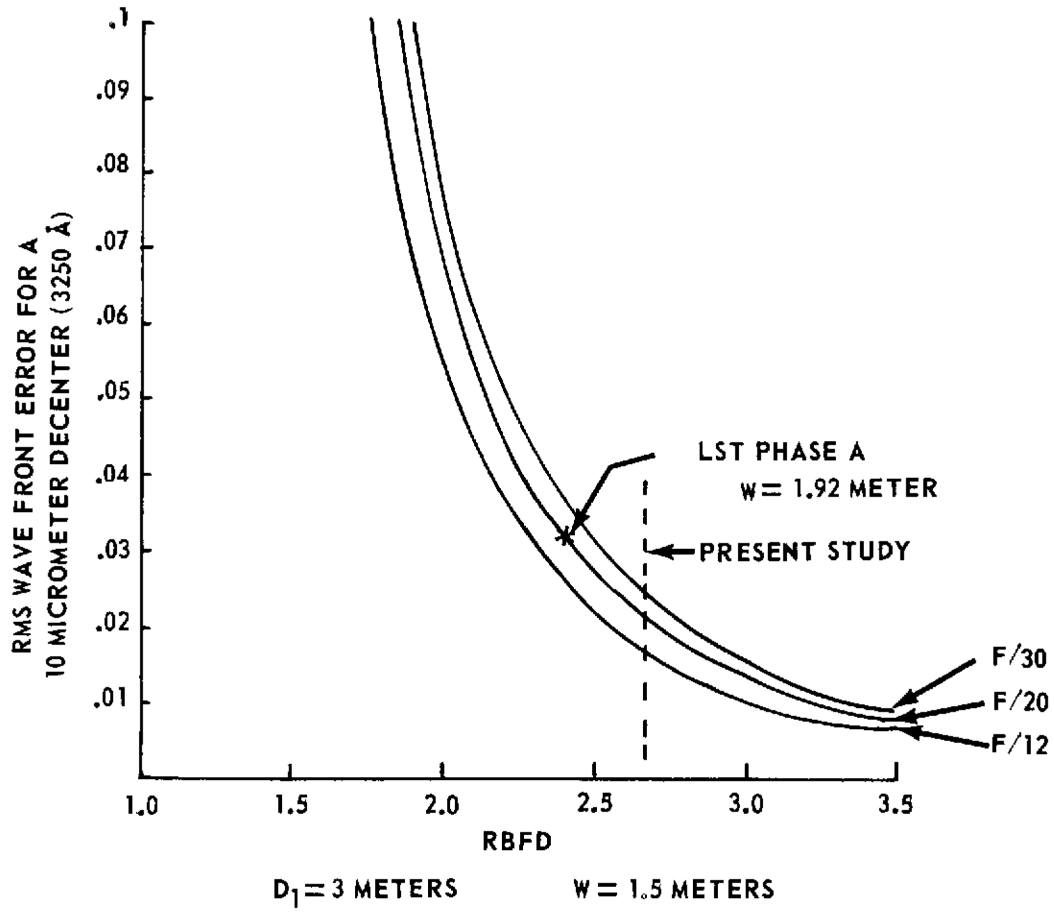

Figure 3. LST–systematic tolerance analysis decenter errors.

