KORSCH OPTICS, INC.
10111 BLUFF DRIVE, HUNTSVILLE, ALABAMA 35803
(205) 881-1166

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AN OPTICAL TECHNOLOGY STUDY ON LARGE APERTURE TELESCOPES

FINAL REPORT

PREPARED BY

DIETRICH KORSCH

FOR

GEORGE C. MARSHALL SPACE FLIGHT CENTER
ALABAMA 35812

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I CONSIDERATIONS ON VERY LARGE APERTURE TELESCOPES

INTRODUCTION

Two distinctly different concepts of large, highly sophisticated space telescope systems are being widely discussed nowadays. On the one hand there is the, in the field of optical astronomy, relatively new concept involving large arrays of two or more individual yet optically combined and mutually phased telescopes. The primary objective of these systems is to achieve the highest possible resolution for a given total collecting area. These are highly specialized and extremely elaborate systems, yet unfortunately characterized by a lack of versatility and low efficiency. On the other hand there is the search for a more conventional multipurpose space observatory based on a single large telescope that would serve as a greatly advanced successor to the Hubble Space Telescope with significant improvements in both, light gathering capability and resolution.

The subject-matter of this study is concerned with the latter of the two concepts, namely, the single large telescope. It specifically deals with the difficult and crucial problem of selecting a suitable telescope concept for such an advanced space observatory. To this end two-and four-mirror telescopes were analyzed and compared . Both configurations are very practical and structually similar. Three-mirror systems were not considered here because of their generally awkward geometry, and, in particular, because of the poor image accessibility.

Since the design and performance characteristics of two-mirror telescopes are already very well known, almost all of the analytical work has been concentrated on four-mirror telescope systems.

The theory related to the treatment of four-mirror telescopes was published in a previous report by D.Korsch to MSFC[1], and the programs used to do this work were developed by, and are exclusively available to KORSCH OPTICS.

ANALYTICAL RESULTS

The performance characteristics of the various telescope designs such as the residual aberrations as a function of the field angle and the effects of mirror misalignments on the image quality are presented in this section. These characteristics must be used as criteria for a meaningful comparison.

A major portion of this study is summarized in a paper entitled "Performance and complexity comparison of aspheric-and spherical-primary telescopes" which was given by D.Korsch at SPIE's 29th Annual Technical Symposium on Optical and Electro-Optical Engineering in San Diego, August 1985. A copy of this paper is attached as part of this report. It is concerned with the design and analysis of four-mirror telescope systems with extremely spherical and aspheric primaries

The analysis has since been expanded to include segmented primary mirrors. This obviouly increased the overall alignment complexity significantly. There is a fundamental difference between the effects of a misaligned component and a misaligned segment of, for instance, that particular component. In either case, a misalignment generally affects the image in two ways; in the first place it causes a geometric displacement of the entire image, and secondly, it induces image degrading geometric aberrations.

If an entire component (i.e. a primary or secondary or tertiary etc.) is misaligned, the resulting image displacement is inconsequential because it affects the image as a whole without impairing its quality. The alignment tolerance is, therefore, exclusively determined by the allowable amount of misalignment induced aberrations. If, on the other hand, only a segment of a component is misaligned, then only the energy content of the image that is reflected off that particular segment will be displaced. The consequence of this is a very sensitive, segment related image matching problem; and since the image displacement is a first-order effect, it becomes intolerable even before the misalignment-induced aberrations grow appreciably.

Furthermore, if diffraction-limited performance is required, the axial alignment of all segments with respect to each other must be maintained to within a small fraction of the wavelength so that the light arriving from all segments at an image point in the focal plane is in phase. The important conclusion is that the component segmentation not only adds to the alignment complexity, but indeed constitutes its most sensitive part.

For a numerical example we used the four-mirror configuration presented in the attached paper with an F/.8 primary, and determined, using exact ray tracing, the image displacements caused by a misaligned segment of the 10m primary mirror. For simplicity the segment is represented by a 2m circular portion of the primary centered 4m off axis. Since all surface shapes are rotationally symmetric with respect to the optical axis, we need only consider one lateral motion in radial direction. We also disregard any motion in axial direction since they do not cause any first-order image displacement, but create a phasing problem which has not been a part of this study. The image displacements for the remaining four types of misalignments are given in the following table:

Type of Misalignment	Image Displacement per Unit Misalignment
radial, Δx	1.2 μrad/μm
angular, $\Delta\alpha_x$	1.9 μrad/μrad
$\Delta\alpha_y$	2.0 μrad/μrad
$\Delta\alpha_z$	.43 μrad/μrad

The radial direction coincides, without losing generality, with the x-axis. The angular motions are obtained by rotating about the x-, y- and z-axes, respectively, whereby the origin coincides with the geometrical center of the circular segment.

As expected the misalignment sensitivities are very high as the displacements must be kept within a small fraction of the diameter of the diffraction-limited point image. Because we are dealing with a first-order effect, the sensitivity numbers are independent of the mirror figure. There is, however, a significant difference in the correctibility of a misaligned segment if the figure of the primary mirror is a sphere. While for any aspheric surface the four types of misalignments are independent and must be independently corrected, a misaligned segment of a spherical surface can be corrected by only two independent angular motions, $\Delta\alpha_x$ and $\Delta\alpha_y$. This is true because the segment is allowed to move freely on the spherical surface of which it is a part, and it may also rotate about its surface normal without affecting the image. This is a distinct advantage that must be kept in mind when considering the use of very large and fast mirrors.

OPTICAL CONSIDERATIONS ON THE DESIGN AND CONSTRUCTION OF LARGE APERTURE TELESCOPES

This portion of the report is to be concluded by giving a three-part summary and interpretation of the results as they relate to the design and the construction of very large telescopes. The first part deals with the relavent characteristics of the Cassegrain type telescope configuration. The second part does the same for a quasi-Cassegrainian four-mirror telescope configuration, and the last part addresses some important questions regarding the segmentation of a large mirror and the role of a spherical surface in this case.

1. The Cassegrain Configuration

The Cassegrain configuration has the obvious advantages of a two-mirror telescope. It is simple, compact and requires only two reflections. A Cassegrain telescope with a parabolic primary and a long system length is also well corrected because it approaches the afocal case which is known to be free of spherical aberration, coma and astigmatism. Good image quality, however, is only obtained on a highly curved focal surface, the radius of which is about half that of the secondary mirror which is because of the long focal length already very small.

A Cassegrain telescope with a spherical primary even if rigorously corrected for spherical aberration is essentially a zero field system (see ref.1). It may, therefore, serve adequately as a beamexpander, but hardly as an imaging instrument.

2. The Four-Mirror Telescope in a Quasi-Cassegrain Configuration

It is the two additional surfaces that at first evoke a negative reaction because it increases the alignment complexity, and adds two more reflections. However, it is the same two additional surfaces that offer a wellcome design flexibility that perhaps more than outweighs the abovementioned disadvantages. First it not only allows to achieve an image quality comparable to the long-focal length Cassegrain telescope, but it also achieves it in a much desired flat field. Secondly, the two additional surfaces permit a high degree of correction even when using a spherical primary. Although a spherical primary telescope can never match the off-axis image quality obtained with a parabolic primary, it may very well be adequate and can also provide a flat field if the primary focal ratio is not less than 1.

