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MERIT FUNCTION FOR BIOCULAR MAGNIFIERS

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MERIT FUNCTION FOR BIOCULAR MAGNIFIERS

by

David Randall Wickholm

A Thesis Submitted to the Faculty of the

COMMITTEE ON OPTICAL SCIENCES (GRADUATE)

In Partial Fulfillment of the Requirements
For the Degree of

MASTER OF SCIENCE

In the Graduate College

THE UNIVERSITY OF ARIZONA

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All knowledge, great or small, can only be properly put to use when it is seen as originating in the Creator of all things. It is to the greater glory of the God and Father of our Lord, Jesus Christ, that this work is dedicated. It is written in the book of Deuteronomy: "The secret things belong to the Lord our God, but the things revealed belong to us and to our sons forever, that we may keep all the words of this law."

I wish to personally thank the following individuals who, in one way or other, contributed to the success of this work. First, without the devotion and sacrifice of my wife, Anne, and our children, none of this would have been attempted. Their encouragement has kept me going strong these last three years.

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ABSTRACT

Previously published work on the design and analysis of biocular magnifiers requires that large numbers of rays be traced from the eye locations to selected object points. A variation of this method which is compatible with the CODE V optical design software is discussed. The magnifier to be designed or analyzed is modeled using the multiconfiguration "zoom" option where three configurations are used differing only in stop size and location. The utility of the method is demonstrated in the analysis of two biocular magnifiers. Results are compared with other published methods of analysis.

CHAPTER 1

INTRODUCTION

During the last twenty years or so, applications for an optical system with an exit pupil large enough to encompass both eyes of the observer have arisen. Such a system, wherein both eyes of the observer use different parts of the same optical system from entrance pupil to exit pupil without any discontinuity between, is called a biocular system. Figure 1 depicts the differences between monocular, binocular, and biocular viewers.[1] In this work I shall confine myself to so-called biocular eyepieces or magnifiers. The most common examples of such devices are the standard hand-held 35 mm photographic slide viewers sold at most camera shops. The large magnifiers used as reading aids by some of our elderly citizens are another example of biocular magnifiers. I shall begin this work with a general description of biocular magnifiers and their advantages and disadvantages. We shall then examine the important design aspects of biocular magnifiers including their first order properties and the aberrations that should be controlled to yield a good design. This will logically lead to a proposal and discussion of a merit function to be used in the design and analysis of these devices. The proposed merit function will be used to analyze two common biocular magnifiers. A discussion of the utility of this merit function concludes this work.

Biocular magnifiers are presently used on many night vision devices where they have found wide acceptance. The device is used to present typically a 3x to 5x magnified image of the cathode ray tube (CRT) end of an image intensifier to the observer (figure 2). The observer sees an apparent field of view (FOV) in some cases approaching 50 degrees, though only 60% or less of this may be seen by both eyes simultaneously.

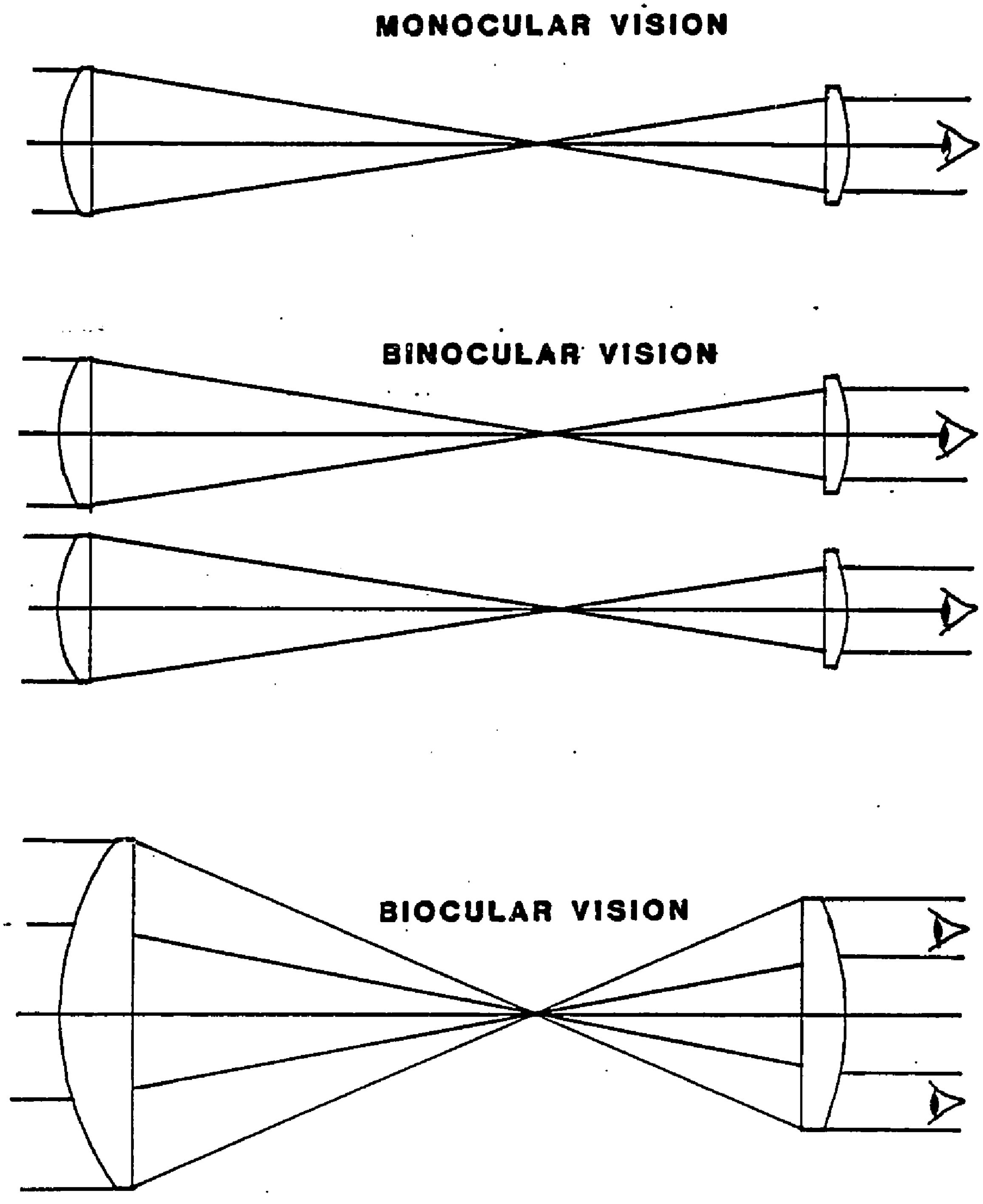


Fig. 1. Monocular and biocular vision.

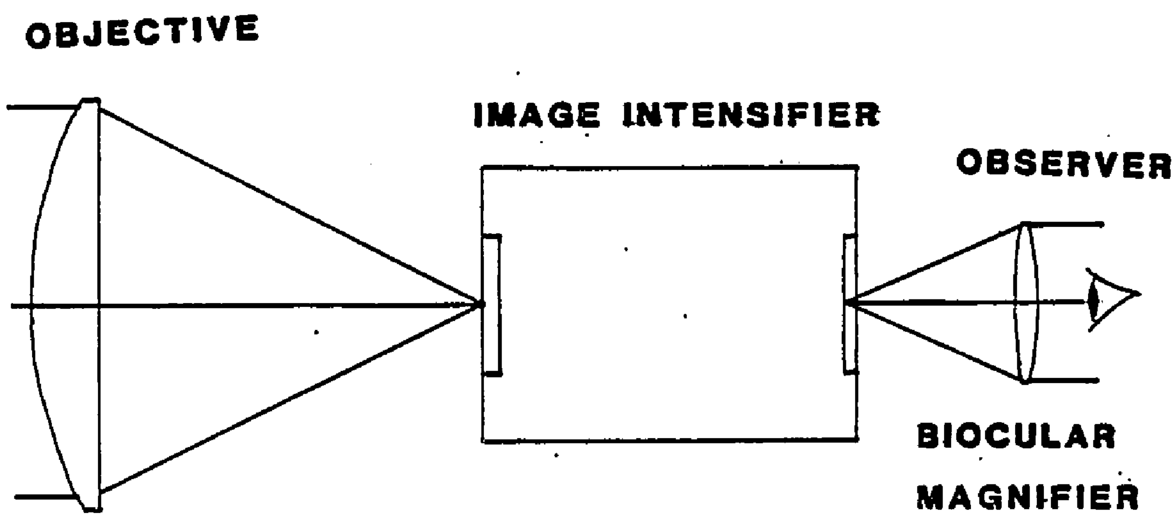


Fig. 2. Night vision device.

Studies[2] have shown that while biocular do not significantly increase the observer's ability to pick out targets, the fact that both eyes are used and that the observer's head has some freedom to move about produces much less fatigue.

It should be noted that the label, "biocular eyepiece," is somewhat of a misnomer in the previous example. A traditional monocular eyepiece produces an exit pupil which is the image of the aperture stop of the system objective. The night vision example has no such exit pupil because the image that the observer sees is formed by a CRT and not an objective lens. The "exit pupil" of a biocular device is defined by the diameter of the lens nearest the eye and the image location. The observer's iris is the instantaneous stop and exit pupil of the biocular device and therefore the device should be called a magnifier and not an eyepiece.

Biocular magnifiers are also used in Head Up Displays (HUD's) on modern fighter aircraft and in various kinds of visual flight simulators (figures 3 and 4). In both cases, the observer is viewing a magnified and sometimes relayed image generated by a CRT. If the image is relayed, then the system will indeed have an exit pupil which is the image of the limiting aperture in the system. In a HUD the magnified image of the CRT is collimated by the biocular magnifier and viewed through a partially transmitting window. The observer sees flight information superimposed on the normal view of the outside world. Since HUD's are often used to aim various weapons systems on the aircraft, the degree of collimation becomes critical to the accuracy of the weapons delivery system. Flight simulators may also be considered collimators, however, their physical size and field of view may be much larger than a HUD or night vision biocular magnifier.

As previously stated, one of the chief advantages of using a biocular magnifier rather than a monocular is that fatigue is much reduced and the observer is more free to move his head about. Two eye viewing is more natural and more comfortable because both eyes see essentially the same light level. The image presented to the observer is

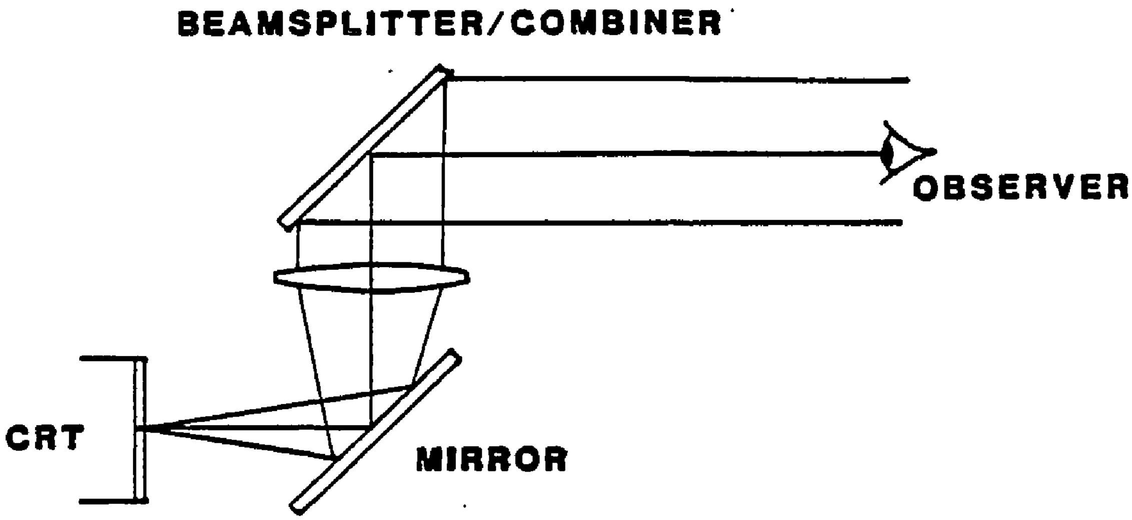


Fig. 3. Head up display.

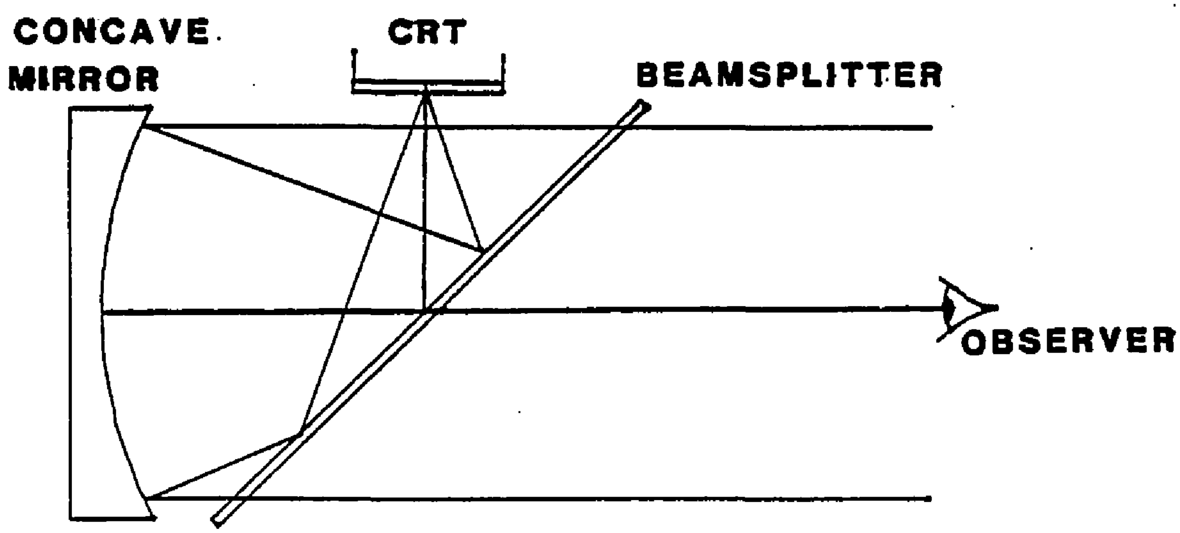


Fig. 4. Flight simulator.

usually brighter than that which would be seen with a binocular viewer because the binocular device divides the available light into two paths, one for each eye. Additionally, binocular magnifiers used with a single CRT require large prism trains that are not required with a biocular magnifier. Finally, biocular sport large eye relief.

Biocular, for all their good points, do have some inherent disadvantages. Since both eyes of the observer are to use a single optical system, the system typically is three inches or greater in diameter. A biocular magnifier is then obviously larger, heavier, and more expensive than a monocular magnifier. But perhaps more importantly, the large diameters of biocular magnifiers, and the fact that the working F# must exceed 0.5, limits the highest magnifications attainable in such devices to about 5.5x. If higher magnifications are required then one must look to other optical systems.

CHAPTER 2

IMPORTANT DESIGN ASPECTS OF BIOCULAR MAGNIFIERS

A thin lens magnifier as shown in figure 5, with focal length f, is used to observe an object of height h, at an object distance of ℓ. The observer at an eye relief d sees an image of height h', at distance ℓ' from the lens. Distances are negative to the left of the lens. The magnification M is given by equation 1:

$$M = \left(\frac{h'}{d-\ell'}\right) / \frac{h}{L} = \frac{L\left(\frac{1}{f} - \frac{1}{\ell'}\right)}{1 - d/\ell'} \tag{1}$$

where L is the standard viewing distance (usually 250 millimeters). It can be seen that when the image is collimated, eqn. 1 reduces to the familiar:

$$M = L/f \tag{2}$$

For an 80 mm diameter F/0.6 magnifier with an image at infinity, M = 5.2x. For a typical image distance of -500 mm and an eye relief of 50 mm, M also equals 5.2x.

