MAGELLAN PROJECT

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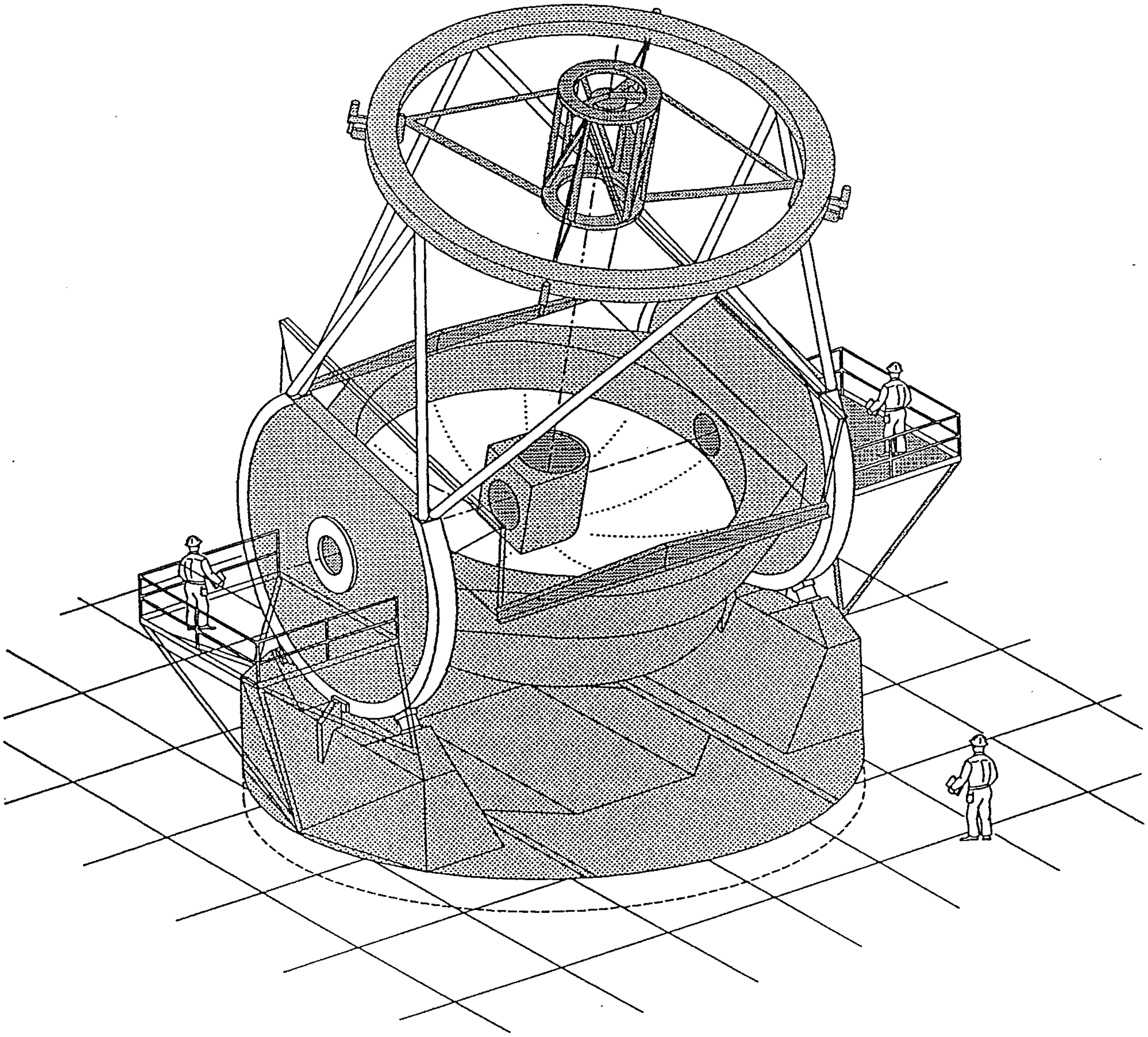

Preliminary Optical Design for the Magellan Telescope Gregorian Nasmyth Focus

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I. Introduction

Previously, the baseline plan for the Magellan telescope has called for the wide-field Cassegrain configuration to provide the principal focus for use at optical wavelengths. The wide-field Cassegrain is specifically optimized for use with fibers. However, a number of operational problems involved with this design have not been completely addressed. In particular, these include the difficulties associated with the installation and removal of the very large baffle system which is required for this focus, of the large optical corrector assembly which is located in the central hole of the primary mirror, and of the secondary mirror itself. In view of these difficulties, there has never been a realistic expectation that it would be possible to change the telescope from the infrared to the optical configuration during the night. In addition, several attempts by Harland Epps to design a wide-field imaging spectrograph for the fast Cassegrain focus have been only marginally successful.

The Gregorian Nasmyth design attempts to address each of the difficulties encountered with the Cassegrain configuration. The Nasmyth flat is mounted on an extension of the Cassegrain instrument rotator which projects through the central hole in the primary mirror. Rapid instrument changes are accomplished by rotating the tertiary mirror turret to one of five focal stations, or folding the flat out of the beam entirely. The Gregorian field corrector is permanently mounted in the tertiary mirror turret, but the flat mirror can be configured so that the optical path passes through the field corrector or does not. The smaller IR Cassegrain secondary can be folded down in front of Gregorian secondary without removing either from the telescope (the Gregorian secondary can be removed to improve the IR performance). Finally, the wide-field imaging function is performed through the spectrograph, where a small baffle at the collimator exit pupil replaces the large conventional baffle system in the telescope. The Gregorian Nasmyth design is specifically optimized for use with the wide-field imaging spectrograph, but is not particularly well-suited for use with fibers. However, eventual implementation of the wide-field Cassegrain focus, although expensive, is not precluded by the new design.