3. Reasons for Segmenting a large Mirror and the Advantages of a Spherical Surface

Manufacturability, transportability and weight are the three predominant problems when the primary mirror of a telescope becomes very large. One way to alleviate these problems at least partially is to divide the large surface into a number of smaller, more manageable segments. Segmentation can reduce the overall weight because the required thickness of a mirror element is roughly proportional to its size, so that the sum of all segments could be significantly lighter than a single-piece primary. It could also allow the primary to be transported disassembled before being reassembled in space, and it could even facilitate the fabrication, or make it at all possible.

Any or all of these reasons may be compelling enough to require segmentation. Unfortunately, this cannot be done without causing a new problem. This problem is associated with the alignment of the individual segments. The misalignment of segments can be divided into two categories according to the effect they cause. One of these effects is a mismatch of the phase, caused by an axial misalignment between segments, and the other one is a mismatch of the image caused by lateral and angular misalignments.

This is an area were a spherical surface could have a distinct advantage over any aspheric surface. While the phasing problem is independent of the surface figure, the correction of an image mismatch is greatly simplified in the case of a spherical surface. An aspheric surface requires four independent motions, one radial and three angular, to correct an image mismatch, whereas a segment of a spherical surface requires only two angular motions to accomplish the same.

Another, even more obvious area where a spherical surface has the clear advantage is the manufacturability. Considering all factors, one must conclude that it is worthwhile to think about the use of a spherical surface for very large primary mirrors.

Reference:

D.Korsch, "Highly-Corrected Spherical-Primary Telescope Designs", Final Report to NASA-MSFC, Oct.1984

Performance and complexity comparison of aspheric and spherical primary telescopes

Dietrich Korsch

Korsch Optics,Inc., 10111 Bluff Dr., Huntsville, AL 35803

Abstract

Four-mirror telescopes of the same configuration, once employing a spherical and the other time employing a parabolic primary are compared with respect to their performance, and the alignment sensitivities of the three correction mirrors. This is done for three different primary focal ratios, F/1, F/.8 and F/.6. The systems with parabolic primaries provide a far superior wide field performance, and are less sensitive to misalignments of the tertiary and quarternary mirrors. The spherical primary systems are highly corrected over a much narrower, though, for many applications possibly sufficiently extended field of view. The attractiveness of the spherical primary is the simplicity of its fabrication, and if segmented, also the largely simplified alignment procedure of the segments.

Introduction

While the design and fabrication of aspheric mirrors has become routine as long as their sizes are moderate, the asphérization of mirrors with sizes of several meters or more imposes a different order of complexity. The problem is further aggravated by the fact that very large mirrors can probably not be fabricated to a very high accuracy as a single unit, but must be segmented in one fashion or another. This requires the production of not only aspheric but also asymmetric elements which would add a significant degree of difficulty to the alignment procedure. For these reasons a fresh look at the spherical primary in comparison to a parabolic primary seems to be timely and appropriate. The fact that the surface figures af all segments are not only extremely simple, but also identical, makes the spherical primary particularly attractive.

Four-mirror telescope design

For the purpose of this comparative analysis the four-mirror telescope configuration shown in fig.1 was chosen. The design and optimization technique used here has been previously described[1]. In this particular case the primary surface is either spherical or parabolic, and the secondary surface is represented by a sixth-order polynomial. Since the tertiary and quarternary mirrors are computed to always yield a rigorously aplanatic system, the fourth-and sixth-order coefficients of the secondary surface equation were used to minimize the residual aberrations dominated by third-order astigmatism.

Three different primary F-numbers were considered, F=1, F=.8 and F=.6. Here the F=number is defined by the slope of the marginal ray, $\tan\alpha$, so that $F=1/2\tan\alpha$. While the mirror diameters are the same for all three cases, the length of the telescope and the system focal length decrease with decreasing F-number. The mirror diameters are:

Primary	: 10m
Secondary	: 2m
Tertiary	: 2m
Quarternary	: .4m

The surface separations(here measured to the edge of each surface)and the focal lengths for the three cases are:

	F=1	F=.8	F=.6
Primary-secondary :	8.00m	6.40m	4.80m
Secondary-tertiary :	8.55m	7.10m	5.65m
Tertiary-quarternary :	8.50m	7.00m	5.55m
Quarternary-focal surface:	9.50m	8.00m	6.55m
Focal length :	237.60m	200.10m	163.80m

The conic section of revolution that closely fits the contour of the optimum secondary is in the case of a parabolic primary a hyperboloid, and in the case of a spherical primary an oblate ellipsoid. Because of the wide-spread fear of oblate ellipsoids among optical designers and manufacturers, a word of clarification may be helpful. A typical secondary corrector surface profile for a spherical primary is shown in fig.2, including the meridional section of the complete oblate ellipsoid. The areas of concern are near the ends of the elliptical profile where the surface slope changes suddenly very fast. However, as long as one stays away from these critical areas, the surface is absolutely well-behaved and, particularly for highly oblate ellipsoids, even flatter than corresponding hyperboloids.