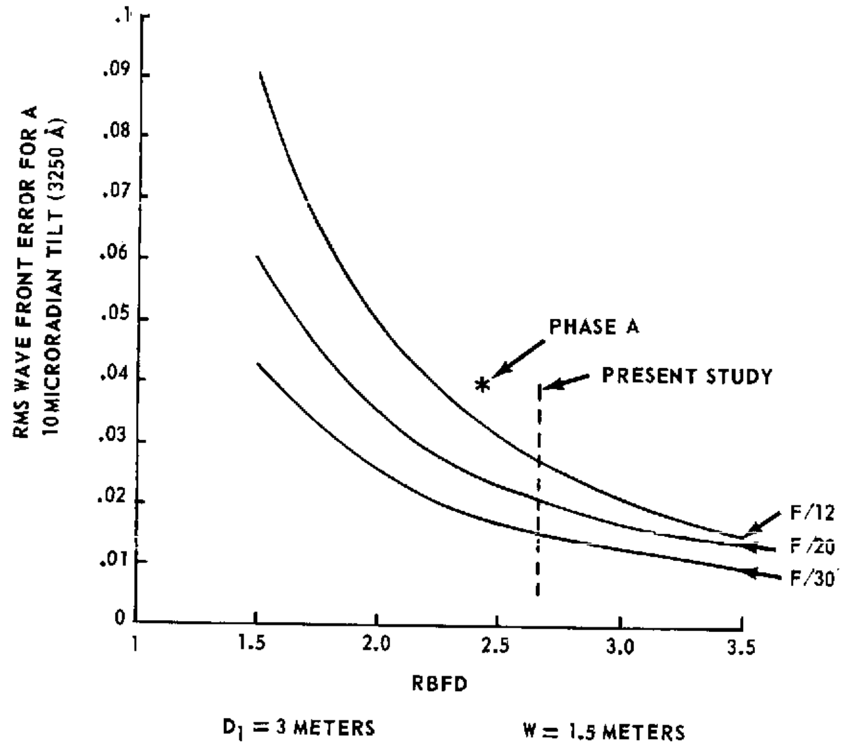

Figure 4. LST–systematic tolerance analysis tilt errors.

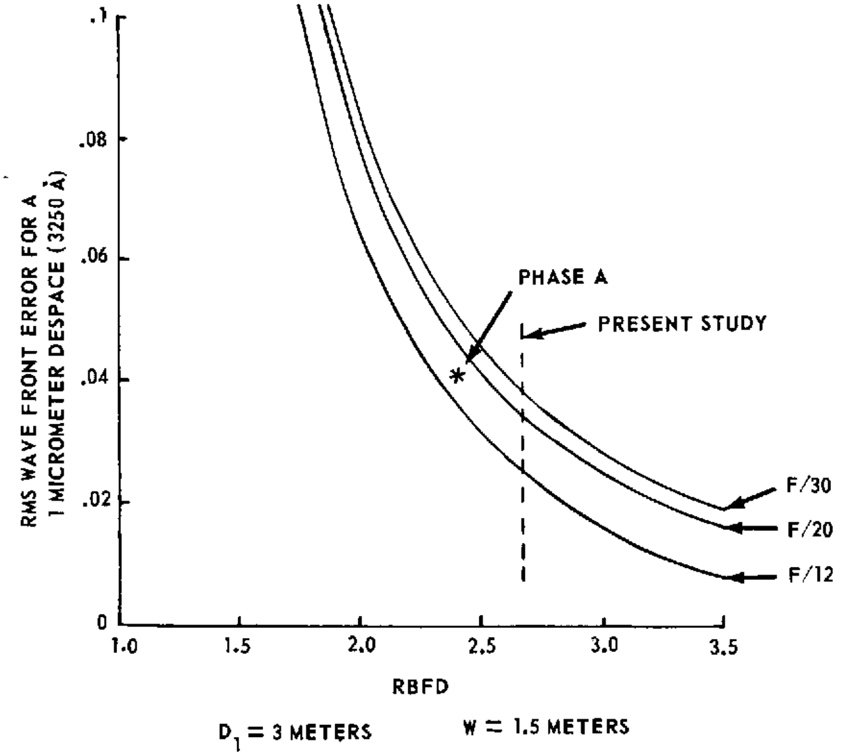

Figure 5. LST–systematic tolerance analysis despace errors.