The apparent FOV of the magnifier is given by:

$$\text{FOV (std)} = 2\tan^{-1}(h'/(d - \ell')) \tag{3}$$

In most biocular magnifiers, however, the eyes are located in such a position that not all of the image is visible by each eye (see figure 6). In this case, the diameter of the eye lens D, the eye relief d, and the interpupilary distance S determine the apparent FOV and the size of the region of biocular overlap. Each eye sees a circular FOV given by:

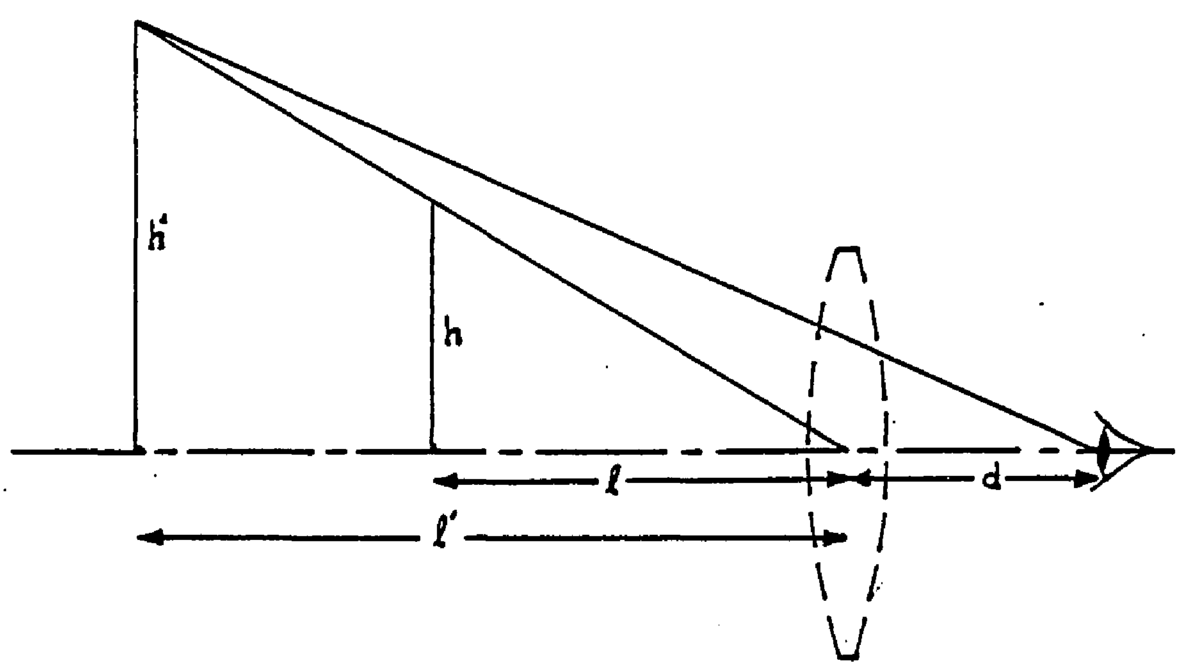


Fig. 5. Magnification.

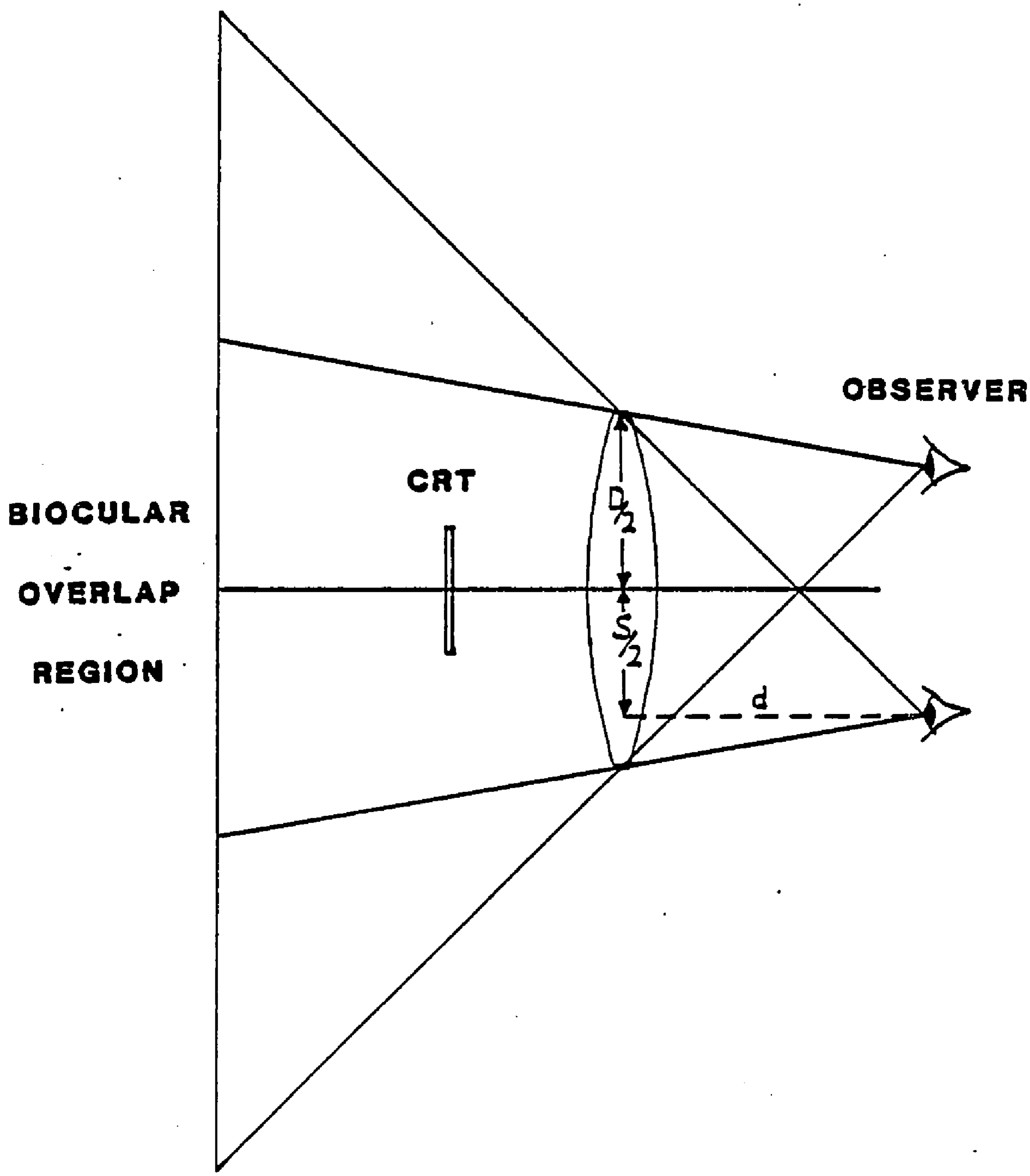


Fig. 6. Field of view.

$$FOV\ (eye) = \tan^{-1}((D + S)/2d) + \tan^{-1}((D - S)/2d) \tag{4}$$

The total apparent FOV seen by both eyes together is given by:

$$FOV\ (total) = 2\tan^{-1}((D + S)/2d) \tag{5}$$

The width of the overlap region is given by:

$$FOV\ (overlap) = 2\tan^{-1}((D - S)/2d) \tag{6}$$

For the example of an 80mm F/0.6 biocular magnifier with an image at infinity, an eye relief of 50 mm, and viewing a 40 mm diameter image intensifier CRT, one can calcualte the following FOV characteristics. The CRT subtends an angle of 45°; each eye can observe 64° of image space with a total FOV of 111° and an overlap FOV of 17°. In this case, the CRT diameter determines the useful field of view, therefore a 45° image is observed but only 38% of the image is seen by both eyes simultaneously.

Many biocular magnifiers, particularly those used in night vision devices, do not collimate the image but are focused at typically -2 diopters. The diverging light from the magnifier does not affect the FOV in any major way, but does permit greater head motion. For a typical eye relief of 50 mm the overall pupil at this location is 10% larger than at the exit surface of the magnifier. Often it is advisable to put a brow pad at the exit end of the magnifier to aid in locating the observer's eyes and to prevent injury in the event of sudden motion. Additionally, to save weight since the upper and lower parts of the magnifier are not used, the lenses are often truncated top and bottom.

Once the first order properties have been determined, the next question to be answered concerns the aberrations that must be controlled in order to yield acceptable imagery. In the case of the biocular magnifier it is very important to recognize that only two small pieces of the lens near the lens edges are used at any given instant. While the entire lens may be faster than F/1, each of the observer's eyes uses an F/10 to F/30 system. At these relative apertures, spherical aberration and coma are not seen as such. These aberrations show up as variations in image location and distance as the observer's head moves about within the overall pupil of the system.

The changing angular position of an image point as the observer's eye is moved within the magnifier's pupil is called parallax, or dynamic distortion. In many applications, parallax is the most important aberration to reduce. Walker, in the March and April 1973 issues of **Optical Spectra**[3,4], remarks that a tolerance of one milliradian (mrad) over the entire clear aperture is commonly applied to parallax errors in HUD systems. Walker proposes to control parallax by requiring that the angular size of the blur circle for the entire lens be kept below one mrad. He points out that if the blur circle size is controlled by chromatic aberration no additional parallax error results when the eye moves about because the peak wavelength dominates and determines the apparent image direction.

Some target value for static distortion (the difference between the paraxial image position for some field point and its real position) is required in order to present to the observer a relatively undistorted view of the world. For example, the optical system ahead of the magnifier may have had a certain amount of distortion deliberately designed in to compensate for distortion that can not be designed out of the magnifier.

System resolution requirements will set an upper limit on the size of the image blur as seen by each eye, and also on the allowable amount of chromatic aberration. The most frequently quoted value for the resolution of the typical human eye is one arc minute, or about 0.3 milliradians. However, the eye is known to tolerate less than perfect aids. Because the eye is afflicted with considerable chromatic aberration it is not absolutely necessary to fully correct the chromatic aberration of the system.

Also, because two eyes are used in biocular magnifiers, the amount of accommodation required of each eye and the convergence required of both eyes together must be addressed. These relate to field curvature and to the astigmatic focal surfaces for the parts of the magnifier that each eye uses, as well as the relative geometry of the two chief rays that pass through the center of both of the observer's pupils. If the distances to the convergence surface and the astigmatic focal surfaces for each eye differ too much, then the brain will receive very unpleasant stereo cues or may not be able to fuse the images from each eye into one. As an example, one certainly does not want a magnifier that requires the observer to focus either eye beyond infinity.

Palmer and Freeman[5] maintain that within the region of biocular overlap, up to a total of 0.6 diopter of defocus (between the convergent surface and astigmatic surfaces) is permissible, and that the astigmatic surfaces must not appear any more than 0.2 diopter closer to the observer than the convergent surface. the total amount of defocus over the full field of view should not exceed 1.0 diopter. Rogers[6] states that the angular differences in the geometry of the images seen by both eyes should be kept below 10 mrad for convergence, 5 mrad for divergence, and 2.5 mrad for dipvergence (vertical misalignment of the eyes' optical axes). Shenker[1] gives slightly different values based on commonly applied tolerances for 7 x 50 binoculars for biocular devices with infinity as their nominal focus setting.

These quantities, then: parallax (dynamic distortion), static distortion, image blur, color, convergence, accommodation, and image misalignment, should be addressed in the construction of a figure of merit for biocular magnifiers.

CHAPTER 3

MERIT FUNCTION CONSTRUCTION

The CODE V optical design and analysis software developed by Optical Research Associates was used in the analysis of several biocular systems. Computer time was generously supplied by the Hughes Aircraft Company in Tucson, Arizona. Before the computer could be used effectively it was necessary to define a merit function in terms compatible with CODE V. This led, logically, to a review of other published work in this area. It was not clear whether the default merit function that CODE V uses would be useful in this study. Within the CODE V package is a feature labeled "Biocular Analysis." Upon investigation it was discovered that this option was intended for HUD's and infinity focus systems and would not yield useful information for finite conjugate systems.

The first detailed discussion of merit function considerations was in a paper given by P. J. Rogers[6] in February, 1972 at Brighton, England. In this paper, Rogers identifies four basic performance characteristics to be controlled. They were: 1) the image blur of any object point in the field of view; 2) the parallax at any point in the field of view (dynamic distortion); 3) the static distortion of each image point relative to its paraxial location when viewed from the center of the magnifier exit pupil; and 4) the geometrical alignment of the images seen by each eye. Rogers states that the maximum angular misalignment permitted for the observer's eyes is 10 mrad for convergence, 5 mrad for divergence, and 2.5 mrad for dipvergence (supravergence). A fifth performance criteria can be inferred from the text: astigmatism and field curvature are to be held to less than the magnitude of the on-axis diopter setting. That is to say that no where within the system field of view will the eye be required to focus beyond infinity. Outside the region of biocular vision the fourth performance criteria is ignored.

Rogers states that Pilkington Perkin Elmer (PPE) has devised an optimization program that implements these criteria into a merit function. Thirty-seven object points and three pairs of eye positions are used to control the performance of the system. The stop of the system is set to 7 mm in diameter and is located at each of the eye positions. In position one, the eyes are centered on the horizontal axis and located 32 mm either side of the vertical axis. In position two, the eyes remain centered on the horizontal axis but displaced 10 mm to the right. In position three, the eyes are elevated 10 mm above the horizontal axis and located 32 mm either side of the vertical axis. Nine points spread over one quadrant of the object are viewed in position 1, sixteen points spread over half the field of view are viewed in position 2, and twelve points spread over half the field of view are viewed in position 3.

The program traces rays from the two eye locations to each object point and calculates the amount of eye convergence/divergence required, the amount of supravergence (dipvergence) present, and the approximate distance from the eye to the convergence surface. If asked, the program also will determine the approximate blur size for a given field point as well as the value of static distortion present. The program checks to see whether each field point is observable by one or both eyes. The user has the freedom to weight each of the rays to drive the design in a preferred direction. Targets and weights for static distortion are also supplied by the user.

Shortly thereafter, Martin Shenker of Farrand Optical published a survey paper[1] on biocular optical systems. While touching on a wide variety of such devices, Shenker devotes most of his paper to collimator type biocular systems such as flight simulators and HUD's. For these systems Shenker proposes a maximum of 24' (7 mrad) for eye convergence, 0' for divergence, and 15' (4.4 mrad) dipvergence. The 7 mrad convergence requirement is equivalent to a decollimation requirement of 1/9 diopter. Throughout the paper, this value is rounded off to 0.1 diopter and recommended as the proper order of magnitude when dealing with collimating biocular systems. It is pointed out that controlling the decollimation also controls parallax in infinity systems.

While not explicitely stated, it is apparent that the angular blur size and chromatic aberration figure in to Shenker's criteria for a good system. The location of the astigmatic and convergence surfaces are covered by the decollimation requirement. Depending on the specific device being discussed these criteria may be adjusted; for example, a Head Up Display used for weapons delivery will have a much tighter requirement on collimation. The main point seems to be that for infinity devices the figure of merit is largely a matter of decollimation.

In 1973, Bruce Walker of Kollmorgen, while not going into as much detail as Rogers and Shenker, seems to say much the same thing[3,4]. In Walker's view, collimation is controlled by controlling the parallax of a paraxially collimated system. Parallax, in turn, is controlled by keeping the angular size of the blur circle for the entire lens below 1 mrad. When it comes to finite conjugate devices such as biocular magnifiers for night vision systems, Walker agrees that astigmatism, convergence, and field curvature all need to be minimized, but offers no upper limit on the allowable amount of these aberrations. He points out that if some value of parallax is inherent in a system it is better that it occur over a large variation in eye position than a small one. Parallax should be controlled both absolutely and as a "rate of change" phenomena. In the example of a biocular eyepiece in Walker's paper it is stated that parallax should be kept below 5 mrad for head motions of 25 mm.