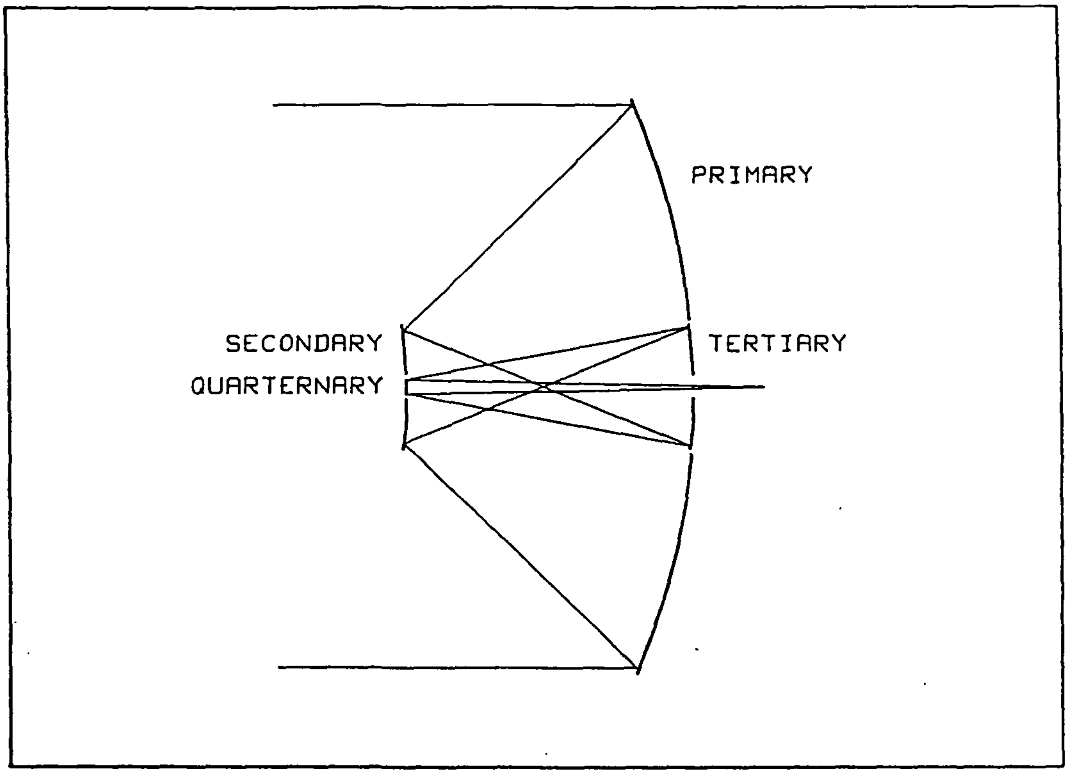


Fig.1: Four-mirror configuration

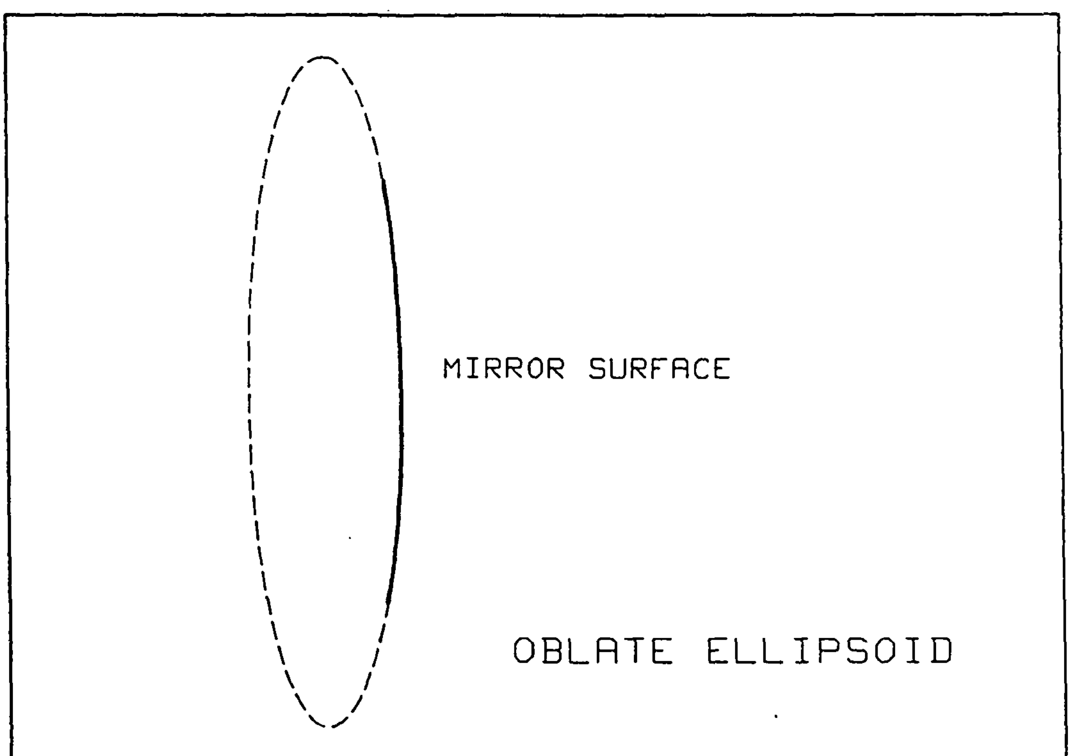


Fig.2: Typical surface profile of a secondary corrector for a spherical primary

The surfaces of the tertiaries and quarternaries are represented by differential equations which can be determined by the method described in reference 1. The profiles of the three corrector surfaces for the two F/.6-systems are shown in figs. 3 and 4.