The optical design presented in this report calls for a 6 x 8 inch reflecting grating spectrograph with a 24 arc-minute diameter field. The choice of 6 x 8 in. grating size is based on practicality. The field corrector and collimator for this configuration have proven to be easy to design and exhibit very high optical performance. A fully satisfactory camera has not yet been designed and will be much more difficult to achieve. The choice of grating size and field size probably deserves further consideration. The primary mirror is still an f/1.25 paraboloid.

II. Gregorian Secondary Mirror

The principal motivation for changing from a Cassegrain to a Gregorian secondary mirror is to change the sign of the field curvature. The Gregorian secondary produces a concave field which is a good match to designs for wide-field refracting collimators. Reflecting collimators in general prefer fields which are curved in the Cassegrain sense (convex). Reflecting collimators have been adopted by the Keck LRIS and DEEP spectrographs. It is not yet clear how well these designs compare to the refracting collimator design which is presented in this report.

The focal-ratio of the secondary is dictated within a narrow range by the design of the collimator. For a spectrograph which uses 6 x 8 in. reflecting gratings, the optimum focal ratio is near f/11 (when the back focal distance is appropriate for the Nasmyth location). Even for more general collimator designs than the one presented here, the allowable range of focal ratio is probably not much greater than f/10 to f/12. Harland Epps investigated a somewhat different configuration and was unable produce acceptable images at a focal ratio which would be equivalent to f/16. He was at least moderately successful at the equivalent of f/13. For the remainder of this report a focal ratio of exactly f/11.0, with a back focal length of 4176 mm has been adopted. These numbers will probably be modified slightly during the detailed design phase.

If the secondary is sized in order to avoid vignetting the 24 arc-min field, then the optical clear diameter is 1327 mm or 52.25 in. Physically, it might be desirable to make the secondary mirror somewhat oversized (perhaps 56 in.?) in order to improve the figure near the edge of the illuminated area. The secondary mirror surface is located 9702 mm or 31.83 ft. in front of the primary mirror.

The Gregorian secondary has a conic constant of -0.63, which is only about half of the value for the equivalent Cassegrain secondary. This means that the aspheric deviation is also about half as large, and commensurately easier to achieve. The Gregorian secondary has 2 real conjugate foci (the prime and Gregorian foci), and is consequently much easier to test. The radius of curvature of the secondary mirror is 2832 mm, so it has a focal ratio of f/1.07, but it is about as aspheric as an f/1.25 paraboloid. It should be easier to figure than the Vatican primary mirror, which is both larger and more aspheric, and much easier to figure than the wide-field Cassegrain secondary, which is larger, has a conic constant of 2.63, and cannot be tested at real conjugate foci.

The secondary mirror produces an image of the primary approximately 1800 mm (70.9 in.) from the secondary. This is probably a good place for an auxiliary baffle, which should be 1100 mm (43.3 in.) in diameter. The region of the prime focus, the secondary mirror and auxiliary baffle is shown in Figure 1. The rays shown are at field angles of -12, 0 and +12 arc-min.

The uncorrected secondary focus produces nominally perfect images on axis, but the usable field size is limited by coma and astigmatism. With a slight re-focus from the on-axis optimum, the image diameter at the edge of a 6 arc-min diameter field is 0.4 arc-sec (100% encircled energy) or 0.25 arc-sec rms (Figure 2).

III. Diagonal Mirror and Field Corrector

In order to deflect the light to the Nasmyth location a flat, diagonal tertiary mirror is required. The tertiary mirror intersects the optical axis 9001 mm (29.50 ft.) from the secondary mirror or 701 mm (27.6 in.) in front of the primary mirror. The sagitta of the primary mirror is 325 mm (12.8 in.) so the deflected optical axis passes 376 mm (14.8 in.) in front of the edge of the primary mirror. The uncorrected Nasmyth focus occurs 4877 mm (192.0 in.) from the primary optical axis. (These dimensions will probably be modified slightly during the detailed design phase.)

The illuminated area of the diagonal mirror is elliptical in shape. For a field 24 arc-min in diameter, the length of the minor axis of the ellipse is 737 mm (29.02 in.), and the major axis 1042 mm (41.03 in.). Because the illuminated area is shrinking on its way to the focus, the center of the ellipse is displaced in the plane of the flat by 13 mm from the place where the optical axis intersects the tertiary. It may be desirable to make the physical size of the diagonal slightly oversize (33 x 45 in.?) in order to improve the figure near the edge.

A two-element field corrector is located close to the tertiary mirror. The region around the tertiary mirror and the field corrector is shown in Figure 3 (the diagonal mirror is shown schematically, without an actual reflection). In the preliminary design the two elements are fused silica. The surfaces are spherical. In the final design, each of the two elements will probably be made from a pair of slightly wedged lenses cemented together to form a zero-deviation prism. The two elements will then be mounted in independently rotatable cells in order to implement an atmospheric dispersion compensator without introducing any additional glass-air surfaces. There may be some loss of UV transmission compared to using a fused-silica field corrector without an ADC. Harland Epps has advised against combining the field corrector and the ADC. I think that his objections stem from the loss in the UV and the greater difficulty of maintaining optical alignment of the rotating lenses. These issues deserve further study.

The optical clear diameter of the field corrector is 710 mm (28.0 in.). The total depth from the front edge of the first element to the back edge of the second element is 171 mm (6.7 in.). The thickness of the elements can be adjusted in order to make the elements easier to fabricate or to improve the UV transmission, so the final front-to-back thickness may be somewhat different. With no loss of optical performance, the overall location of the corrector can be adjusted in the final design to the most mechanically advantageous position.