Dyer and Brennan of Baird Corporation, in a brief paper[7] given in 1977 (updated in 1984 as a general description of biocular eyepieces for potential customers) take a different approach by addressing specific classes of ray aberrations. It is stated that in order to obtain a high MTF at the limiting resolution of the eye, the spherical and chromatic aberrations must be well corrected. Static distortion must be addressed in the overall system design, the distortion inherent in the magnifier being partially cancelled by distortion of the opposite sign in the objective lens and image tube. Image "swimming," a combination of dynamic distortion and image misalignment, is controlled by a "proper correction" of the tangential and sagittal oblique spherical aberration, as well as higher order coma, and astigmatism. "Proper correction" is probably a company private subject, however, since the observer's eyes are near the edge of the overall pupil of the lens one would expect the control of high order aberrations to be important in obtaining smooth aberration curves over the pupil.

Within the last year a paper from Palmer and Freeman[5] reveals that the previously mentioned optimization program using the 37 ray merit function has been superseded by a new ray tracing program also developed by PPE. This program computes the locations of the convergent surface and the tangential and sagittal accommodation surfaces for each eye along the horizontal center line, or along any elevated or depressed horizontal line until the entire field of view is mapped. The graphical output of this program allows PPE to ascertain very clearly the flatness and closeness of the various focal surfaces as well as the state of the geometric alignment of the images. This powerful tool is PPE's primary means for design and analysis of biocular magnifiers.

Some of these design methods are compatible with CODE V while others are not. For example, the only means to include high order aberrations into CODE V's merit function would be to include the lengthy algebraic expressions in user definable constraints. Adding the 37 specific rays that made up PPE's original merit function is not practical, either.

The approach which was taken was as follows. The ideal biocular magnifier would be well color-corrected and have an imperceptibly small blur circle. Also, the convergent and accommodation surfaces for both eyes should be as flat as possible and should fall on top of each other. The biocular magnifier to be analyzed (or optimized) was modeled using the multiconfiguration "zoom" option. Three configurations were chosen differing only in the size and lateral location of the stop. The stop is located axially at the eye position and is also the exit pupil of the magnifier. Configurations 1 and 2 represented right and left eye viewing and consisted of the lens system with a 20.0 mm diameter stop decentered horizontally by plus and minus 32.5 mm. The size of the stop was chosen to permit some head motion. The observer will, of course, use only a small portion of the 20.0 mm stop. In the third configuration, the stop has an outside diameter equal to 85.0 mm and an inside diameter of 45.0 mm corresponding to the portion of the lens used. Last for this configuration an aperture is added that only passes light within 10.0 mm of the x-axis. In effect, the stop for configuration 3 consists of two separated and approximately square apertures (see figure 7).

Rays are traced from the object through the lens to the stop and then back to the virtual image surface. During analysis or optimization the only parameters that differ in each configuration (zoomable parameters) are the stop parameters. Notably, the image surface is the same for all three configurations and represents the best compromise image surface for the three configurations. This tends to drive the mean accommodation surfaces for each eye in configurations 1 and 2 toward the convergent surface in configuration 3. Tangential and sagittal focus distances from this surface can be monitored using XFO and YFO for the desired field points. Dipvergence can be monitored by observing the Y component of an XFAN in configuration 3 set at the desired pupil positions. Alternatively, a user defined constraint can be constructed which controls the difference between the Y intercepts of the chief rays at the image surface for both eyes. The convergence or divergence of the eyes will be controlled by watching the sag of the image surface. Divergence is not a problem for finite conjugate systems. Target values for static distortion can be requested in configuration 3. CODE V's default merit function

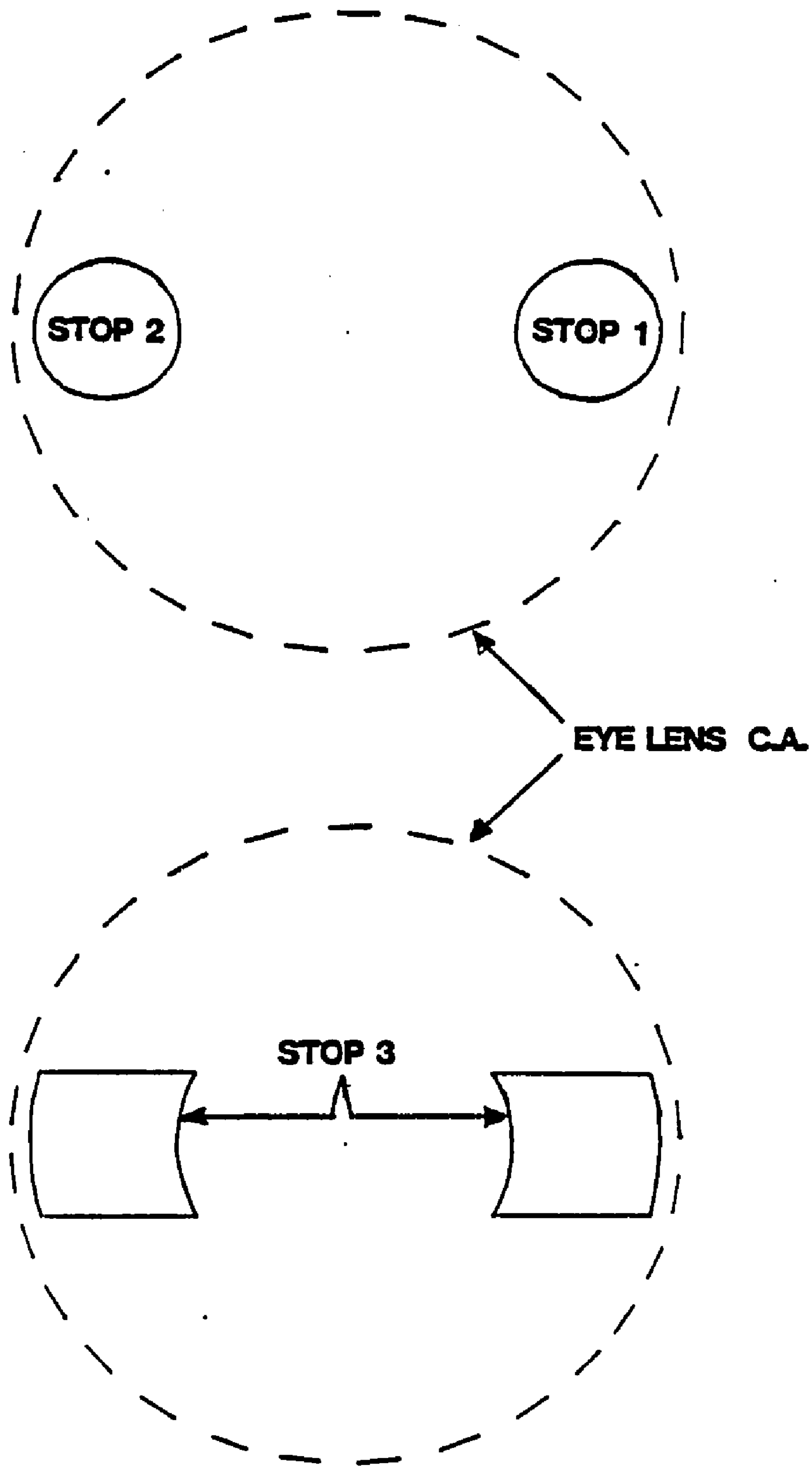


Fig. 7. Stop configuration.

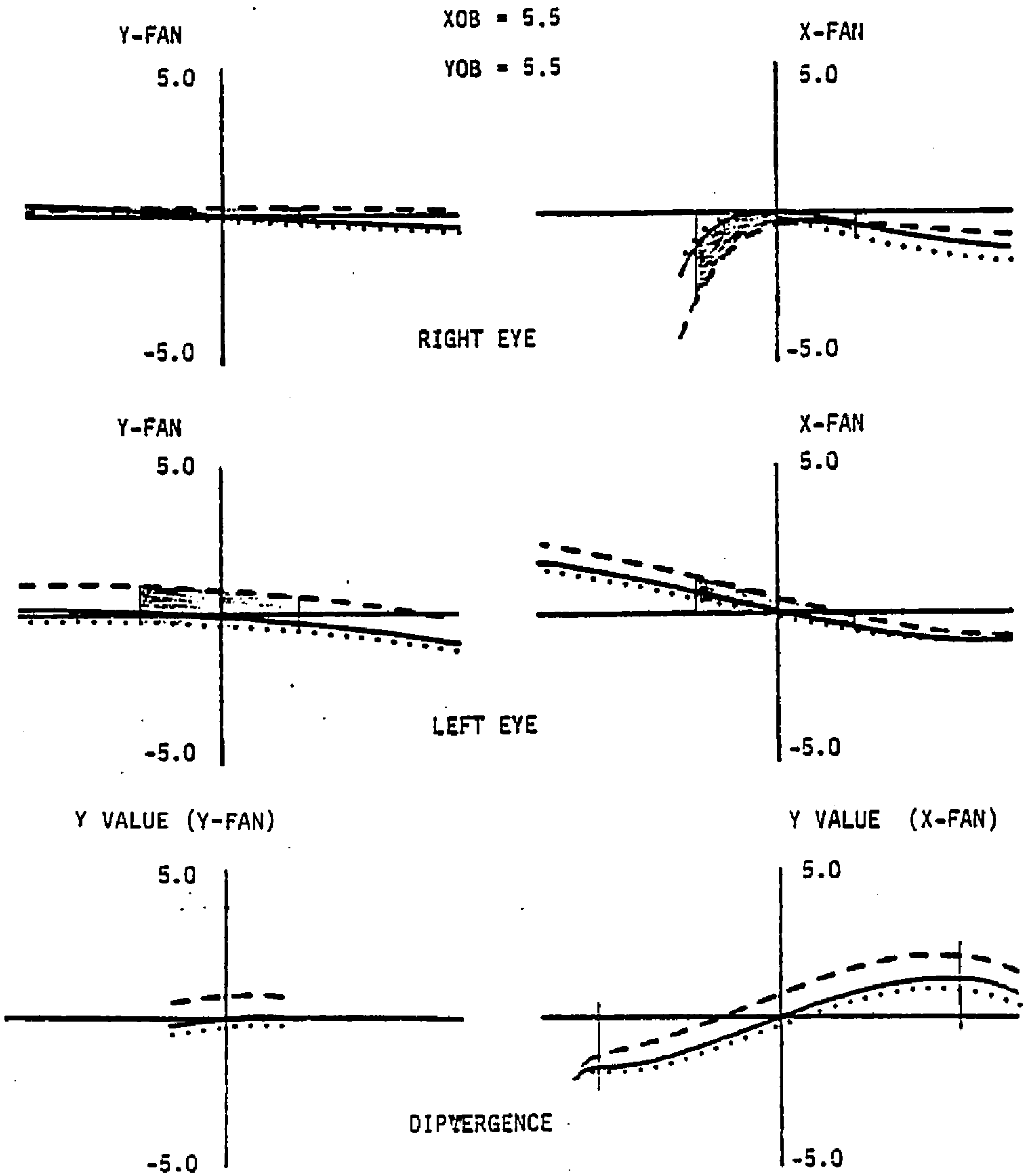
is used to reduce the image blur circle and the chromatic aberration for configurations 1 and 2. The smallness of the blur circle and the smoothness of the ray fans over the 20 mm diameter pupil control parallax.

CHAPTER 4

ANALYSIS OF TWO SYSTEMS WITH THE PROPOSED MERIT FUNCTION

The first system that was analyzed was a magnifier designed by Philip Rogers and Michael Roberts of PPE and assigned U.S. Patent No. 4,183,623 (first embodiment) . The device is described in the patent literature as having a focal length of 49.37 mm, operating at F/0.61, producing a 60 degree FOV, and intended for use as a magnifier for the CRT end of a night vision device. Rogers informed me that the diameter of the CRT was 50 mm and standard 3 x 4 video format was to be used. The CRT image size is then assumed to be 40 mm wide and 30 mm in height. Lens diameters were not included in the patent and had to be approximated by measurement of the patent figures. Analysis was performed at 656, 589, and 486 nanometers because the spectral characteristics of the CRT were not available. The three wavelengths had weights of 1, 3, and 1 respectively. This range of wavelength is admittedly greater than that of a typical green CRT phosphor and will result in larger values for blur size than that which will actually be seen by an observer. A pupil separation of 65 mm and a viewing distance of 63.5 mm (2.5 inches) was assumed. Three object positions were chosen: the axis; XOB = 8 mm, YOB = 0 mm; and XOB = YOB = 5.5 mm. The second and third positions were chosen to be near the edge of the biocular overlap region. CODE V was requested to determine the location and curvature of the best image surface based on the blur sizes obtained with the three previously mentioned stop configurations. The lens is shown in figures A.1 and A.2 in Appendix A and the lens parameters are listed in A.3, also in Appendix A.

The following first order properties can be calculated from equations 1 and 3 through 6.



Rogers Pat. 4183624

RAY ABERRATIONS (Milliradians)

- - - - - - -486 NM

———————589 NM

...........656 NM

Fig. 8. Typical ray fans.

M =	4.9 x
FOV (std) =	42.8° x 32.7°
FOV (eye) =	55.5°
FOV (total) =	97.6°
FOV (overlap) =	13.5°

It can be seen that about 32% of the horizontal field of view would be expected to be seen by both eyes simultaneously. Real ray tracing reveals that about 40% of the field of view is within the region of biocular overlap.

Five object points were chosen in order to examine the optical quality of the overlap region. Additionally, two object points at the edge of the CRT format were chosen as "worst case" examples of monocular imagery. The large size and symmetry of the eye boxes reduce the number of object positions required for the analysis. Figure 8 displays the ray aberrations that the observer's right and left eyes see for a typical off-axis object point. The shaded region represents the area of the stop used by a 7 mm eye pupil. The results of head motion can be seen by sliding the shaded regions for each eye along the aberration plots for the requisite amount. The extreme values of the ray aberrations give a measure of the amount of parallax present at the field point on the "best compromise" image surface. The extreme values of the ray aberration within the shaded region give a measure of the size of the visible blur patch. Also shown is the dipvergence associated with the object point. The tick marks locate the nominal eye positions. Figures showing the location of the seven object points and their associated ray fans are found in Appendix A. Table 1 summarizes the accommodation characteristics for all seven object points.

In several instances the ray fans present a pessimistic view of image quality because each eye will, in reality, focus on a separate image surface displaced by some amount from the "best compromise" image surface. This is particularly true at the extreme positions 6 and 7 where refocusing would clearly improve the fans.

At the center of the CRT, image quality is excellent. Blur, mostly caused by chromatic aberration, is less than 1 mrad. Parallax varies slowly over a maximum range of 2 mrad. Dipvergence, due to symmetry, is zero. Elsewhere within the overlap region blur size and parallax are below 2.5 mrad. Color sometimes contributes as much as 1.5 mrad to image blur when the effects of focus are removed. It should be noted that the contribution of color to blur size is exaggerated in this analysis and is, in reality, much smaller due to the narrower spectral distribution of typical night vision CRT's. It was stated that 0.6 diopters range of accommodation was acceptable, no more than 0.2 diopters of which could be in the crossed condition. Accommodation is close to acceptable limits except for position 2 which is literally on the edge of biocular vision. Dipvergence slightly exceeds the 2.5 mrad limit set by Rogers in position 3, but again this is near the edge of the overlap region. At the extreme object positions parallax becomes quite large, particularly at the edge of the CRT along the meridian passing through both eyes (position 6). At position 6 it is difficult to tell just where the eye would focus due to an expected 4 mrad blur and nearly an equal amount of color. Ignoring position 2 at the edge of the overlap region, the total dioptric range required is from -1.92 to -2.75 diopters, well within the 1.0 diopter requirement stated by Palmer and Freeman. Finally, the distortion plot in Appendix A shows that a rather small amount of distortion has been designed into this magnifier.

Table 1. Accommodation in Diopters.