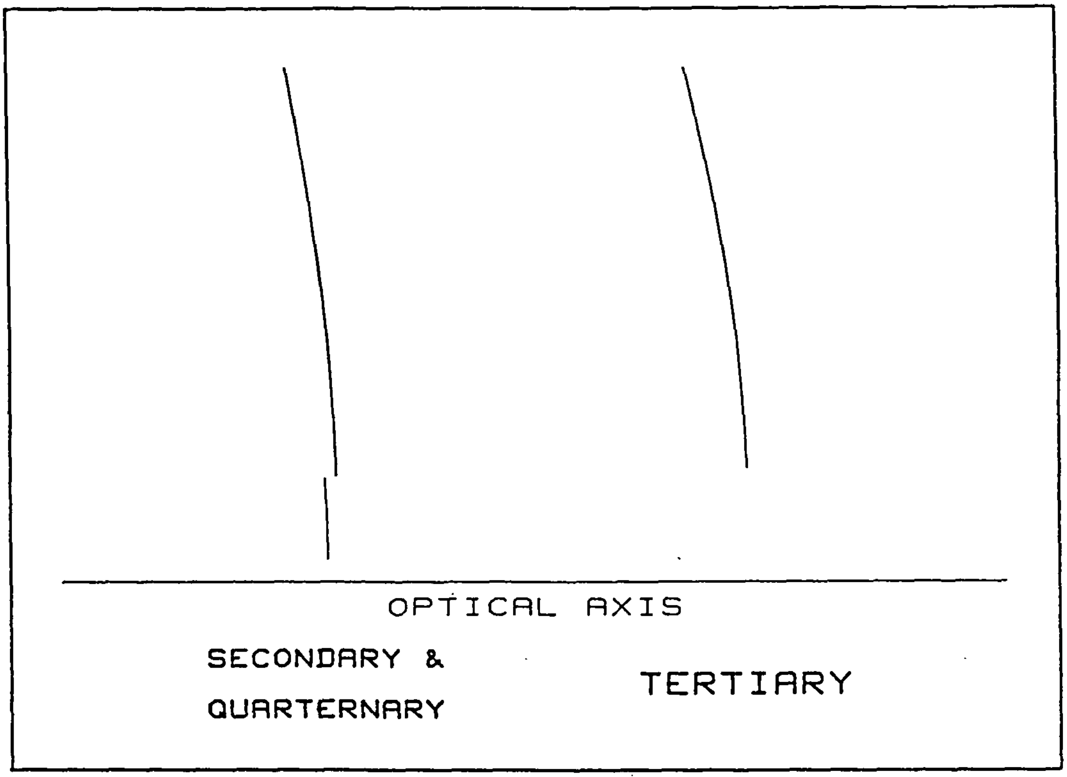


Fig.3: The three corrector surface profiles for an F/.6 parabolic primary

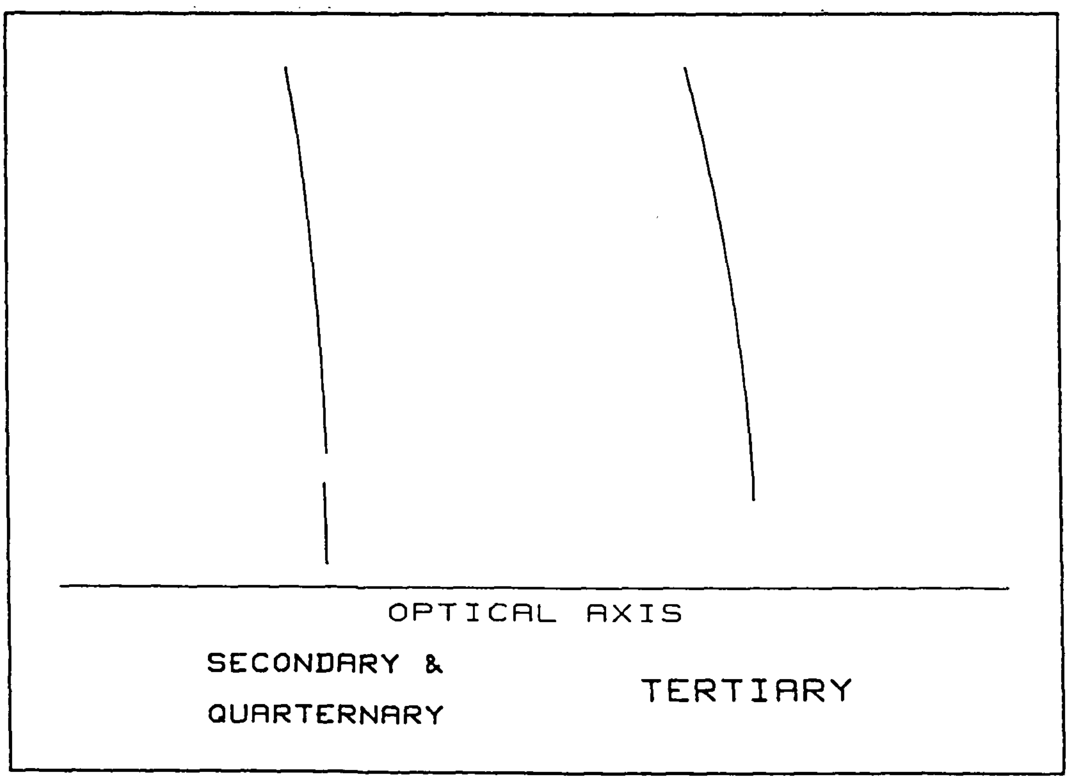


Fig.4: The three corrector surface profiles for an F/.6 spherical primary

Comparative analysis

Six telescope designs were analyzed with respect to their imaging quality and with regard to the alignment sensitivities of their three corrector mirrors. Curves of the geometric rms-spot sizes as a function of the field angle are given in fig.5. The superior wide-field performance of the parabolic primary systems is, of course, not unexpected. However, in high resolution, long focal length applications this advantage may not be real because the physical dimensions of a wide field and the large number of detectors necessary to cover it may soon become unmanageable. In this case the narrower, but well corrected field of view offered by a spherical primary telescope may be quite satisfactory.

The misalignment sensitivities of the corrector mirrors for the six systems are summarized in table 1. It is interesting to notice that the secondary mirrors of spherical primary telescopes is less sensitive to two out of three misalignments. Only the sensitivitiy to tilt is less for parabolic primary systems. The sensitivity differences for the tertiaries and quarternaries are more obvious, and favor the parabolic primary systems.

In the case of segmented primaries one must also consider the alignment complexities and sensitivities of the individual segments. An aspheric segment requires for its alignment, because of its asymmetry, a minimum of five degrees of freedom, three angular, one radial and one axial. For a spherical primary the number of degrees of freedom reduces to three, two angular and one axial. The misalignment sensitivities, in particular for the additional two degrees of freedom (azimuthal and radial) in the case of the parabolic primary, are yet to be determined.

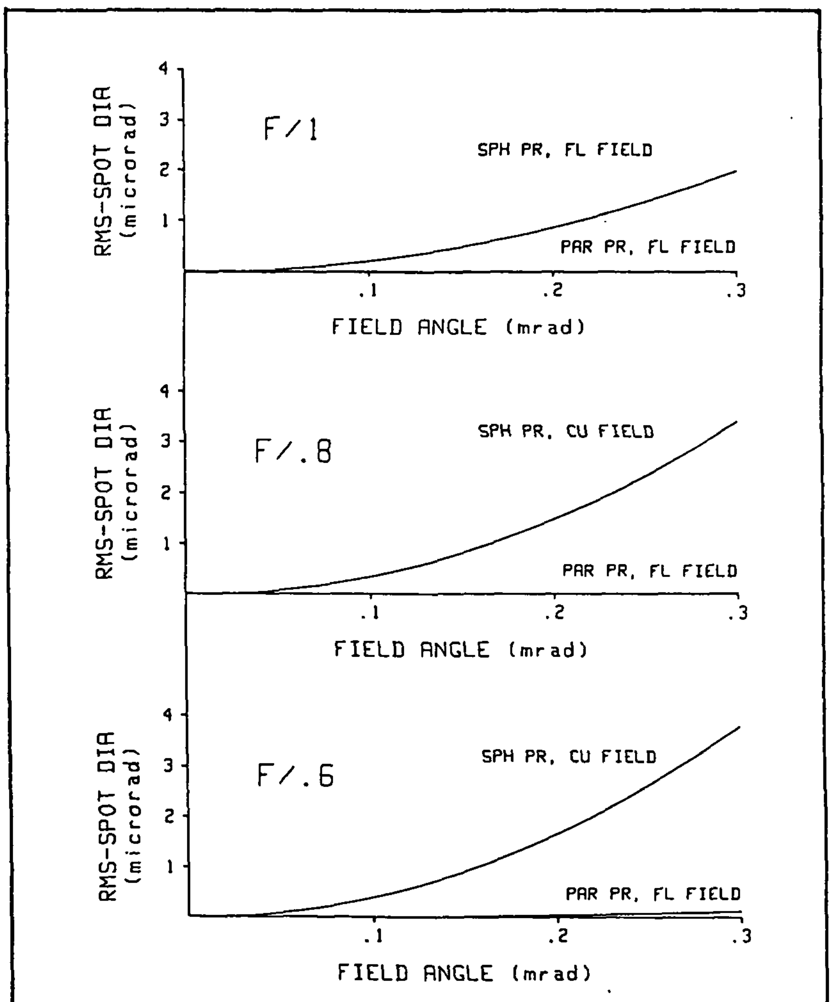


Fig.5: Geometric rms-spot sizes as a function of the field angle (FL=flat, CU=curved)

Table 1: Misalignment Sensitivities of the three Correction Mirrors

SECONDARY

RMS-SPOT SIZE INCREASE IN RAD PER

	μrad TILT		mm DECENTER		mm DESPACE	
	SPH PRIM	PAR PRIM	SPH PRIM	PAR PRIM	SPH PRIM	PAR PRIM
F=1	1.1E-7	2.3E-8	2.6E-6	7.9E-6	1.6E-7	2.0E-6
F=.8	1.6E-7	3.1E-8	8.0E-6	14.E-6	9.2E-7	4.3E-6
F=.6	2.5E-7	4.5E-8	22.E-6	26.E-6	56.E-7	10.E-6

TERTIARY

RMS-SPOT SIZE INCREASE IN RAD PER

	μrad TILT		mm DECENTER		mm DESPACE	
	SPH PRIM	PAR PRIM	SPH PRIM	PAR PRIM	SPH PRIM	PAR PRIM
F=1	3.4E-8	3.6E-9	8.7E-6	9.6E-7	1.7E-6	8.2E-7
F=.8	14.E-8	4.9E-9	10.E-6	16.E-7	1.5E-6	16.E-7
F=.6	29.E-8	7.2E-9	35.E-6	30.E-7	7.8E-6	32.E-7

QUARTERNARY

RMS-SPOT SIZE INCREASE IN RAD PER

	μrad TILT		mm DECENTER		mm DESPACE	
	SPH PRIM	PAR PRIM	SPH PRIM	PAR PRIM	SPH PRIM	PAR PRIM
F=1	1.3E-10	1.6E-10	1.8E-6	4.5E-8	1.9E-7	7.4E-9
F=.8	4.3E-10	2.3E-10	10.E-6	9.2E-8	11.E-7	18.E-9
F=.6	11.E-10	3.7E-10	27.E-8	27.E-8	41.E-7	60.E-9

Conclusions

This comparative study of parabolic primary and spherical primary telescopes was conducted in view of the large and very large telescopes that are expected to be built in the future for ground-based as well as for space-based applications. To the optical designer the parabolic primary system represents unquestionably the preferred system. To the telescope maker this may not necessarily be true. Since the primary mirror is by far the largest component in the telescope system, its complexity will most certainly be an important consideration. This is particularly true for segmented mirrors. A spherical primary surely offers the utmost simplicity. This now prompts the following question: what would be the advantage in making the largest component as simple as possible while imposing a higher degree of complexity upon the much smaller and, therefore, more manageable components? The answer depends on the specific application and should be carefully considered.