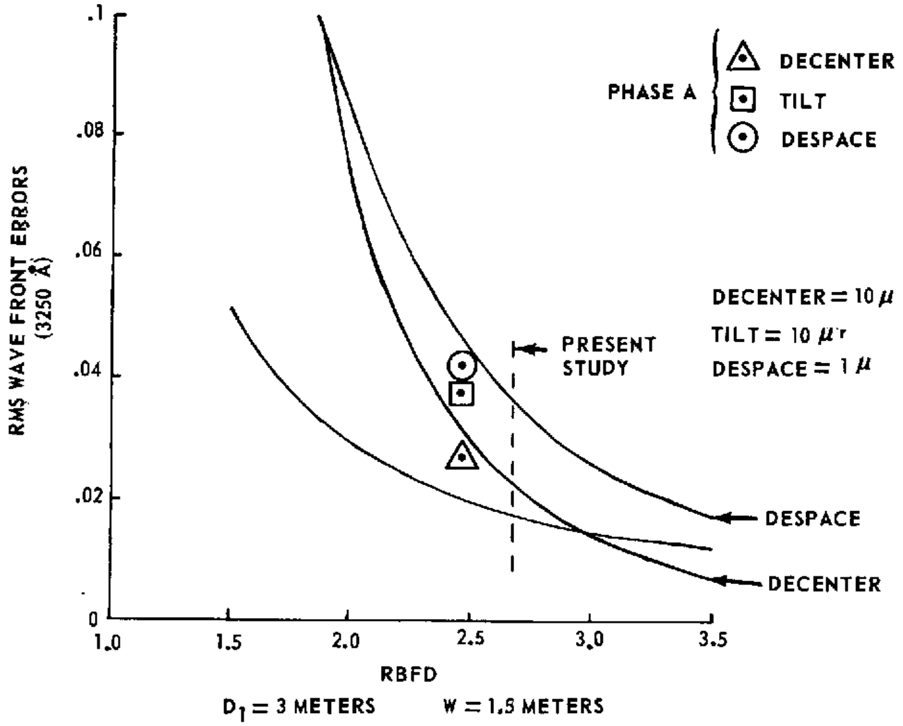

Figure 6. LST–systematic analysis errors for an F/24 system.

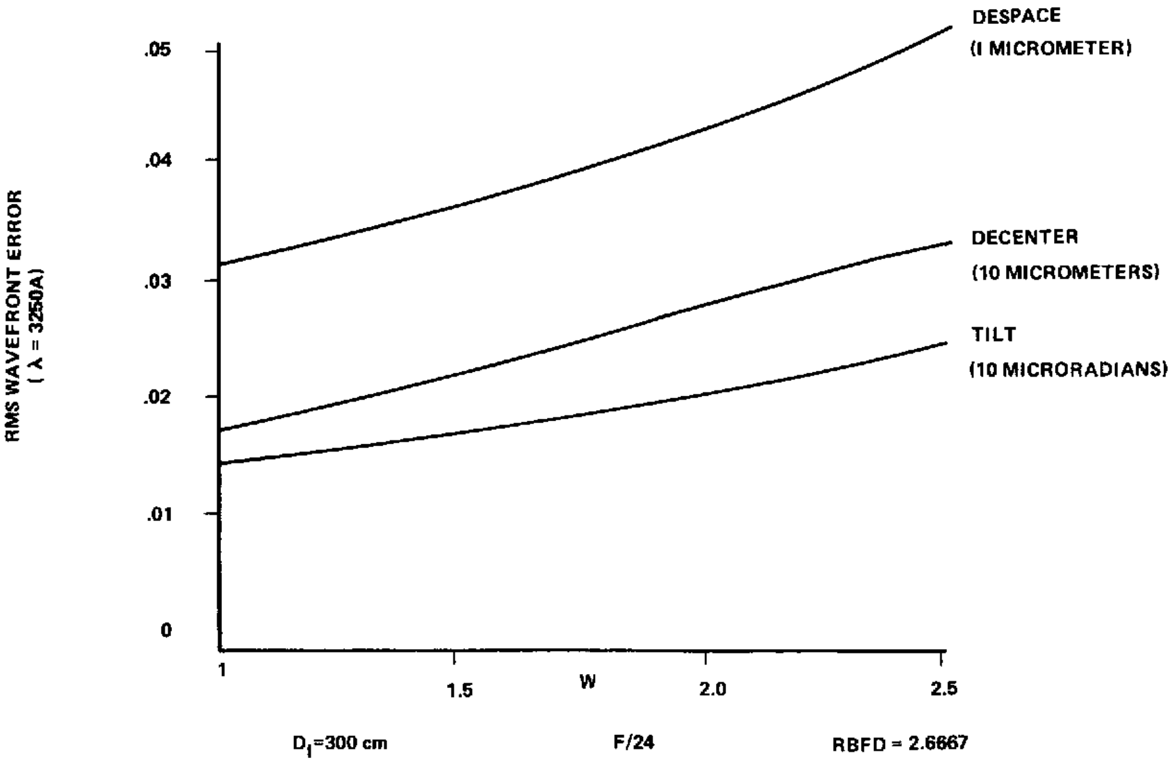

Figure 7. Tolerance effects as a function of working distance.

REFERENCES

1. Born, M.; and Wolf, E.: Principles of Optics. Permagon Press, New York, 1965, pp. 203-230 and 395-416.

2. Korsch, D: J. Opt. Soc. Am., vol. 63, 1973, p. 667.

3. Korsch, D: J. Opt. Soc. Am., vol. 63, 1973, p. 497.

4. Chretien, Henri: Revue d'Optique Theorique et Instrumentale, Feb. 1922, pp. 49-64.

NASA-Langley, 1974