The polychromatic spot diagram produced by this corrector is shown in Figure 4. The spots are traced at 3 wavelengths (365, 500 and 1000 nm). The four field positions correspond to diameters of 0, 12, 17 and 24 arc-min. The scale-bar is 0.25 arc-sec long. The largest spot is 0.08 arc-sec in diameter (100% e.e.).

The corrector shifts the location of the Nasmyth focus 89 mm (3.5 in.) closer than the uncorrected focus (the secondary must be moved out 1.6 mm when the corrector is in use). The images produced by a corrector which does not introduce this focus shift are about a factor of 2 larger. In order to allow for fabrication tolerances in the conic constants of the primary and secondary mirrors, it is also necessary to allow for some additional variation in the focus position, perhaps to a total of 125 or 150 mm. This can be accomplished by using spacers at the instrument rotator mounting flanges. In this case the nominal position of the uncorrected Nasmyth focus (15 in. beyond the flange) is probably not large enough, and should be changed in the final design. Because of the focus shift, special provisions will be required to effect rapid changes from using an instrument with the corrector/ADC to using the same instrument without the the corrector/ADC.

The corrected focal ratio is f/10.97 and the corrected scale is 0.346 mm / arc-sec. The diameter of the 24 arc-min field is 498 mm (19.6 in.). The radius of curvature of the focal surface is 1214 mm, so the sag across the 24 arc-min field is 25.5 mm. In all likelihood the same diagonal and corrector can be used over a 30 arc-min field (diameter 622 mm or 24.5 in.). For a point source the diameter of the illuminated area at the corrector is 376 mm (14.8 in.). For a point at the edge of a 30 arc-min field, the illuminated area will move off the edge of the corrector by 41 mm (1.60 in.), which will result in vignetting of less than 9%.

IV. Collimator

The optical layout of the collimator is shown in Figure 5. The first element is a large fused-silica field lens which is required since the field is much bigger than the collimated beam. The field lens cancels most of the field curvature of the telescope (this is the advantage of the Gregorian configuration). The optical performance improves if the field lens is moved closer to the focal plane, but a minimum separation of 50 mm has been maintained. Any dust on the field lens will be sufficiently out of focus that the flat-field performance will not be degraded by microscopic flexure or drift in the spectrograph. The thickness of the field lens has been held to a minimum in order to reduce material weight and cost (a detail is shown in Figure 6). If necessary, the lens can be made slightly thicker with negligible effect on the optical performance.

The optical power is supplied by a cemented fluorite triplet which is kept 300 mm away from the exit pupil so that there is room to put in a reflecting grating. Between the field lens and the triplet are two weak correcting lenses made of fused silica. All surfaces are spherical.

The nominal diameter of the collimated beam is 150 mm, but aberrations of the exit pupil raise the optical clear diameter at this point to 154 mm (6.1 in.), which slightly overfills the grating. The optical clear diameter of the fluorite lens is 251 mm (9.9 in.) which is still a practical size according to Epps. The front and back elements of the triplet are UK50 glass which is no longer available, but other glasses can be substituted. (Or, for enough money, UK50 could probably become available again.) The transmission of UK50 glass in the ultraviolet (average thickness 65 mm) is 70% at 334 nm. The lenses can probably be made thinner in order to improve the UV transmission. Because of the difference in thermal expansion coefficient, the triplet must be cemented with a compliant cement; this technique has been used successfully on 2 smaller spectrographs at Las Campanas.

The polychromatic spot diagram produced by the telescope and collimator are shown in Figure 7. The spots are traced at 3 wavelengths (365, 500 and 1000 nm). The four field positions correspond to diameters of 0, 12, 17, and 24 arc-min. The scale-bar is 0.5 arc-sec long. The largest spot is less than 0.2 arc-sec in diameter (100% e.e.). The rms spot diameters at the four field positions are 0.03, 0.05, 0.07 and 0.08 arc-sec, respectively. There are more than 20,000 rms-spot diameters across the 24 arc-min diameter field.

A worst-case test of the imaging performance of the collimator in the ultraviolet is shown in Figure 8. The spots have been traced with equal weights at 5 wavelengths (390, 375, 360, 335 and 320 nm). The secondary mirror position has been adjusted by 5 microns in order to produce the best focus. The spots are 0.5 arc-sec in diameter (100% e.e.), or 0.19 arc-sec rms. For any other typical broad-band color, the spots are as good or better than the ones in Figure 7.

V. Camera

The 24 arc-min field of the telescope corresponds to a field diameter of 17.3 deg at the camera. Ideally the field diameter should be somewhat larger to allow for some dispersion at the grating for objects near the edge of the field. A practical camera must be fast enough to reimage the field onto a single large CCD or perhaps a 2 x 2 array (for example, a set of four 4K x 4K x 15 micron CCD's covering a 123 x 123 mm area).

The Epps refracting camera for COSMIC (Figure 9) is an interesting starting point. The field diameter is 21.2 deg. The Epps design must be scaled by a factor of 1.73 in order to match the collimator exit pupil. The entrance pupil is too close to the lens (88 mm) for use with reflecting gratings, but is adequate for use with transmission gratings or direct. The lens is optimized over the wavelength range 365 nm to 1100 nm. The scaled focal length of the camera is 387 mm, the collimator-camera reduction ratio is 4.26 and the final image scale is 81 microns / arc-sec. The scaled diameter of the 21.2 deg camera field is 145 mm, whereas the reimaged diameter of the 24 arc-min telescope field is 117 mm. The typical rms image diameter of 35 microns corresponds to 0.44 arc-sec. This is soft, but even at this resolution the performance is likely to be better in some respects than a fiber-optic spectrograph used over the same field.