The particular four-mirror configuration used for this study was chosen because it resembles the functional simplicity of a Cassegrain telescope, and because it offers the possibility to integrate two pairs of mirrors into common mounts. Different tertiary and quarternary locations as, for instance, used by A. Meinel et. al.[2] may be chosen to yield a shorter focal length and, if required, a flat field. Finally, the aspheric primary telescope could be further improved by freeing its surface figure to gain an additional degree of freedom for the optimization.

Acknowledgments

This work was done under NASA contract NAS8-36610

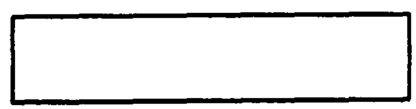
References

1. Korsch, D., "Highly Corrected Spherical-Primary Telescope Designs", Final report to Marshall Space Flight Center, Ord. No.: H-73833B (Oct. 1984)
2. Meinel, A.B., et.al., "Four-mirror spherical-primary submillimeter design", Appl. Opt. 23,3020 (1984)

II POINT SPREAD FUNCTIONS OF VARIOUS APERTURE GEOMETRIES

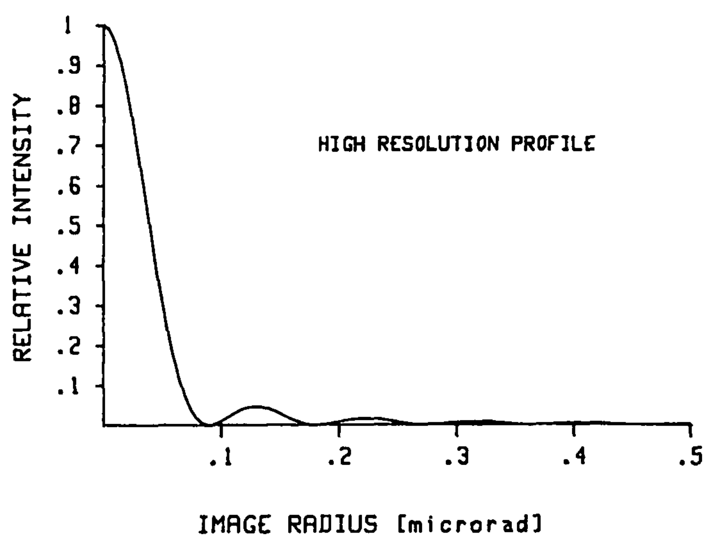
There may be various reasons for not selecting a conventional circular aperture for large telescopes. One reason may be to obtain the highest possible resolution for a given total surface area. Another reason may be physical constraints imposed by the launch vehicle, and yet another reason may be to save the cost and time required to fill a very large aperture, and one could, therefore, start with an underfilled aperture that could later be completed as time and money allow.

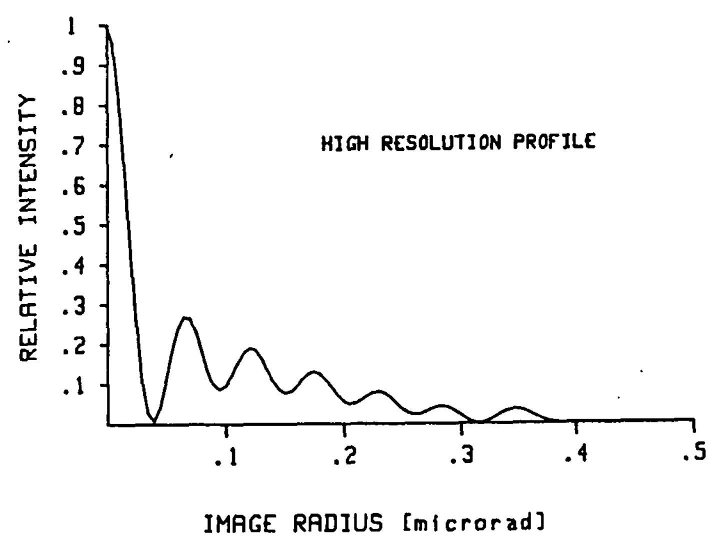
To this purpose point spread functions for a variety of aperture shapes and configurations were computed and plotted. The examples shown on the next four pages give an idea of how the point spread functions change with the shape of the aperture, and how it is possible to find optimum solution by slightly changing the geometry as, for instance, indicated by the examples of the annular aperture arrangements.