POSITION	RIGHT EYE		LEFT EYE	
	XFO	YFO	XFO	YFO
1	-2.55	-2.49	-2.55	-2.49
2	-3.95	-2.45	-2.22	-2.33
3	-2.43	-2.45	-2.32	-2.44
4	-2.36	-2.50	-2.36	-2.50
5	-2.51	-2.75	-2.51	-2.75
6			-2.61	-1.92
7			-2.40	-2.25

The second system that was analyzed consisted of a 30 inch F/1.0 spherical mirror nominally collimating a curved object surface. Two observer positions were considered. In the first case, the stop (observer) was located at the radius of curvature of the mirror and the radius of the object surface was set equal to the radius of curvature of the mirror. The stop was 10 inches in diameter. In this configuration there is no coma, petzval, astigmatism or color and the image blur is below the resolution limit of the eye. The only aberrations to be considered are dipvergence and accommmodation or residual decollimation caused by the spherical aberration. The system was focused for collimation of an axial object point at the 0.7 zone of the stop. This causes light to be divergent from the simulator within the central 7 inches of the stop and convergent at the edges of the stop.

For the second case, the stop (observer) was located 36 inches from the mirror, and the object curvature and distance were chosen to yield a flat tangential field. Tangential objects will then be nominally collimated and sagittal objects will be slightly divergent and hence appear slightly closer than infinity. A similar system was described in Shenker's survey paper. Case 1 and 2 are summarized in Appendices B and C, respectively.

It became immediately obvious that the 3-position zoom configuration used in modeling the previous magnifier had to be modified. The 'best image' surface was designed to be at infinity and therefore the AFOCAL option had to be used on CODE V. Also, analysis with the observer's eyes placed symmetrically about the axis was deemed to be insufficient, so a second analysis was performed with the eyeboxes 1.5 and 4.0 inches to the right of the axis. In both cases the eyebox diameter was assumed to be .75 inches.

The following first order properties can be calculated from equations 2 through 6. Object heights of 7.0 and 12.0 inches were used.

	CASE 1	CASE 2
M =	0.33 x	0.33 x
FOV (eye) =	26.3°	43.6°
FOV (eye) =	28.1°	43.6°
FOV (total) =	30.3°	48.6°
FOV (overlap) =	25.8°	41.8°

Analysis was confined to the biocular overlap region because it comprises most of the FOV of the simulator. Refer to Appendix B for figures showing the ray fans for each of the object points and eyebox locations used in the analysis of case 1. As before, the shaded region represents the area of the stop used by a 7 mm pupil. Table 2 summarizes the accommodation requirements of case 1. As can be seen from the ray fans, case 1 represents a very well corrected biocular system with excellent collimation and imperceptibly small blur, parallax, and dipvergence. Distortion is less than 3% over the field. The only major drawback to this system is the fact that the FOV is severely limited by the physical layout of the components.

In case 2, the observer is located 36 inches from the mirror. Refer to Appendix C for figures showing ray fans for each of the object points and eyebox locations used in the analysis of case 2. Table 3 summarizes the accommodation characteristics of case 2.

Blur has increased to a perceptible level, as has dipvergence and variation in accommodation over the field. Distortion has grown to 7% at the edge of the field. Parallax has also become noticeable but appears to be below the 5 mrad per 25 mm head motion limit set by Walker. The larger amount of parallax present in this system could be of some concern, depending on the specific use of the simulator. Total dioptric range required of the eye is less than 0.1 diopter; however, the eye is required to focus slightly beyond infinity at the edge of the field. Elsewhere all is acceptable. This is not

Table 2. Accommodation in Diopters (Case 1)

POSITION	RIGHT EYE		LEFT EYE	
	XFO	YFO	XFO	YFO
1,2,3,4	-.002	-.002	-.002	-.002
5,6,7,8,9,10	+.006	.000	-.001	-.002

Table 3. Accommodation in Diopters (Case 2)

POSITION	RIGHT EYE		LEFT EYE	
	XFO	YFO	XFO	YFO
1	-.002	-.002	-.002	-.002
2	-.041	-.007	-.041	-.007
3	-.018	-.039	+.007	-.031
4	-.033	-.011	-.024	-.008
5	-.020	-.033	+.002	-.026
6	-.024	-.019	-.028	-.014
7	+.006	+.001	-.001	-.002
8	-.026	-.003	-.034	-.006
9	-.027	-.030	-.015	-.027
10	+.046	-.025	+.010	-.036
11	+.021	-.008	-.005	-.017
12	-.028	-.017	-.023	-.015

surprising, because similar devices are used in the flight simulation industry.

As previously pointed out in this work, other tools have been developed for the design and analysis of biocular magnifiers. CODE V analyzes collimating type magnifiers by calculating the angular difference between the chief rays from a single object point entering both eyes. This difference is resolved into horizontal and vertical components and presupposes that the observer is focused at infinity. The result is a pair of plots of the amount of vertical and horizontal image doubling that the observer sees at various field angles. Figures near the end of Appendices B and C show the results of such analysis when performed on the spherical mirror (case 1 and case 2). Vertical doubling is similar to the Y component of the XFAN's used to measure dipvergence in this paper. Horizontal doubling is related to decollimation.

In case 1, essentially no vertical doubling takes place in agreement with the previous dipvergence results. Horizontal doubling is positive in the symmetric view and negative in the asymmetric view indicating that the eyes must converge very slightly in the former and diverge slightly in the latter view. The mirror, it will be remembered, was focused so that within the central 70% of the 10 inch stop the eyes would indeed be required to converge and outside this region, the eyes would be required to diverge.

In case 2, the vertical doubling suggests a maximum dipvergence of 1 milliradian in the symmetric view and about 1.5 milliradians in the asymmetric view, not too different from the results shown on the corresponding XFANS. The horizontal doubling shows that convergence of the eyes is required in the symmetric view and that convergence or divergence in the asymmetric view is dependent upon which field angle is observed. Convergence was also designed into the central region of case 2 by focusing slightly inside the paraxial focus. Some divergence of the eyes is required in the outer zone of the stop and the presence of coma and astigmatism produces additional decollimation.

Walker proposed that blur size be used to control parallax and dipvergence. The last figure in Appendix A shows the aberration fans produced by the entire 85 mm diameter "stop" of the Rogers magnifier at various field points. It is readily seen that the maximum implied size of the blur is greater than the amount of parallax, dipvergence, or blur resulting from the proposed merit function. Figures in Appendices B and C show similar results for case 1 and case 2 of the spherical mirror.

Shenker uses decollimation as a measure of quality for the collimating devices described in his survey paper. The "X" through the YFANS and sideways "V" through the XFANS in the full aperture aberration fans mentioned in the previous paragraph represent an amount of aberration corresponding to 0.1 diopters of decollimation. Decollimation increases beyond this limit in the Roger's magnifier at about halfway to the edge of the field of view. Shenker's disclaimer concerning the 1/9 diopter decollimation tolerance should be called to mind at this point. His statement was that experience suggests that it is "the proper order of magnitude for biocular displays having infinity as their nominal focus setting." The Roger's magnifier is a finite conjugate device and no tolerance for these devices was proposed by Shenker. The magnifier performs well in all other respects so one is inclined to think that the decollimation tolerance for the outer parts of the field of view may be opened up somewhat for finite conjugate devices.

In case 1 and 2 decollimation is found to be well within the 0.1 diopter tolerance with case 2 being the less well behaved.

CHAPTER 5

CONCLUSIONS

When analyzing biocular systems, or most optical systems, it should be pointed out that the proposed tolerances for various aberrations discussed herein are not to be considered absolute limits. That is to say that if an aberration were to exceed one of the stated limits the magnifier would still function, but with reduced performance and perhaps increased user discomfort. The human eye is known to be able to tolerate less than perfect aids. For example, near the edge of the biocular overlap region one eye will see a sharp image while the other may be trying to focus on a considerably degraded image at some distance from the first image. In this case it is likely that the observer's vision is dominated by the good image and, in a sense, does not "see" with the other eye at all.

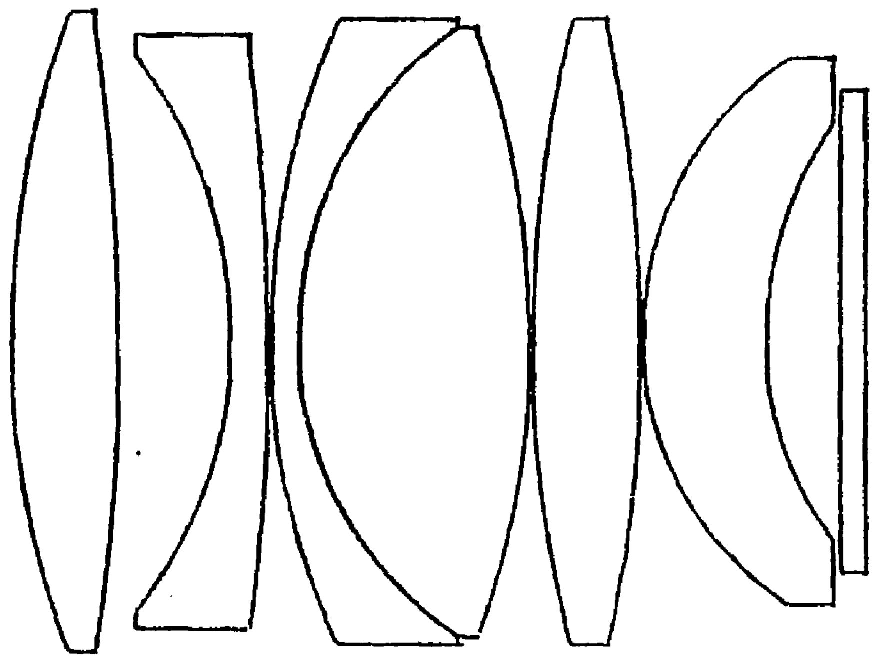
The fact that analysis by means of the proposed three-position zoom construction and merit function contained herein yielded results that were in good agreement with previously accepted limits for good biocular systems and are similar to results obtained with other methods of analysis are strong points in favor of the proposed merit function. The simplicity of the concept is another point in its favor.

Two limitations came to light during the analysis. First, systems with large amounts of freedom in eye location, such as the spherical mirror, require several eye positions to be adequately designed or analyzed. Modifying the three-position zoom construction for alternate eye locations presents no difficulty as far as analysis is concerned. However, Shenker's approach may indeed be faster and more relevant to this kind of system. If one were to use the three position construction during design, the recommended approach would be to design about the nominal eye positions and periodically check performance at additional eye positions.

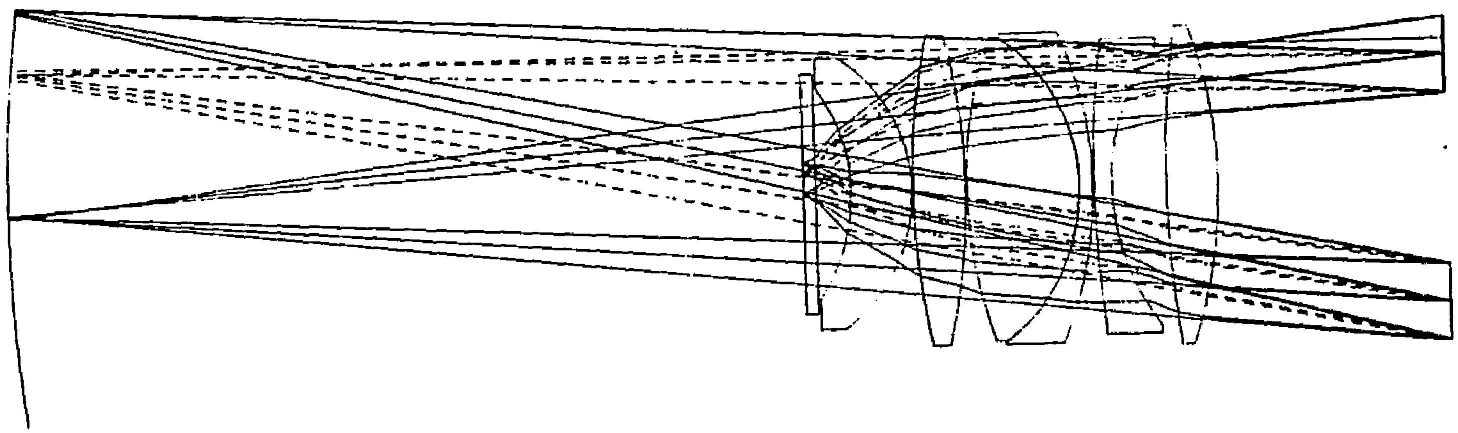
The second limitation that was discovered was that the amount of time per optimization cycle increases enormously when a multiconfiguration system is being designed. In the early stages of design considerable time might be saved by beginning with Walker's blur size approach and shifting to the three configuration system when the blur size from the entire aperture is 2 to 5 milliradians across. Apart from these two limitations, the proposed method should be quite useful in the design and analysis of biocular magnifiers with CODE V.

APPENDIX A

ANALYSIS OF ROGERS MAGNIFIER



A.1. Rogers biocular, Pat. 4183624.



A.2. Raytrace of Rogers biocular, Pat. 4183624.

SURFACE DATA

	RADIUS	CCY	THICKNESS	THC	GLASS	GLC	GCH	STOP
OBJ	1.0000E+18	300	0.000000	100		100		
1	1.0000E+18	300	3.470000	100	620400.60300	100		
2	1.0000E+18	300	9.850000	100		100		
3	-45.31000	300	16.680000	100	850300.32200	100		
4	-42.15000	300	0.200000	100		100		
5	181.09000	300	14.670000	100	744000.44800	100		
6	-157.72000	300	0.250000	100		100		
7	112.93000	300	31.290000	100	620400.60300	100		
8	-47.47000	300	3.770000	100	748400.27700	100		
9	-95.59000	300	0.250000	100		100		
10	271.63000	300	4.990000	100	653500.33500	100		
11	57.25000	300	15.160000	100		100		
12	257.83000	300	14.480000	100	620400.60300	100		
13	-116.52000	300	63.500000	100		100		
14	1.0000E+18	300	0.000000	100		100		
15	DECE	32.500000	0.000000	0.000000	0.000000	0.000000		
	DECC	100	100	100	100	100		
	1.0000E+18	300	0.010000	100	1000.99900	100		
16	1.0000E+18	300	0.000000	100		100		S
17	DECE	-32.500000	0.000000	0.000000	0.000000	0.000000		
	DECC	100	100	100	100	100		
	1.0000E+18	300	-400.021940	0		100		
18	382.52096	200	0.000000	100		100		

ZOOM DATA

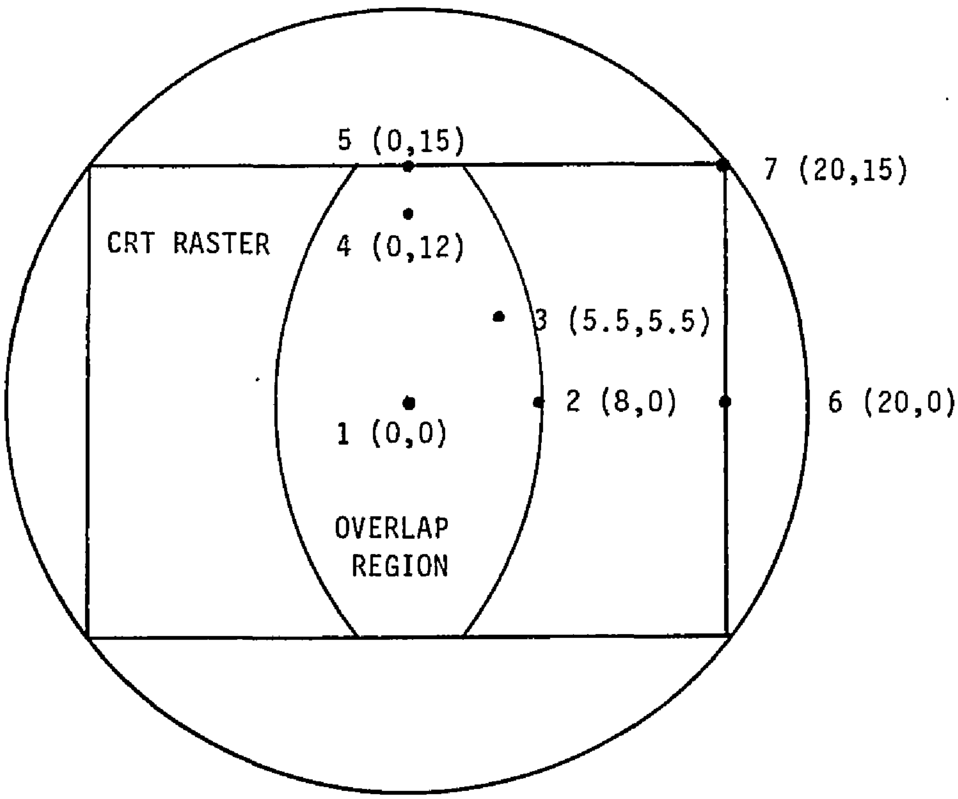
	POS 1	POS 2	POS 3
HAO	-0.343287	-0.343287	-0.716775
STO	16	16	16
VUY 1	0.435189	0.435189	0.830253
VLY 1	0.435189	0.435189	0.830253
VUY 2	0.698296	0.477816	0.827924
VLY 2	0.698296	0.477816	0.827924
VUY 3	0.362230	0.470970	0.830931
VLY 3	0.326137	0.439689	0.820388
VUX 1	0.328692	-0.000000	-0.000000
VLX 1	0.000000	0.328692	-0.000000
VUX 2	-0.074018	0.337071	0.189491
VLX 2	0.988777	0.460395	0.129504
VUX 3	0.070005	0.271190	0.148916
VLX 3	0.476591	0.427624	0.005685
XDE 17	-32.500000	32.500000	0.000000
XDC 17	100	100	100
CIR 15	10.000000	10.000000	42.500000
CIR 16	10.000000	10.000000	42.500000
XDE 15	32.500000	-32.500000	0.000000
XDC 15	100	100	100
CIR 16 A	-0.010000	-0.010000	-21.250000
REX 14	42.500000	42.500000	42.500000
REY 14	42.500000	42.500000	10.000000