In all likelihood the spectrograph will be built with 2 or more cameras. As the cameras are made slower, the image quality should improve rapidly. The "long" cameras will not cover the complete 24 arc-min field, but will work at the highest possible resolution. For example, a catadioptric camera has been designed which covers an 11 x 11 arc-min field with very high resolution, and with adequate spacing from the entrance pupil for use with reflecting gratings. The "short" cameras will cover the entire field, but with only moderate resolution. Conceivably, some or all of the cameras could be designed to share the same CCD mosaic.

VI. Acknowledgements

Some of the early work on the Gregorian configuration was performed in collaboration with R. Buchroeder. Some additional work was done by Harland Epps. Most of the optical design was performed using CODE V on a computer at the JPL Optical Sciences and Applications Section, which was made available by Jim Breckinridge. Help with the system was provided by Mark Markle. The design for the COSMIC camera was provided by Alan Dressler. The diagram of the COSMIC camera was made by Bill Kells.

Magellan Telescope
Gregorian Nasmyth Collimator
Preliminary Optical Design
Run 076: 24 arc-min Field

Surface	Radius	Thickness	Glass	Aperture	Comments
01	-16250.00000	-9703.6236375	REFL.	6500.000	Primary mirror (k = -1.000000)
02	2832.25520	9544.7210000	REFL.	1327.200	Secondary (k = -0.633486)
03	-6424.01244	60.0000000	SILICA	710.030	1st corrector element
04	-4108.26943	10.0000000		710.064	
05	1957.46577	50.0000000	SILICA	705.498	2nd corrector element
06	1633.98252	4126.1508833		696.090	
07	1213.90622	0.0000000		499.370	Telescope focal plane
08	1213.90622	50.0000000		499.370	
09	839.40756	55.0000000	SILICA	507.848	Field Lens
10	-6637.60848	1090.5208648		506.660	
11	-446.91171	20.0000000	SILICA	296.442	Collimator
12	-966.66400	123.2243853		299.478	
13	1155.24427	35.0000000	SILICA	297.650	Collimator
14	-3773.40217	225.3626876		295.612	
15	2274.04071	20.0000000	UK50	256.334	Triplet
16	381.01884	50.0000000	CAF2	250.700	Triplet
17	-796.35250	30.0000000	UK50	248.494	Triplet
18	-812.11570	0.0000000		245.764	