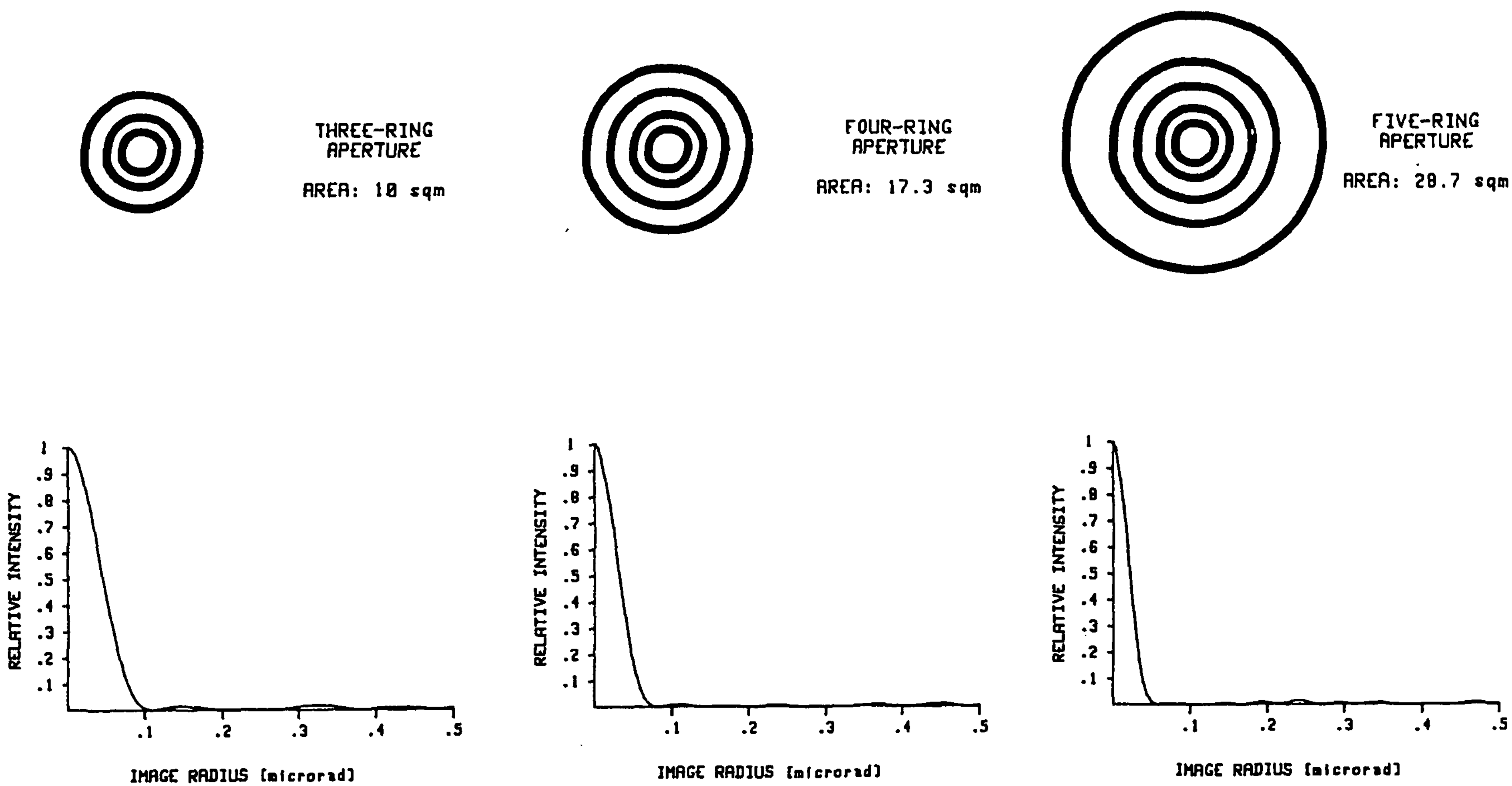


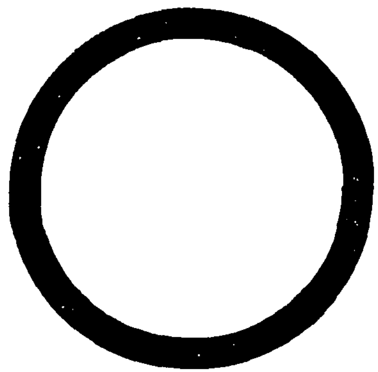
BAR-SHAPED APERTURE
AREA: 10 sqm

MINIMUM REDUNDANCY ARRAY OF 4 MIRRORS
AREA: 10 sqm

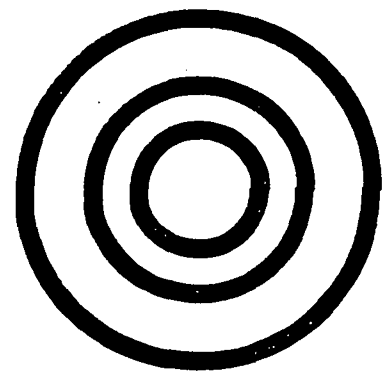




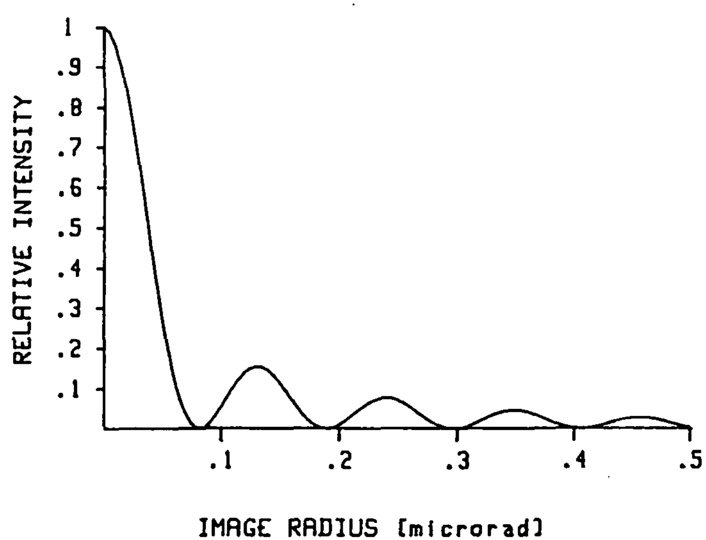

THREE-RING
APERTURE
AREA: 10 sqm
FOUR-RING
APERTURE
AREA: 17.3 sqm
FIVE-RING
APERTURE
AREA: 28.7 sqm
RELATIVE INTENSITY
1
.9
.8
.7
.6
.5
.4
.3
.2
.1
.1
.2
.3
.4
.5
IMAGE RADIUS [microrad]