APERTURE DATA

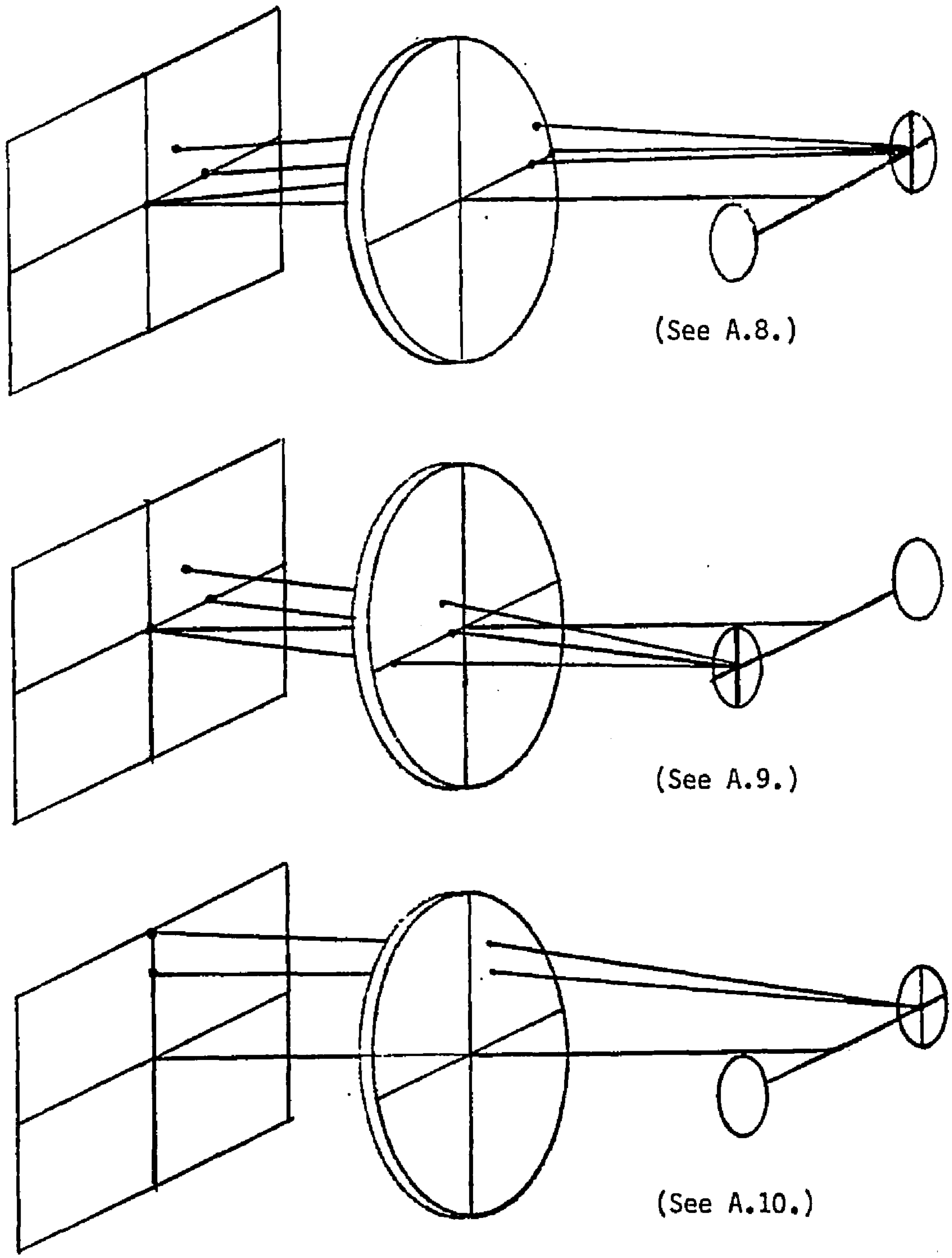
CIR 1	30.000000
CIR 2	30.000000
CIR 3	27.000000
CIR 4	34.000000
CIR 5	39.000000
CIR 6	39.000000
CIR 7	37.000000
CIR 8	38.000000
CIR 9	39.000000
CIR 10	37.000000
CIR 11	36.000000
CIR 12	40.000000
CIR 13	40.000000
REX 14	42.500000
REY 14	42.500000
CIR 15	10.000000
CIR 16	10.000000
CIR 16 A	-0.010000

DIM	M		
WL	656.00	589.00	486.00
WTW	1	3	1
REF	2		

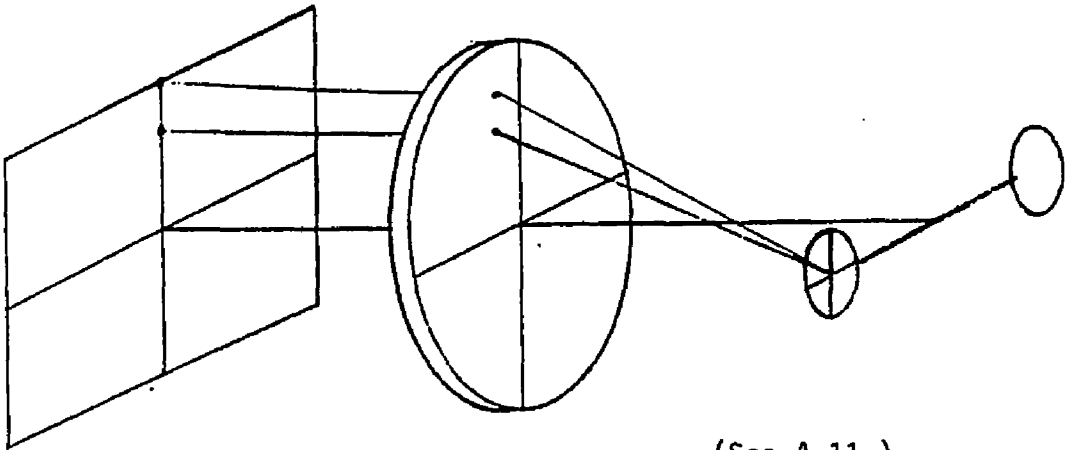
A.3. Rogers biocular, Pat. 4183624.



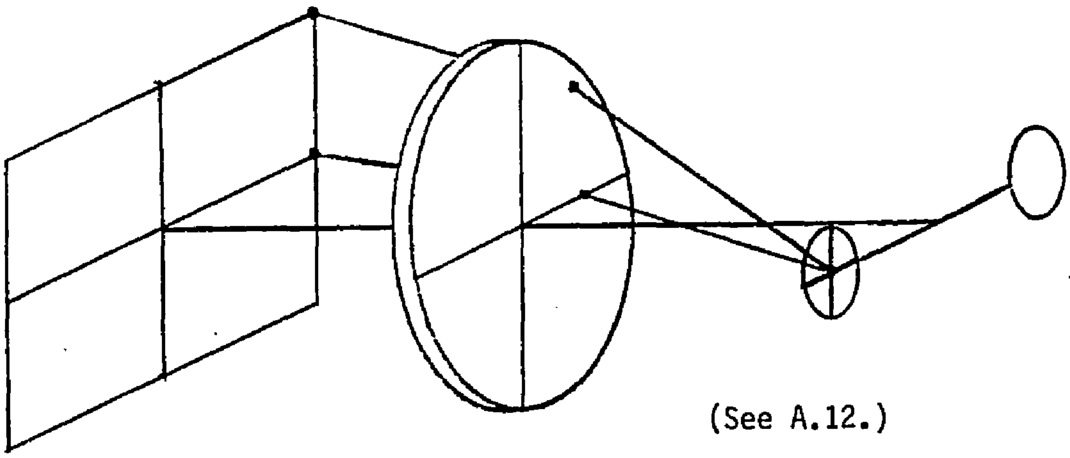
A.4. Object points, Pat. 4183624.



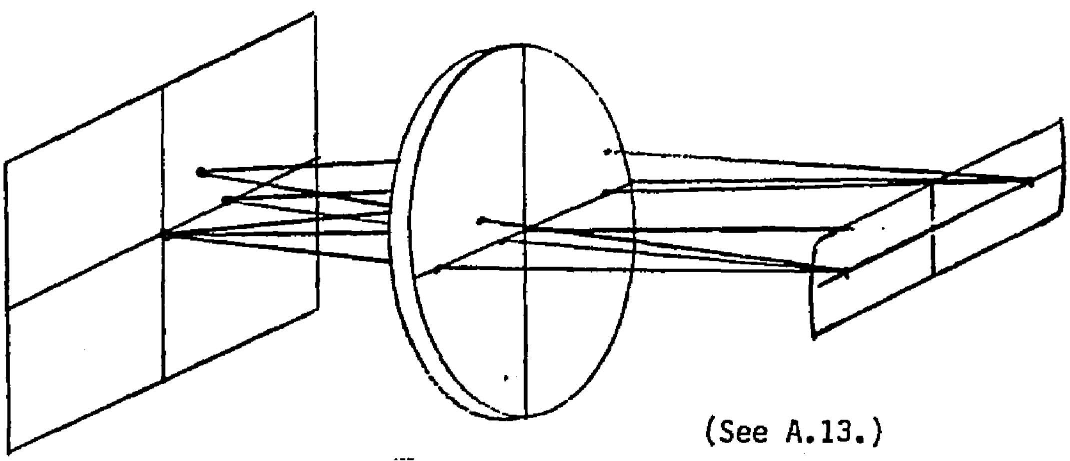
A.5. Key to ray fans for Rogers magnifier.



(See A.11.)

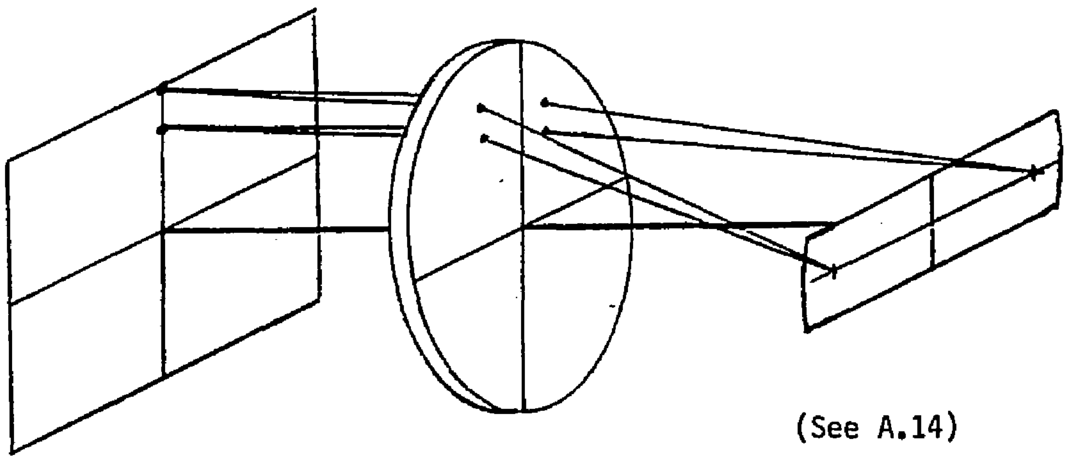


(See A.12.)



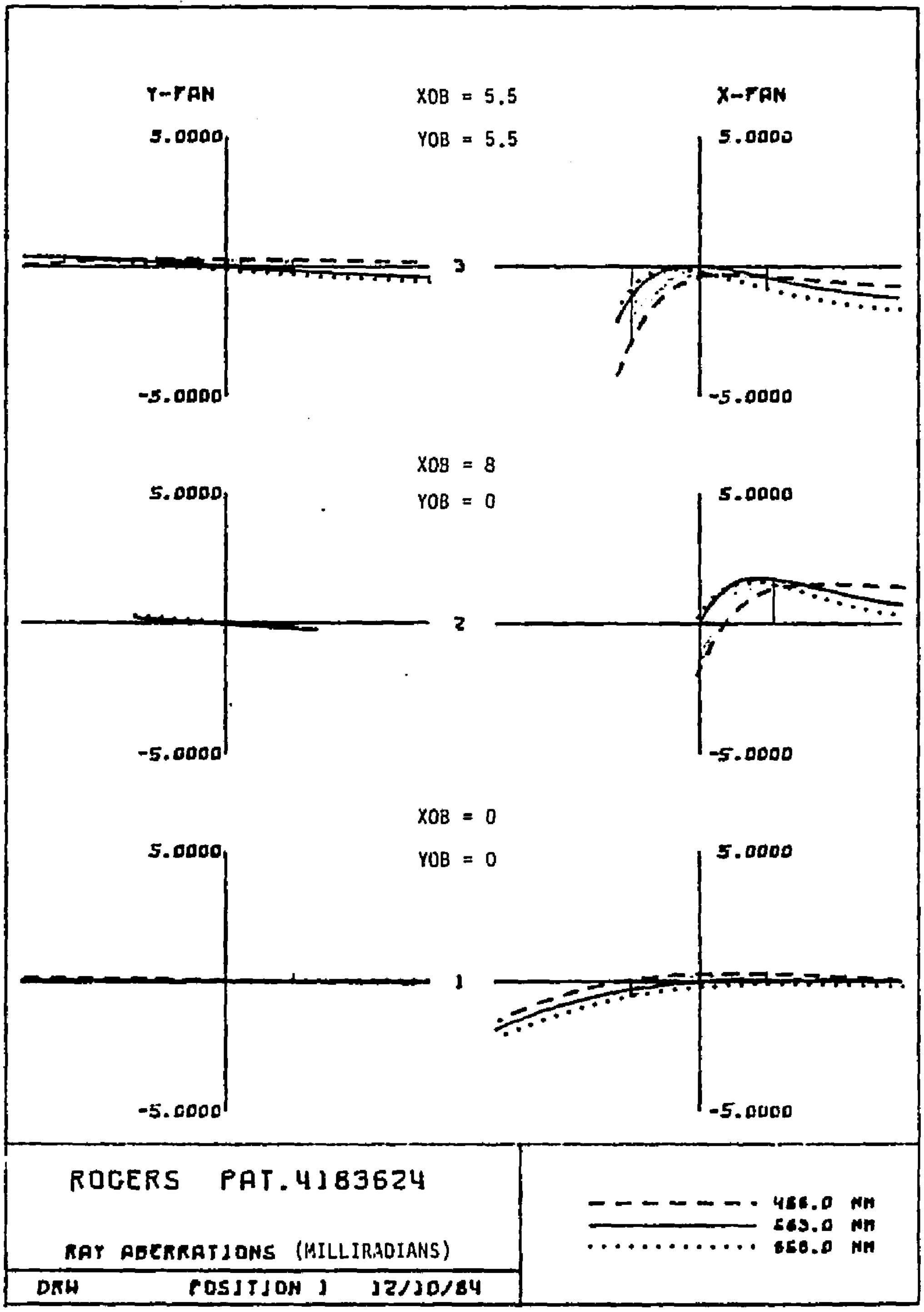
(See A.13.)