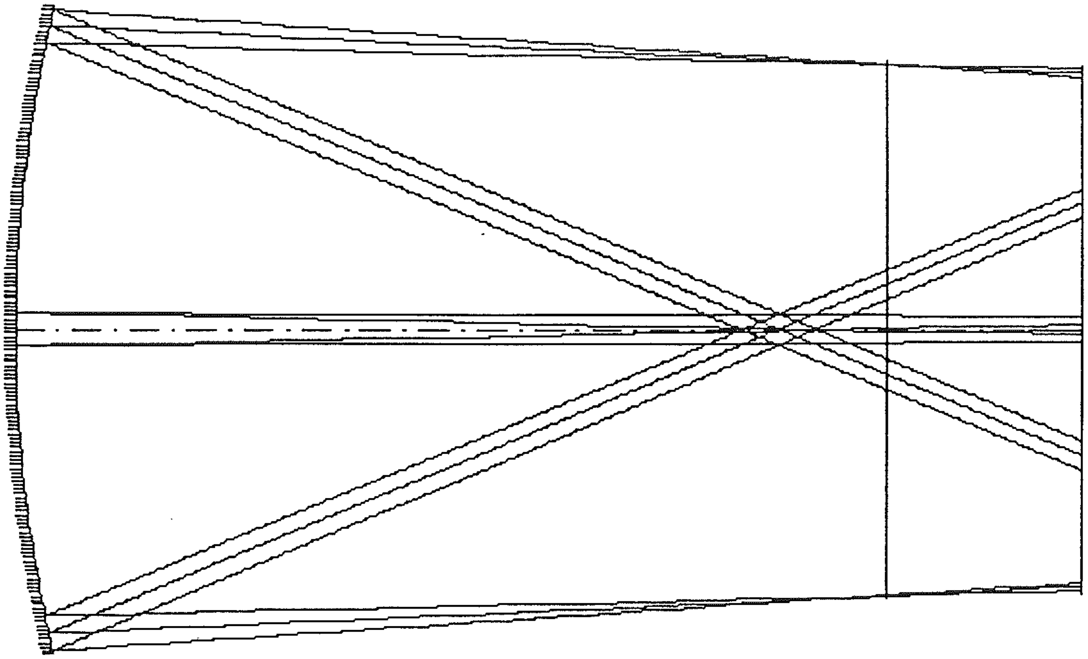


Figure 1

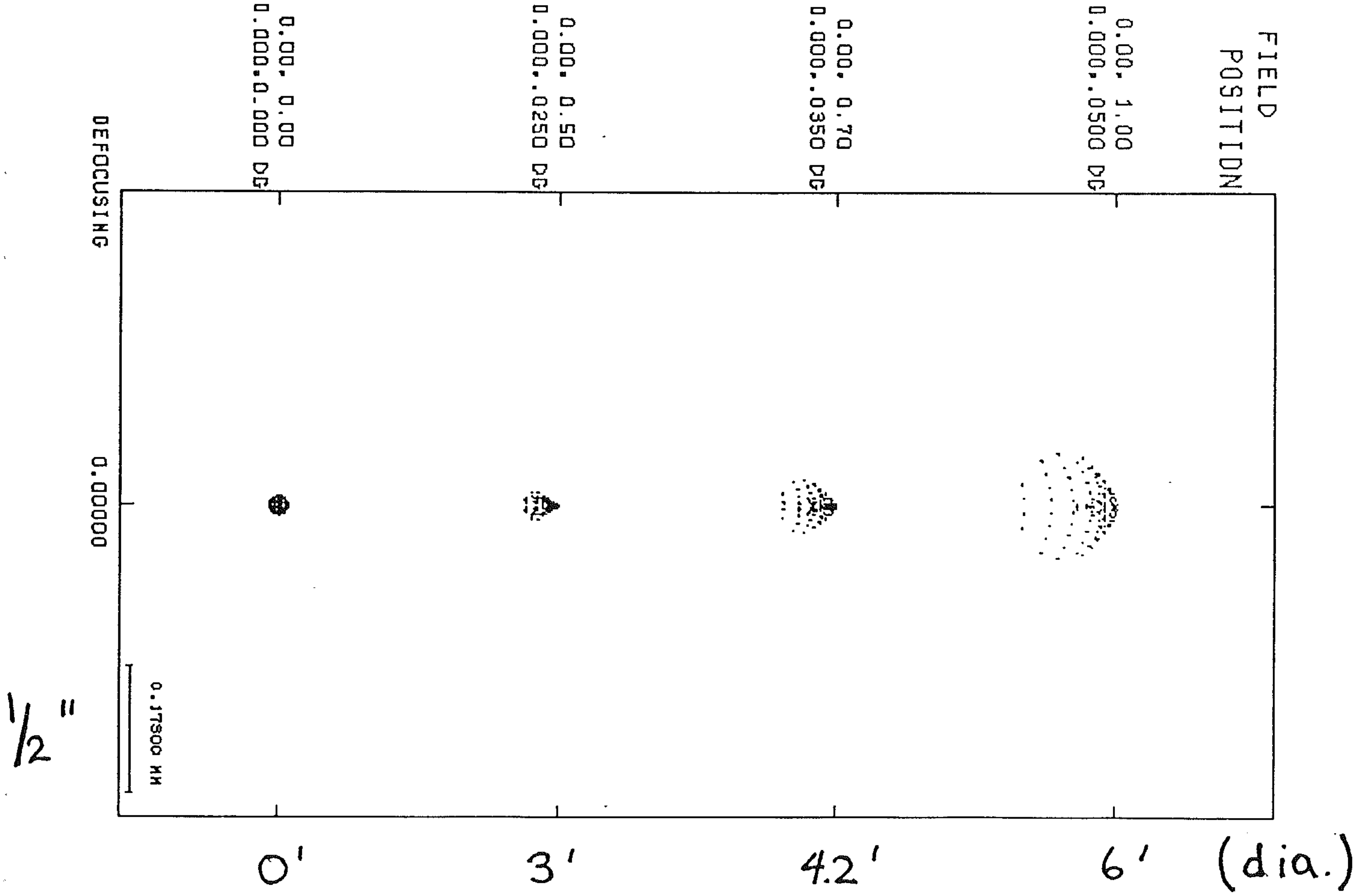


Figure 2

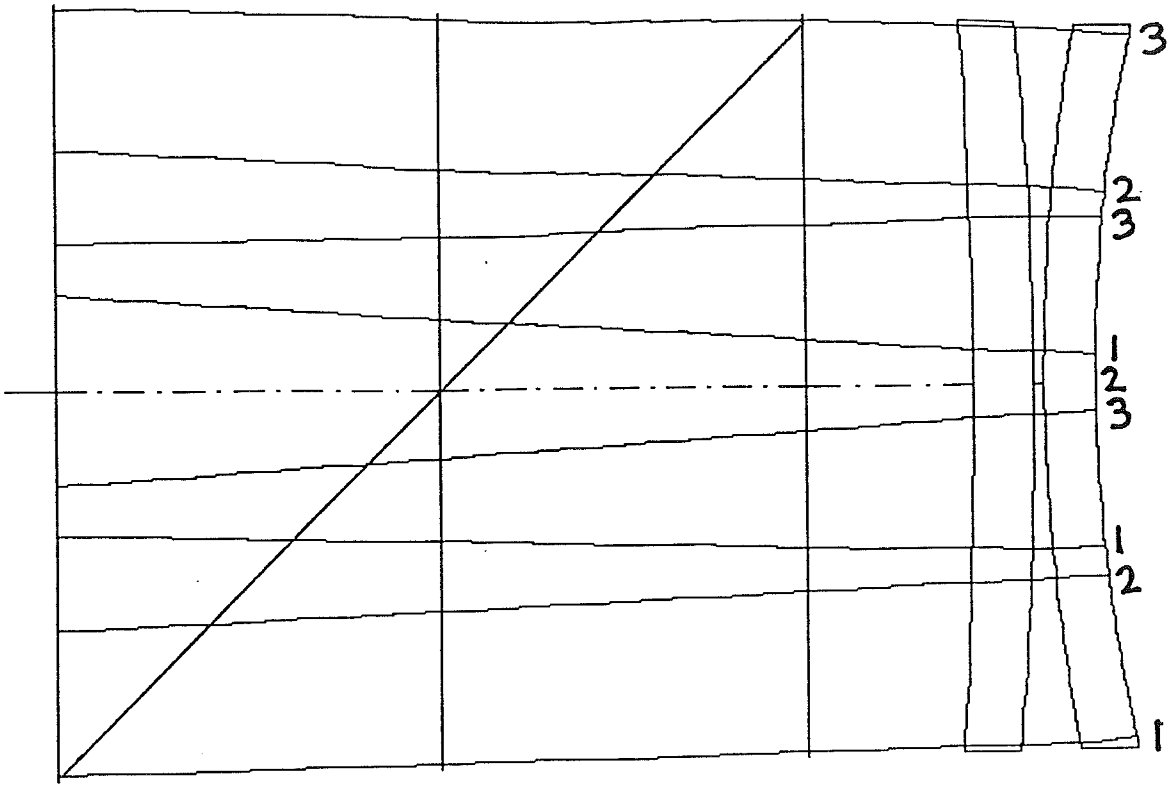