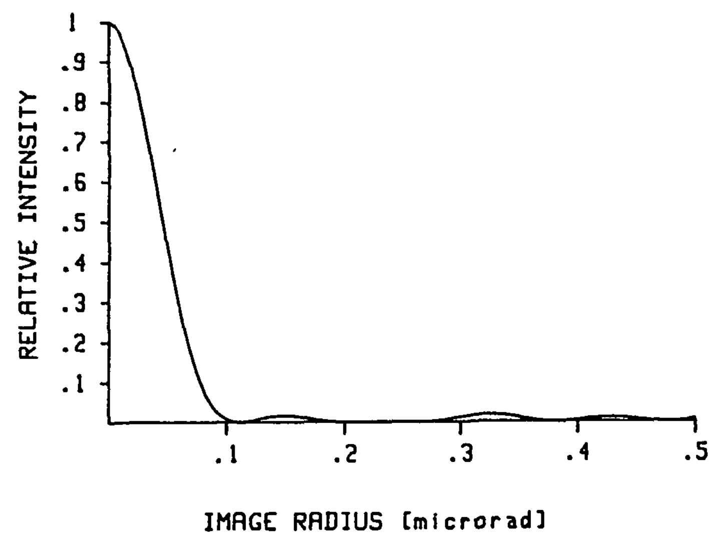


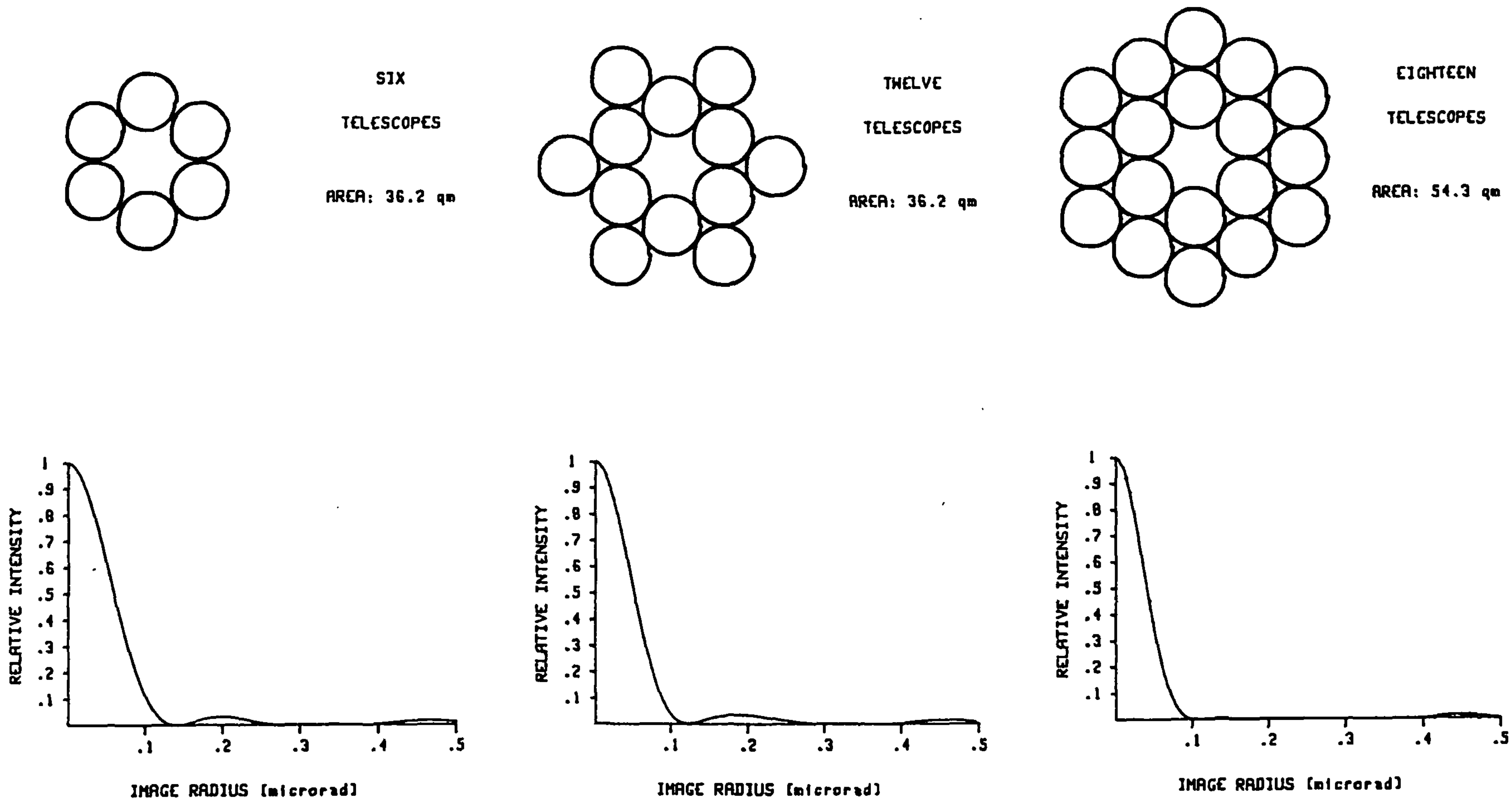
RING-APERTURE
AREA: 10 sqm



THREE-RING APERTURE
AREA: 10 sqm






SIX
TELESCOPES
AREA: 36.2 qm
TWELVE
TELESCOPES
AREA: 36.2 qm
EIGHTEEN
TELESCOPES
AREA: 54.3 qm
RELATIVE INTENSITY
IMAGE RADIUS [microrad]
RELATIVE INTENSITY
IMAGE RADIUS [microrad]
RELATIVE INTENSITY
IMAGE RADIUS [microrad]

III LAG ANGLE COMPENSATED 1.25 METER AFOCAL TELESCOPE

The purpose of this effort was to design a 1m class afocal telescope system with lag angle compensation which is to be used in a LIDAR type experiment, currently under investigation at the Marshall Space Flight Center.

The classical Cassegrain configuration is an excellent choice for an afocal telescope because it is corrected for all primary aberrations, except for field curvature and distortion. Spherical aberration and coma are even beyond the third order rigorously corrected. A possible disadvantage of the Cassegrain telescope is that the exit pupil is virtual and located in the shadow of the secondary mirror which causes a lateral beam shift for off-axis angles in the narrow beam. This is usually acceptable for small field angles. If not, the configuration must be changed to a focusing telescope followed by a collimating lens (mirror) that at the same time relays the exit pupil to the desired location.

The following design parameters are for an afocal Cassegrain type telescope with an aperture diameter of 1.25m on one side and 6.25cm on the other side.

Primary Mirror

shape	: paraboloid
vertex radius	: -400cm
diameter	: 125cm

Secondary Mirror

shape	: paraboloid
vertex radius	: -20cm
diameter	: 6.25cm

primary-secondary separation	: 190cm
secondary magnification	: 20
exit pupil location	: 9.5cm behind secondary

A meridional section of the afocal telescope is given in fig.1. The beam quality in terms of the residual aberrations (rms-decollimation) as a function of the off-axis angle is given in fig.2. The alignment sensitivities were determined by exact ray tracing. To this end the secondary was moved relative to the primary to simulate the three types of misalignment, tilt (angular), decenter (lateral) and despace (axial). The sensitivity values are given in terms of the rms-decollimation per unit misalignment.

Tilt : 1.9 μrad decoll. per mrad tilt
Decenter: 19 μrad decoll. per mm decenter
Despace : 2.2 μrad decoll. per μm despace

This telescope system is to be used in a LIDAR type experiment where an expanded laser beam will be projected onto a target, and its range will be determined by processing the return beam. Because of the finite propagation time of light, a relative motion between telescope and target causes the return beam to form an angle (lag angle) with the initial line-of sight of the telescope. A method to compensate the lag angle within the return beam processing train is depicted in fig.3. The return beam is shown to form an angle with the initial outgoing laser beam. The beam is then folded by a beam splitter towards a set of two tip-tilt mirrors. The first tip-tilt mirror directs the beam towards the center of the second tip-tilt mirror which in turn directs the beam along an axis parallel to the optical axis of the following beam reducer. The purpose of the beam reducer is to match the diameter of the return beam with that coming from the local oscillator. Both beams are then united by means of a beamsplitter and finally focused onto a detector for comparison.