A.6. Key to ray fans for Rogers magnifier.



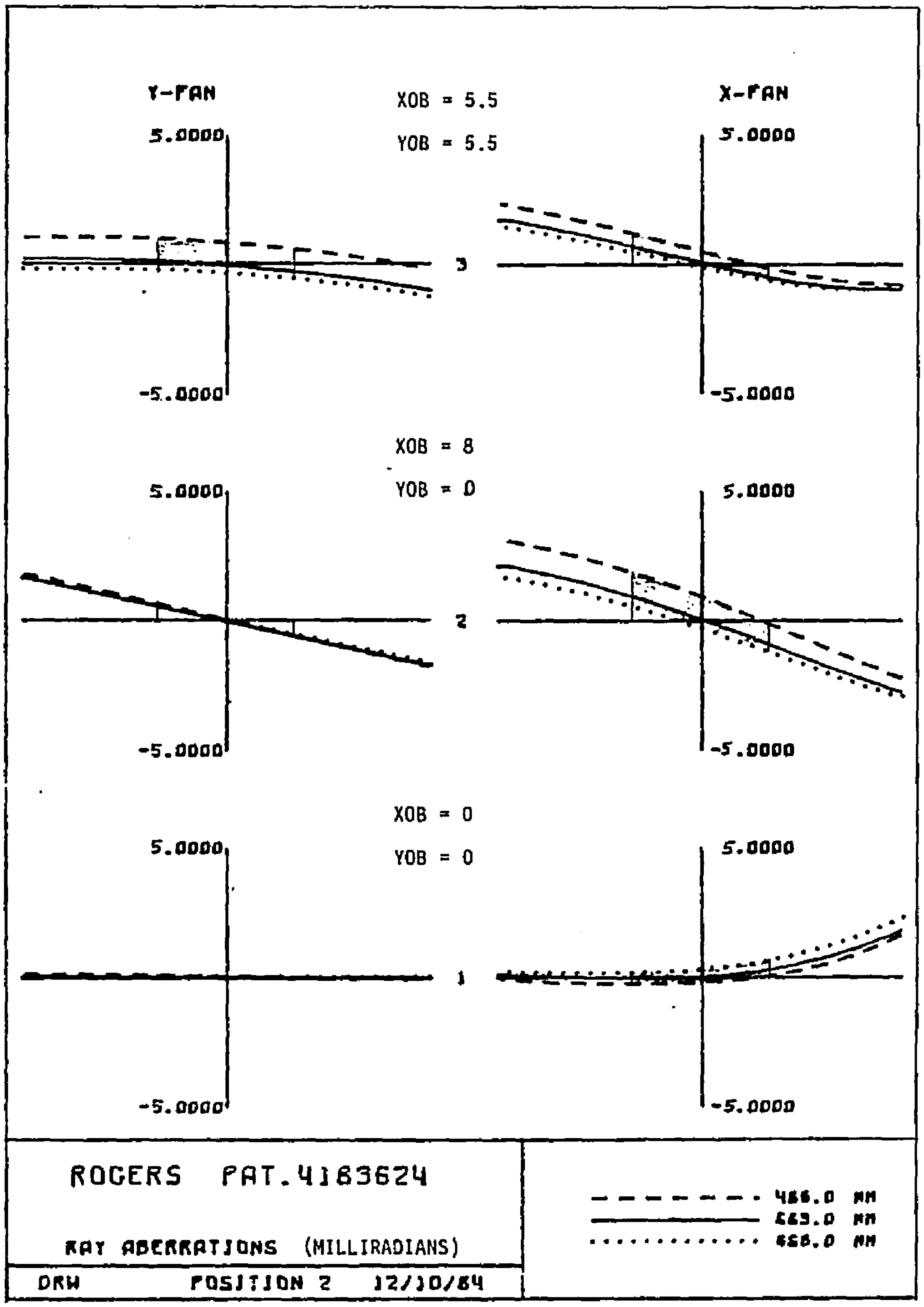
(See A.14)

A.7. Key to ray fans for Rogers magnifier.

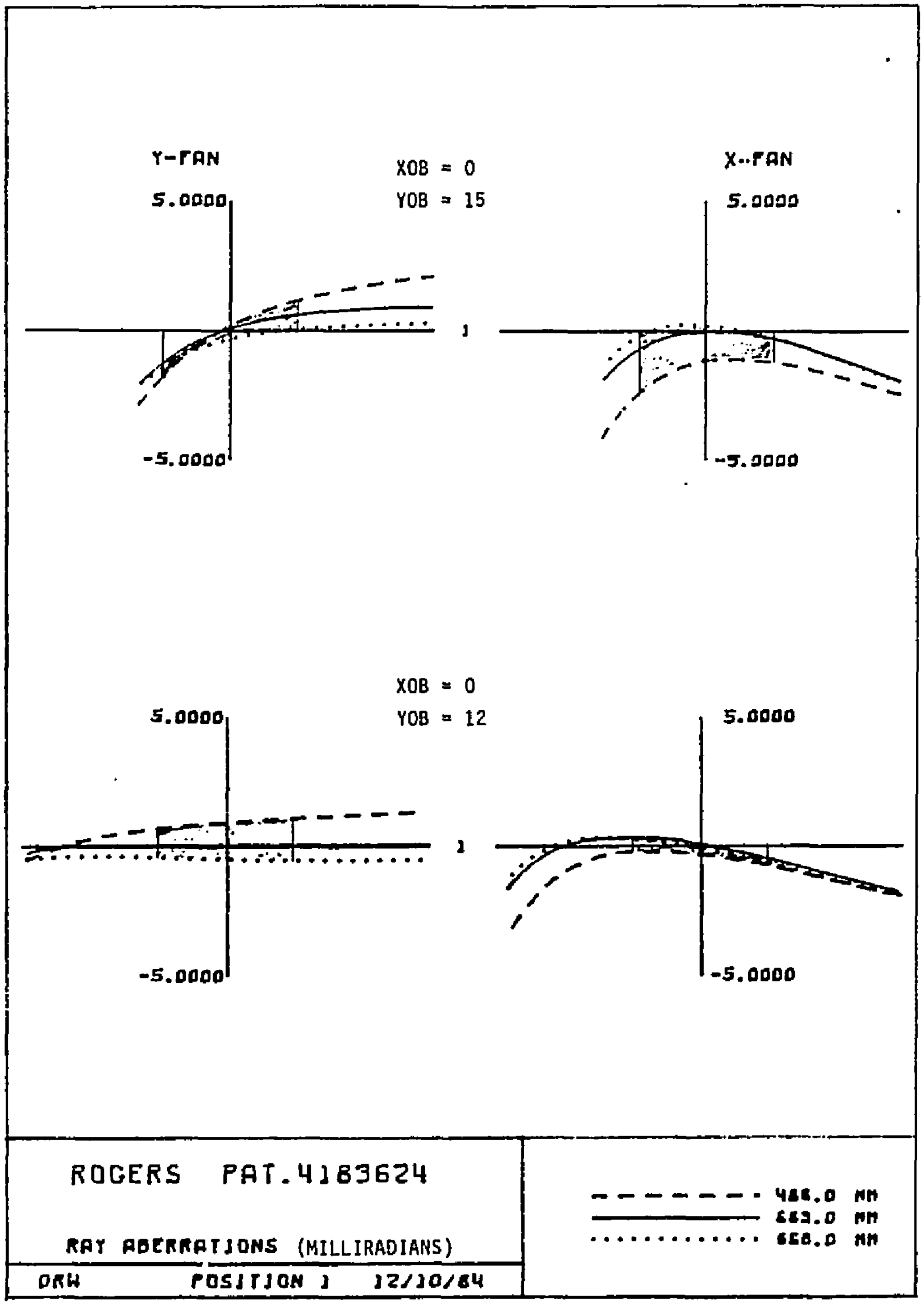


Y-FAN
XOB = 5.5
YOB = 5.5
X-FAN
5.0000
-5.0000
3
XOB = 8
YOB = 0
2
XOB = 0
YOB = 0
1
ROGERS PAT.4183624
RAY ABERRATIONS (MILLIRADIANS)
DRW POSITION 1 12/10/84
486.0 NM
563.0 NM
656.0 NM

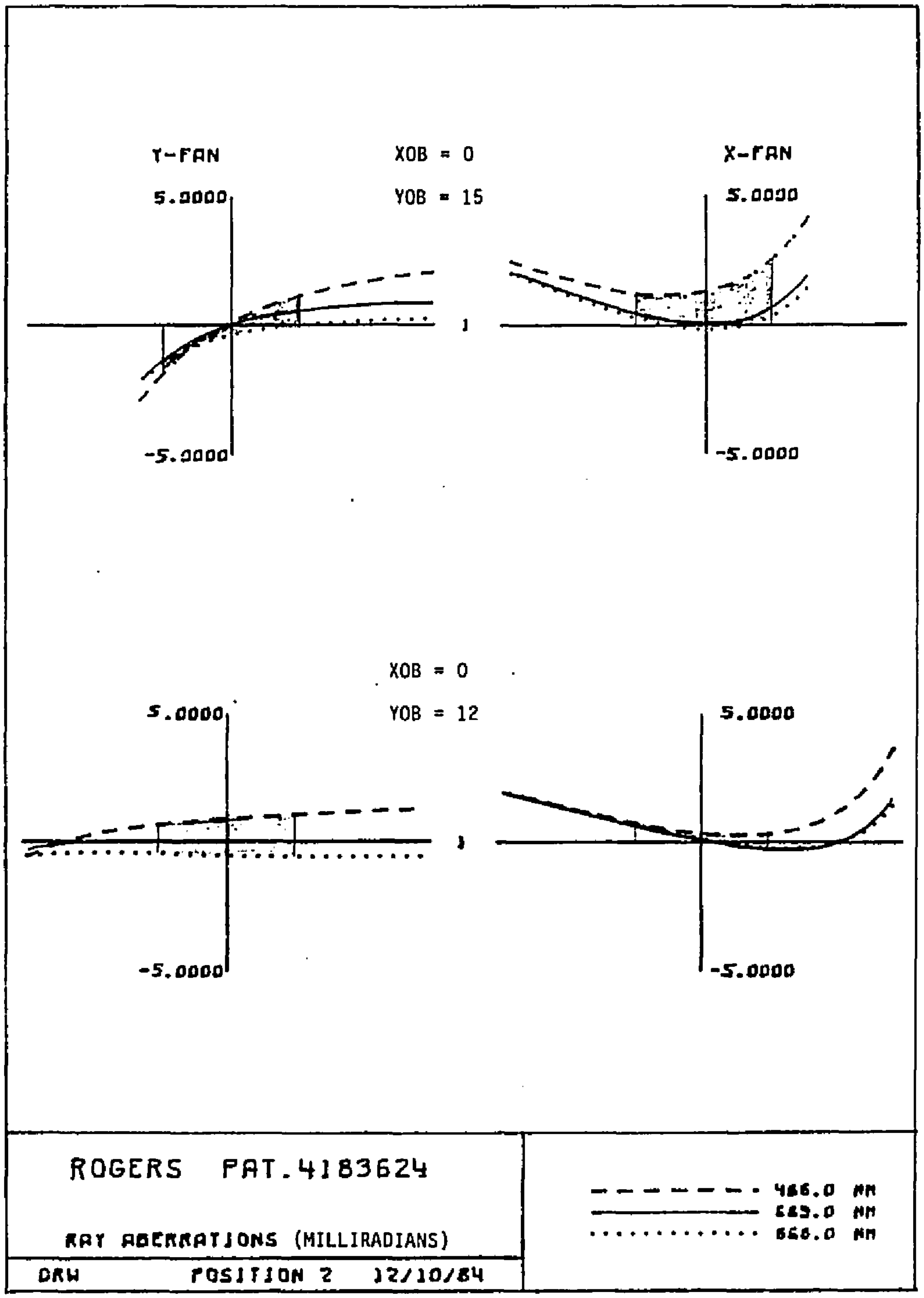
A.8. Right eye.


Y-FAN
X-FAN
XOB = 5.5
YOB = 5.5
5.0000
-5.0000
3
XOB = 8
YOB = 0
2
XOB = 0
YOB = 0
1
ROGERS PAT.4183624
RAY ABERRATIONS (MILLIRADIANS)
DRW POSITION 2 12/10/84
486.0 NM
643.0 NM
656.0 NM

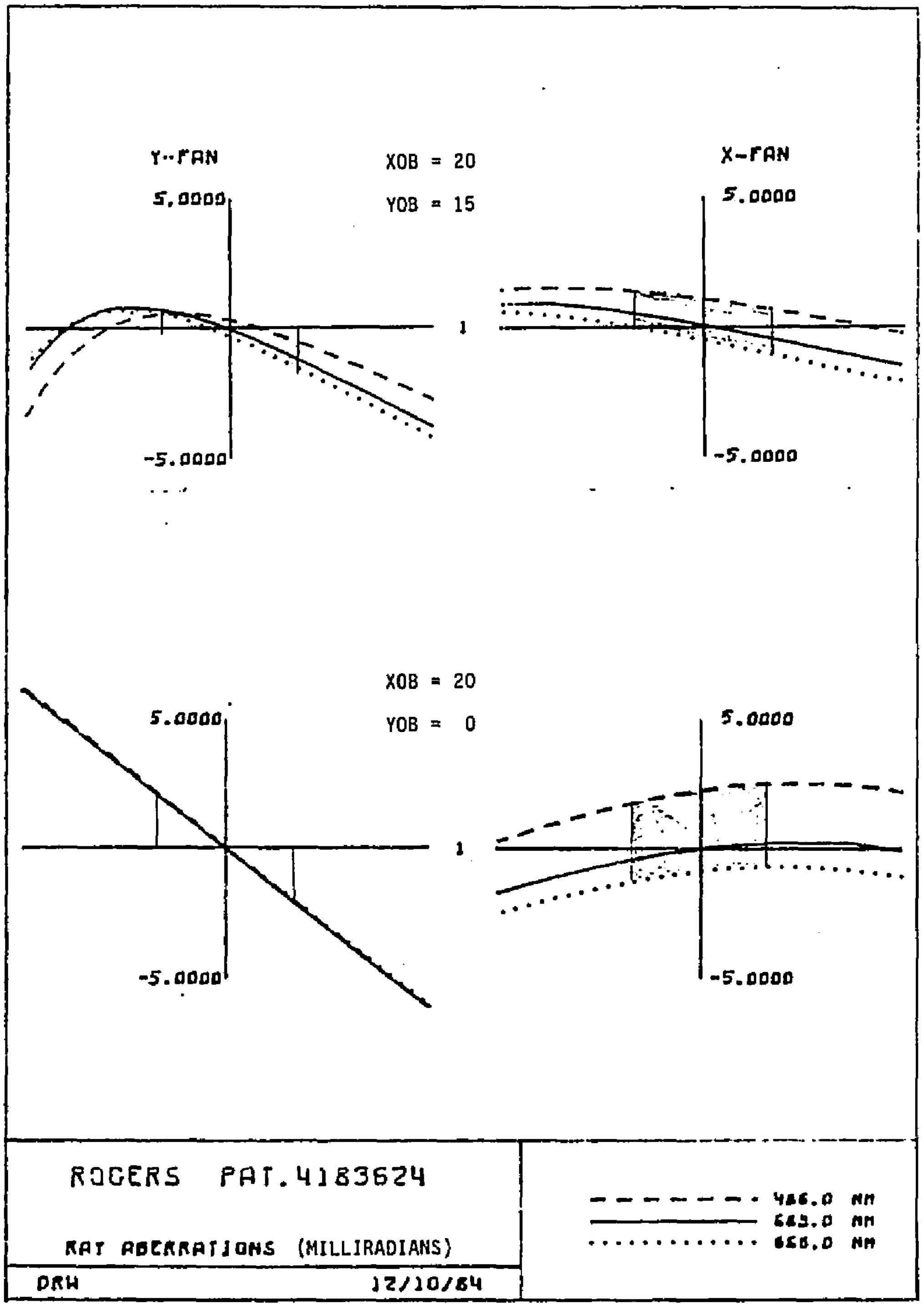
A.9. Left eye.