Figure 3

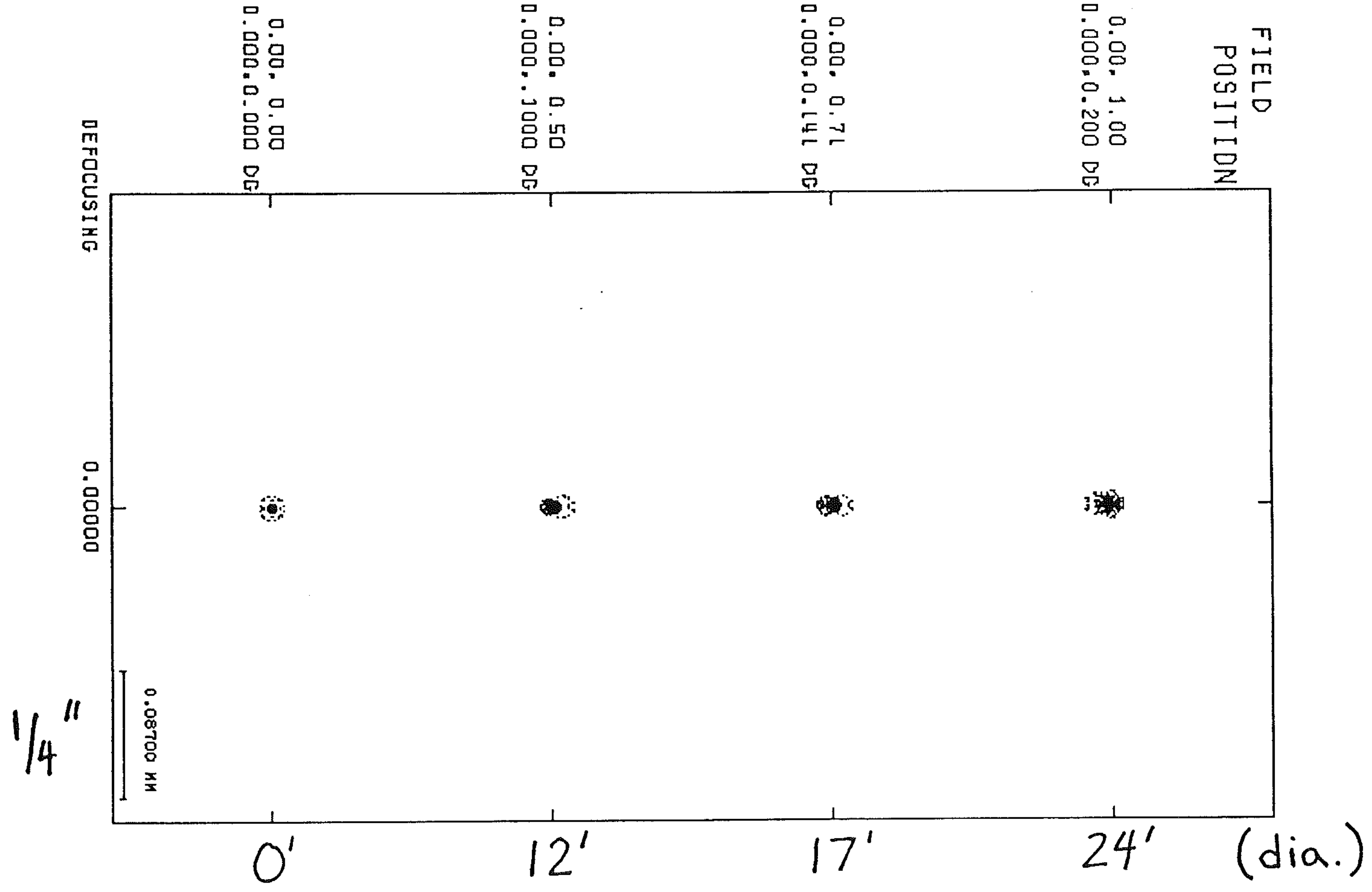


Figure 4

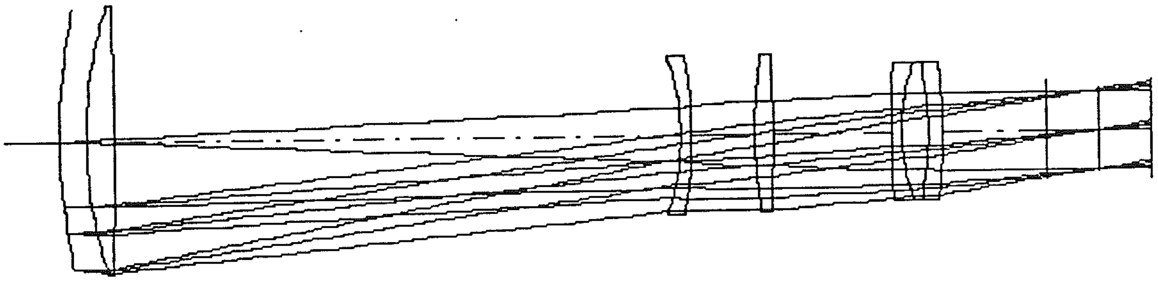


Figure 5