It should be noted that the target-sided lag angle appears,

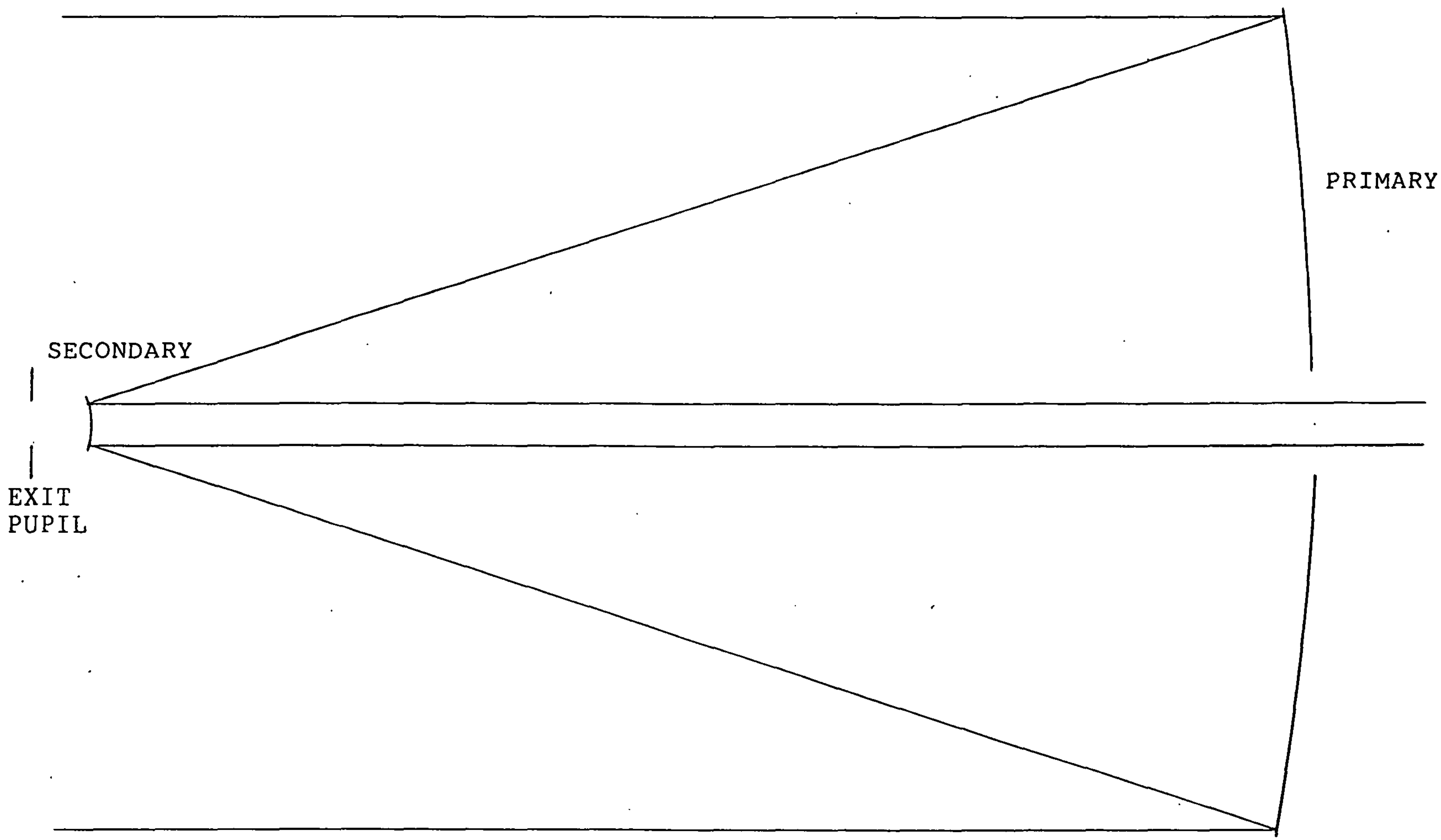


FIG. 1: TELESCOPE CONFIGURATION

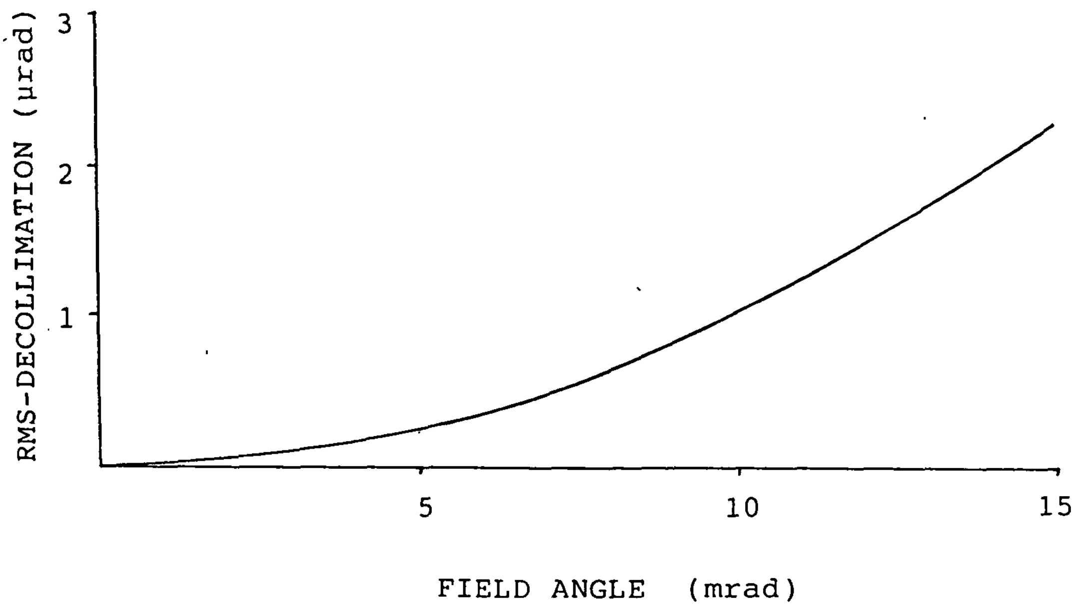


FIG. 2: BEAM DECOLLIMATION AS A FUNCTION OF THE FIELD ANGLE

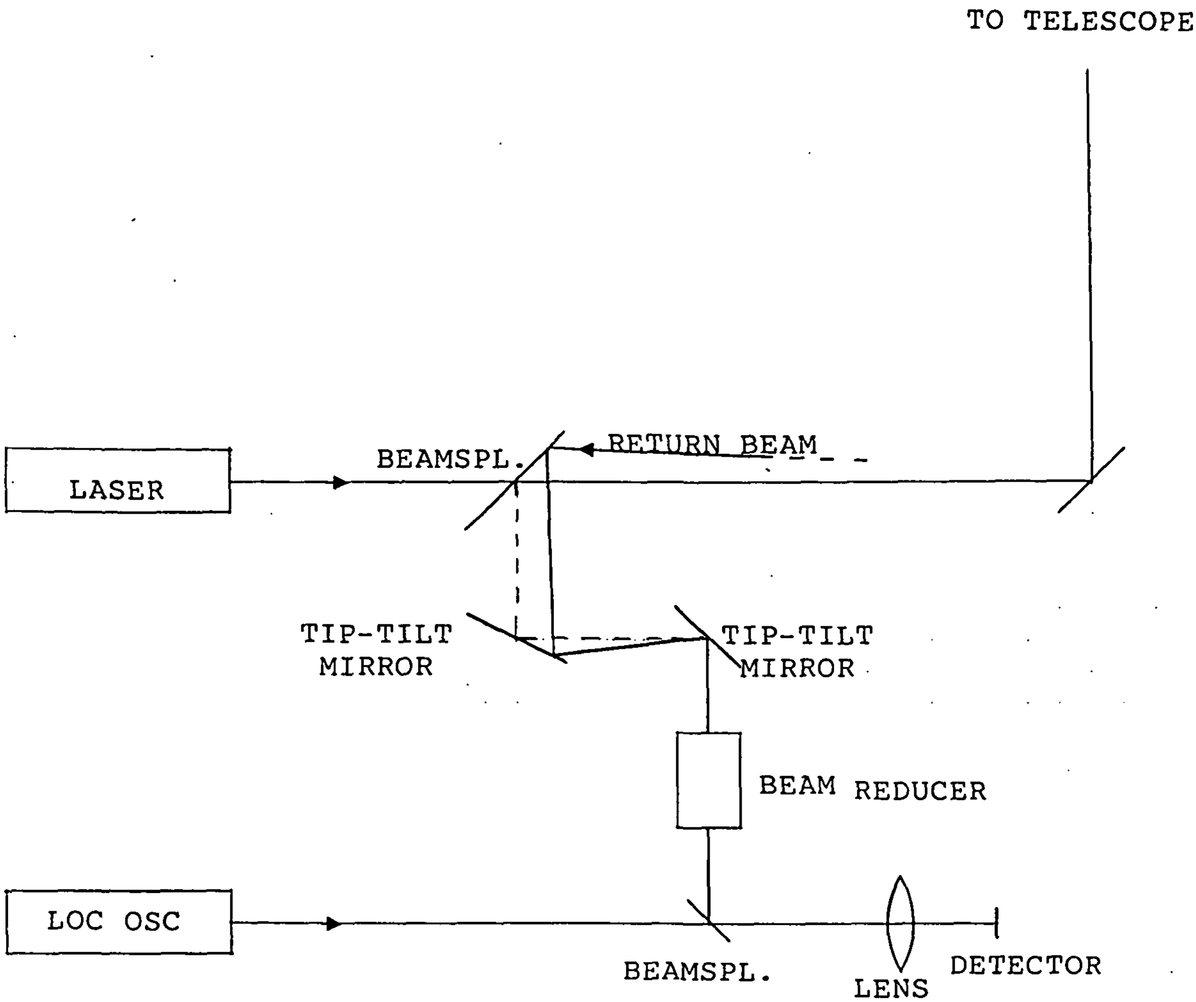


FIG. 3: BEAM COMPENSATION AND PROCESSING TRAIN

because of the secondary magnification, twenty times enlarged after being reflected off the secondary. That is, the lateral beam shift at the location of the beamsplitter is, if α is the target-sided lag angle and l the distance from the exit pupil to the beamsplitter, $20\alpha l$. With $\alpha=.00011$ rad and $l=250$cm we obtain a beam shift of 5mm.