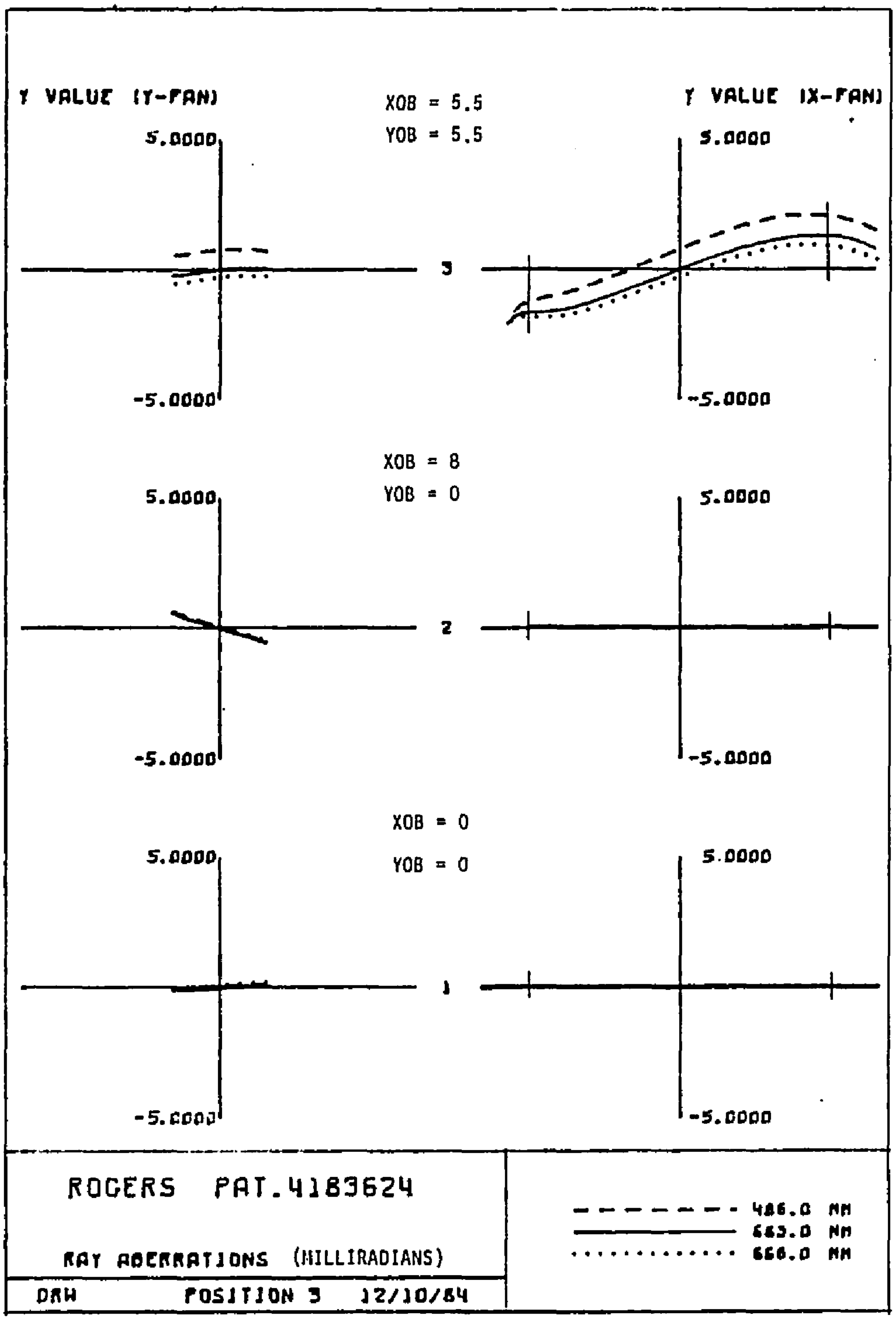
A.10. Right eye.


Y-FAN
XOB = 0
YOB = 15
X-FAN
5.0000
-5.0000
5.0000
-5.0000
XOB = 0
YOB = 12
5.0000
-5.0000
5.0000
-5.0000
ROGERS PAT.4183624
RAY ABERRATIONS (MILLIRADIANS)
DRW POSITION 2 12/10/84
486.0 NM
589.0 NM
656.0 NM

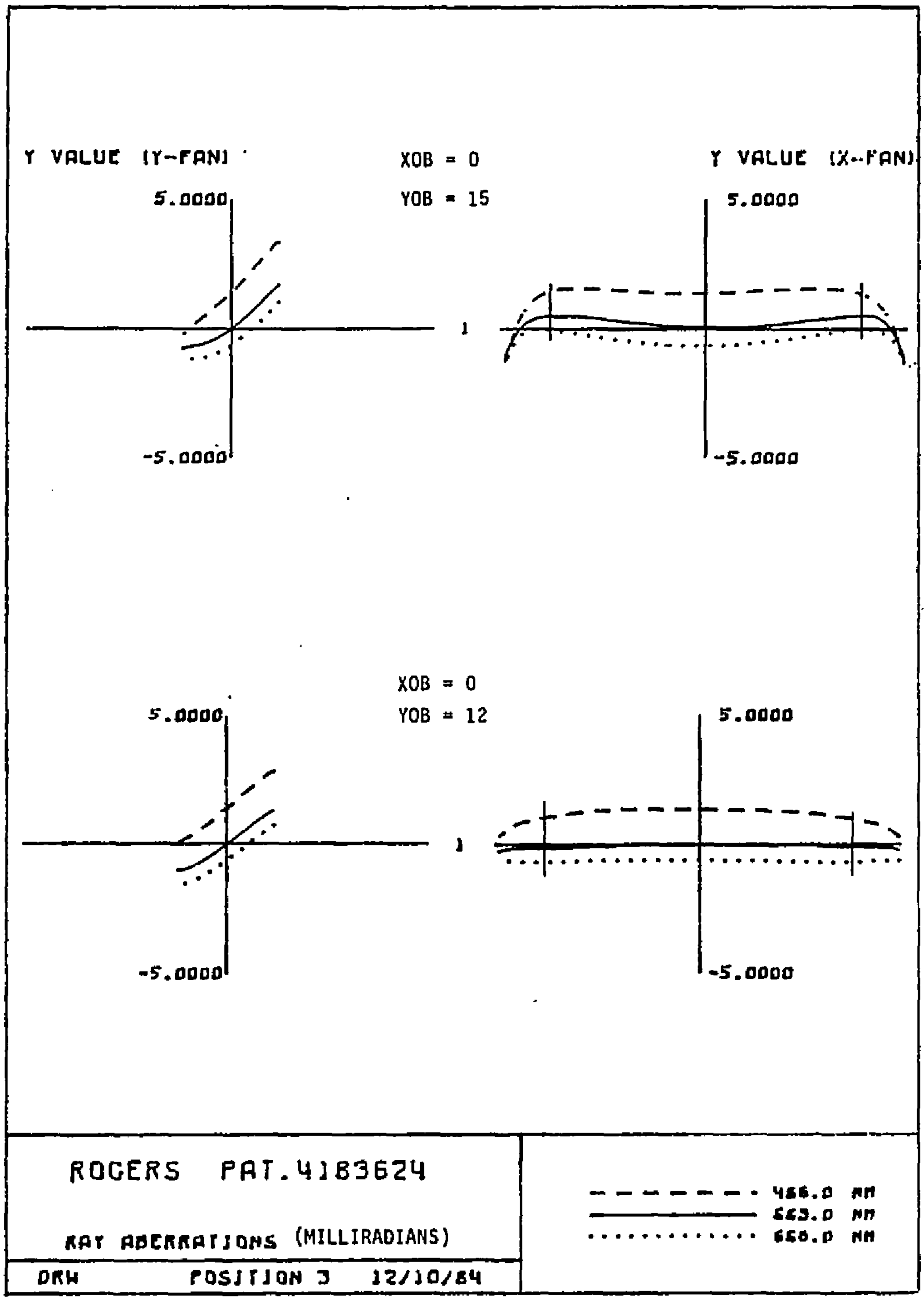
A.11. Left eye.



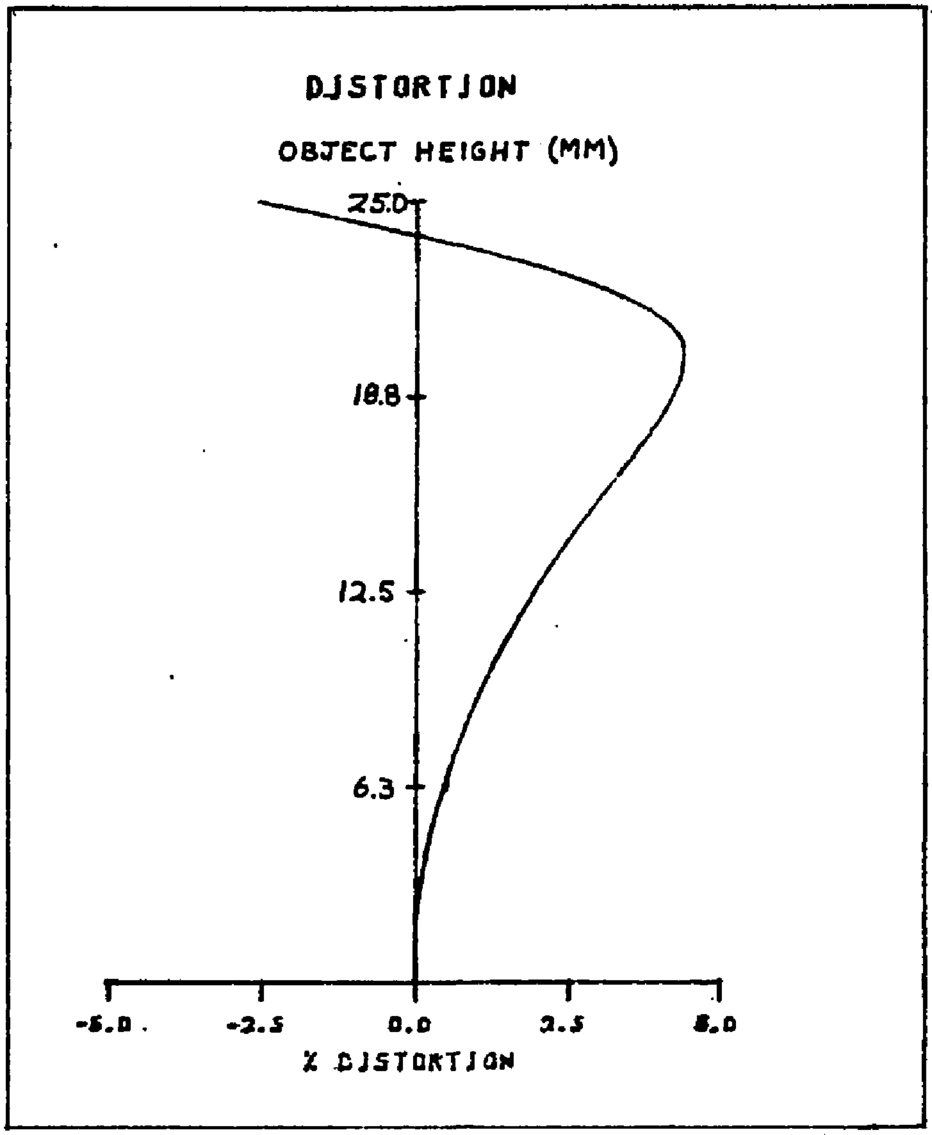
A.12. Extremes.



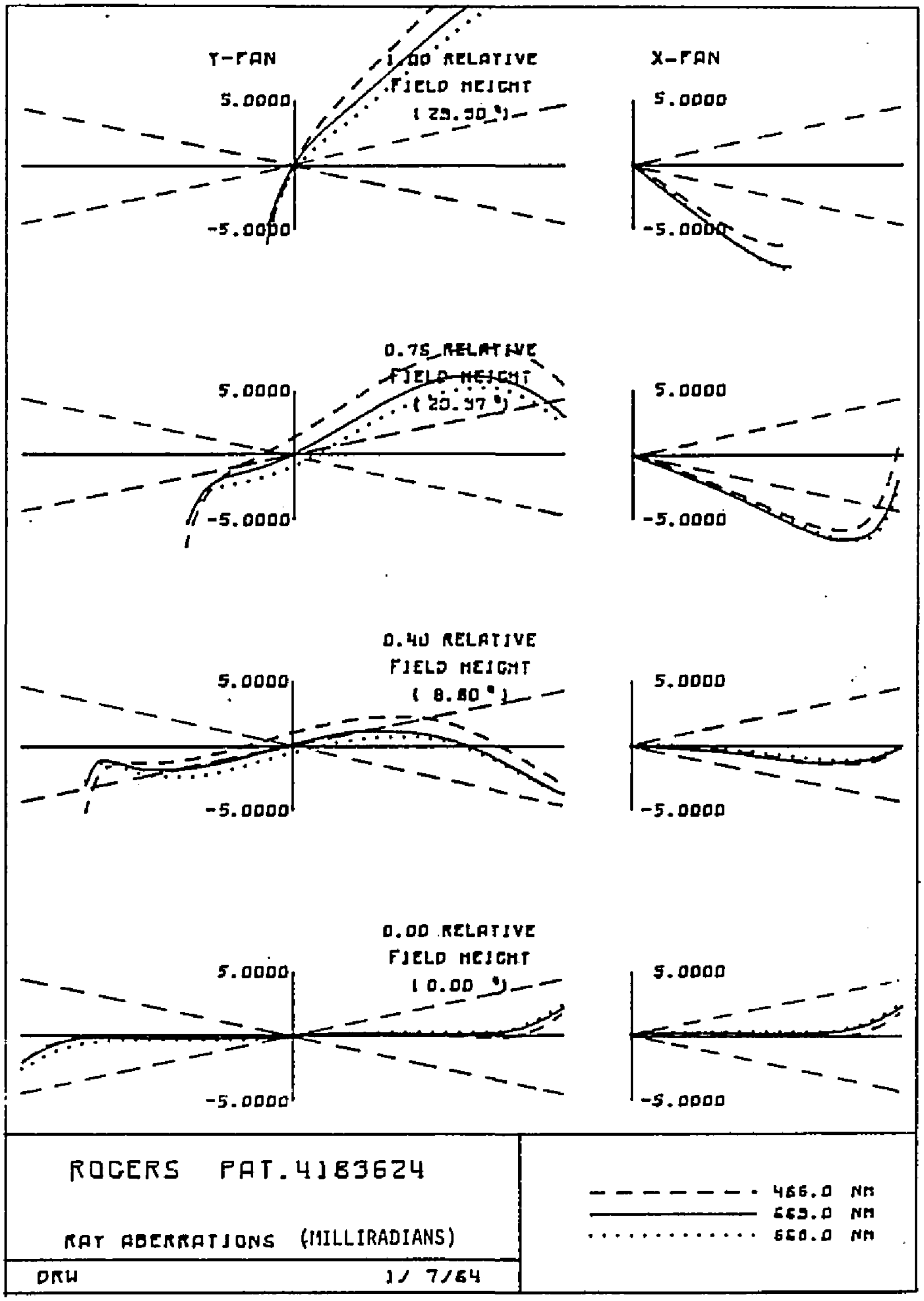
A.13. Dipvergence.



A.14. Dipvergence.