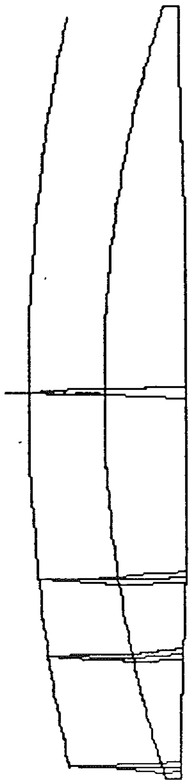


Figure 6

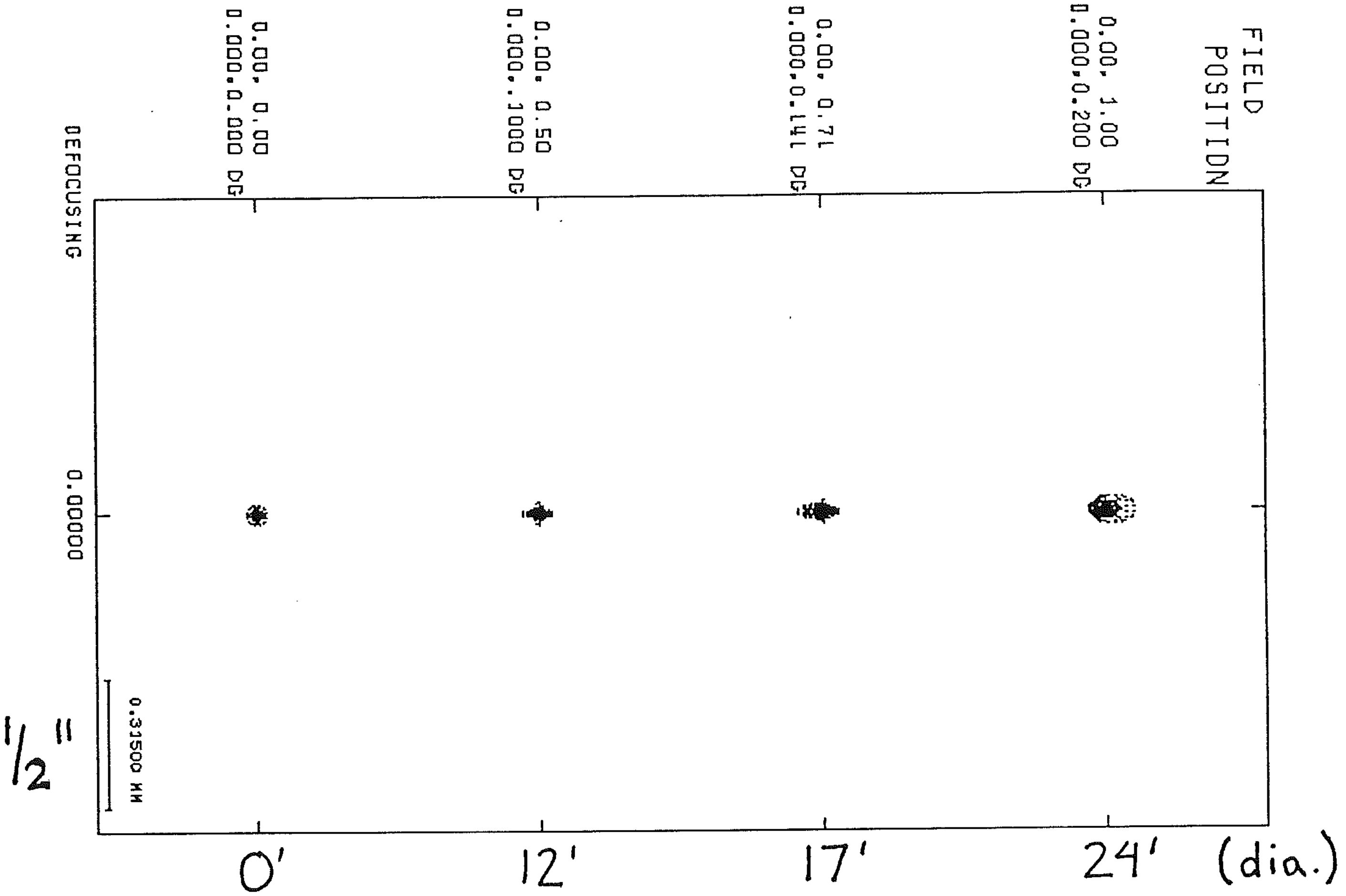


Figure 7

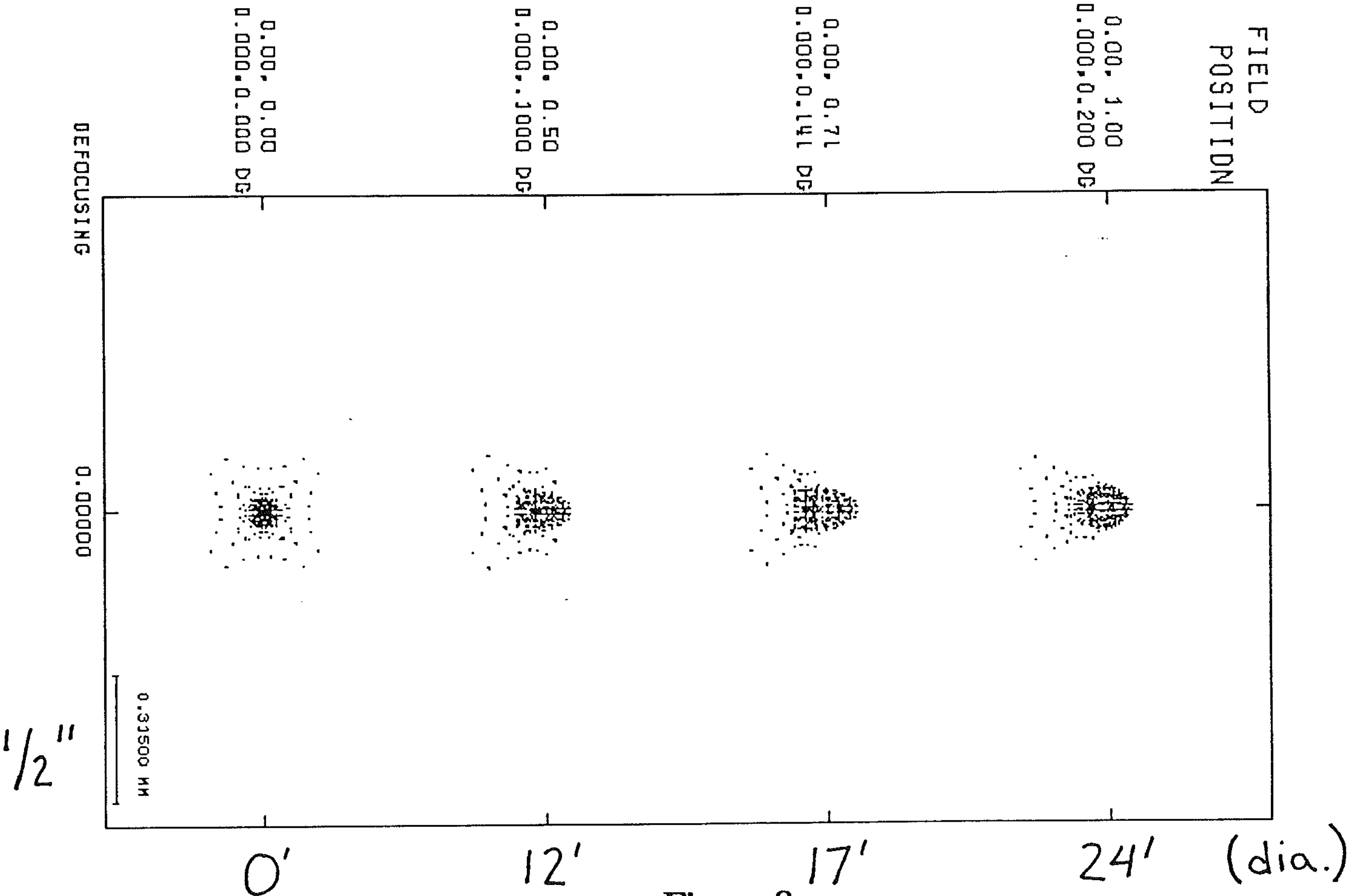
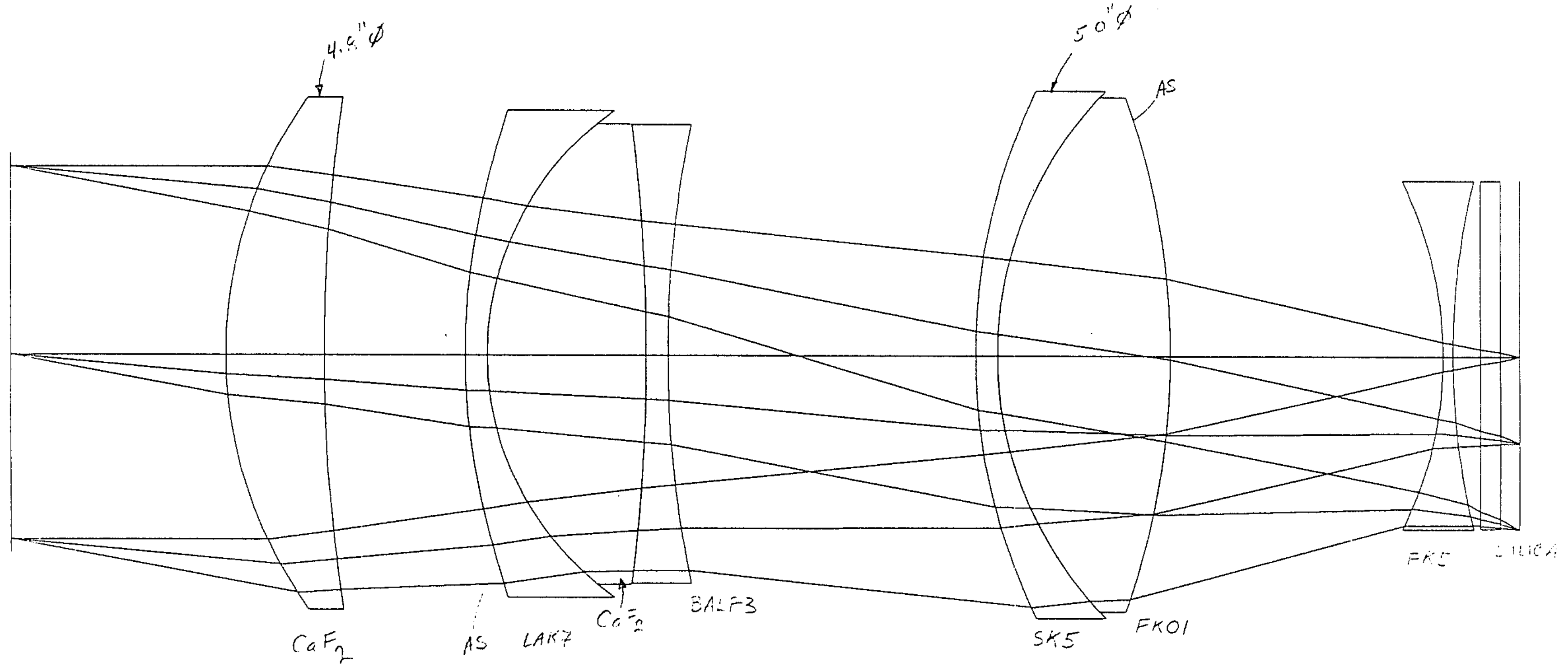


Figure 8

COSMIC



LAYOUT

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Figure 9