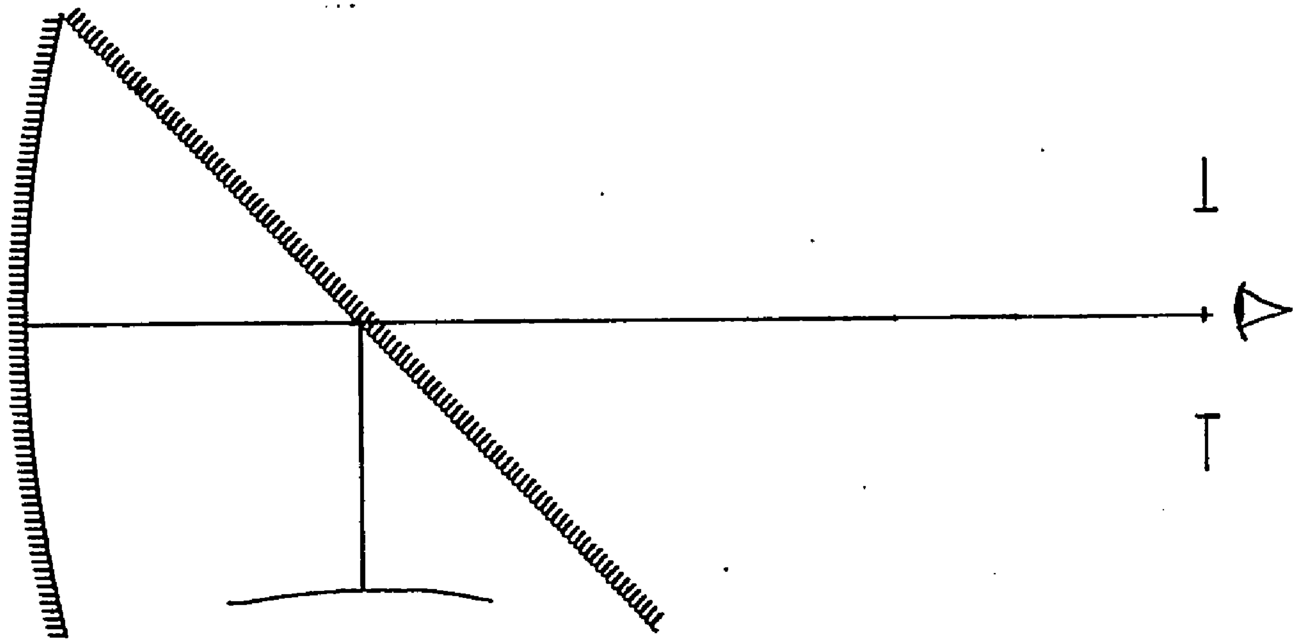
A.15. Distortion, Pat. 4183624.



A.16. Blur size, Rogers biocular magnifier.

APPENDIX B

ANALYSIS OF SPHERICAL MIRROR (CASE 1)



B.1. Spherical mirror (Case 1).

SPHERICAL MIRROR

SURFACE DATA

	RADIUS	CCY	THICKNESS	THC	GLASS	GLC	GCH	STOP
OBJ	-30.00000	300	12.941891	100		100		
1	1.0000E+18	300	0.000000	100		100		
2	DECE	0.000000	0.000000	-45.000000	0.000000	0.000000	BEND	
	DECC	100	100	100	100	100		
	1.0000E+18	300	-17.000000	100	REFL	100		
3	60.00000	300	60.000000	100	REFL	100		
4	1.0000E+18	300	0.000000	100		100		
5	DECE	1.250000	0.000000	0.000000	0.000000	0.000000		
	DECC	100	100	100	100	100		
	1.0000E+18	300	0.000000	100		100		
6	1.0000E+18	300	0.000000	100		100		S
7	DECE	-1.250000	0.000000	0.000000	0.000000	0.000000		
	DECC	100	100	100	100	100		
	1.0000E+18	300	0.000000	100		100		
8	1.0000E+18	300	1000.000000	100		100		
9	1.0000E+18	300	0.000000	100		100		

ZOOM DATA

	POS 1	POS 2	POS 3
EPD	0.750000	0.750000	10.000000
STO	6	6	6
VUY 1	-0.000943	-0.000943	0.924995
VLY 1	-0.000943	-0.000943	0.924995
VUY 2	-0.026266	-0.026266	0.923094
VLY 2	-0.032248	-0.032248	0.922645
VUY 3	-0.030079	-0.013075	0.923451
VLY 3	-0.030079	-0.013075	0.923451
VUX 1	-0.001896	-0.003460	0.674525
VLX 1	-0.003460	-0.001896	0.674525
VUX 2	-0.030281	-0.031889	0.665304
VLX 2	-0.031889	-0.030281	0.665304
VUX 3	-0.037056	-0.004649	0.671402
VLX 3	-0.043858	-0.008130	0.664211
XDE 5	1.250000	-1.250000	0.000000
XDC 5	100	100	100
XDE 7	-1.250000	1.250000	0.000000
XDC 7	100	100	100
CIR 5	0.375000	0.375000	5.000000
CIR 6	0.375000	0.375000	5.000000
CIR 6 H	-0.010000	-0.010000	-0.875000
REX 4	1.625000	1.625000	1.625000
REY 4	1.625000	1.625000	0.375000

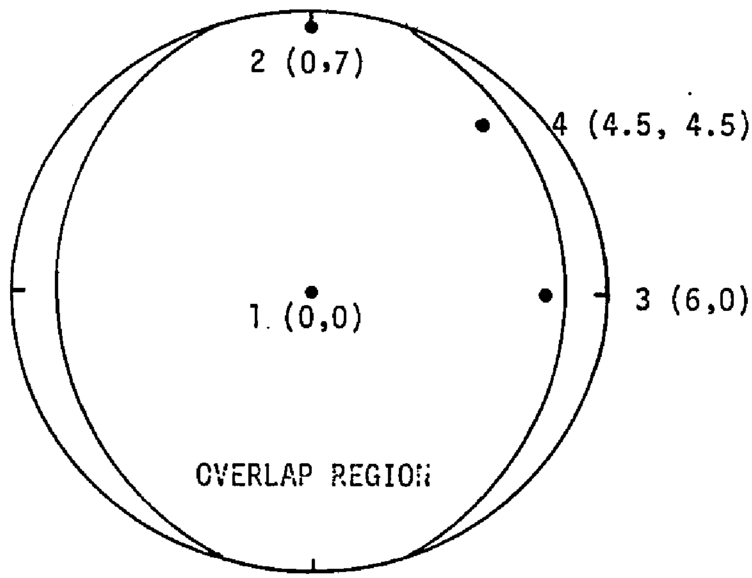
SPECIFICATION DATA

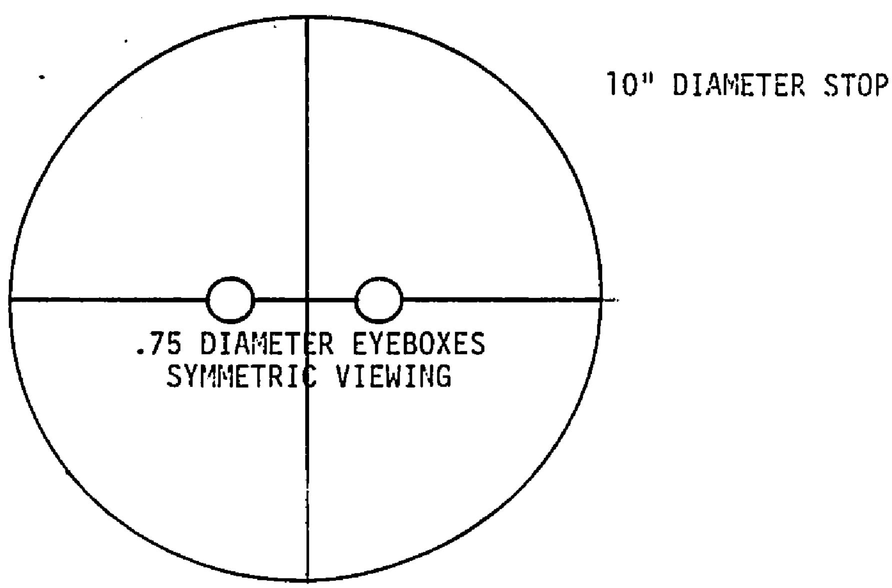
EPD	0.75000
AFO	
DIM	I
WL	589.00
WTW	1
REF	1

APERTURE DATA

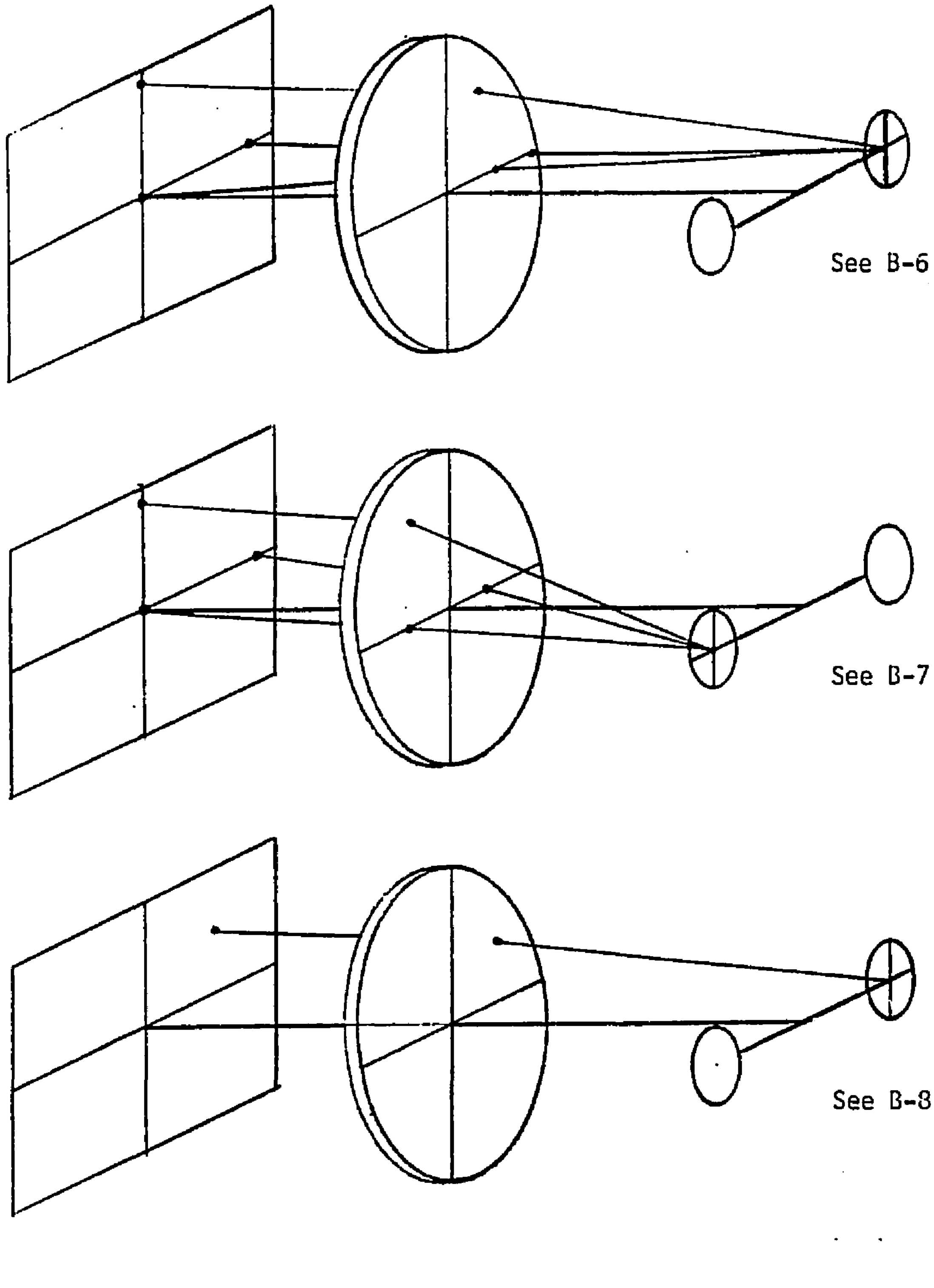
CIR	3	14.999985
REX	4	1.625000
REY	4	1.625000
CIR	5	0.375000
CIR	6	0.375000
CIR	6 A	-0.010000

B.2. Spherical mirror (Case 1).

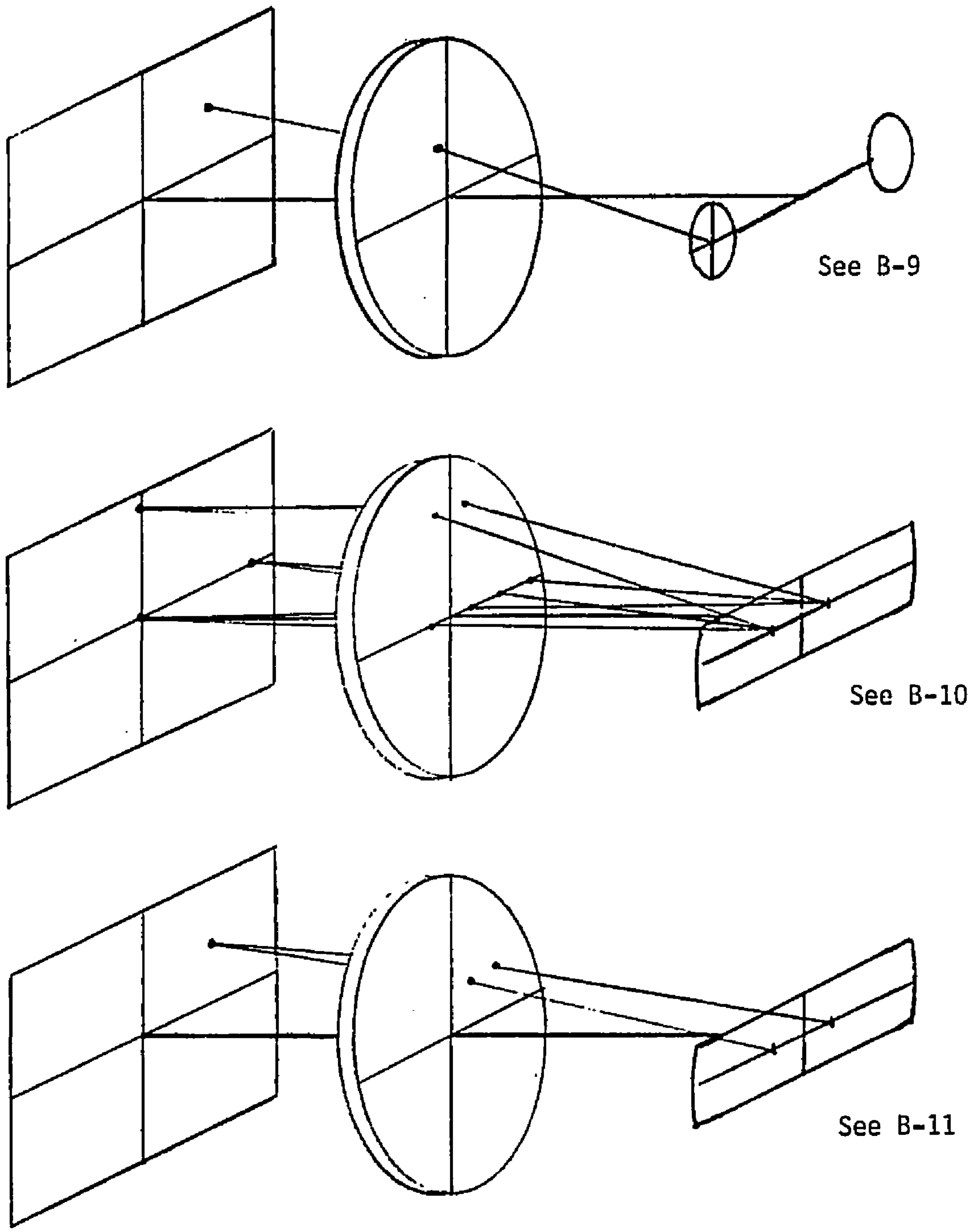




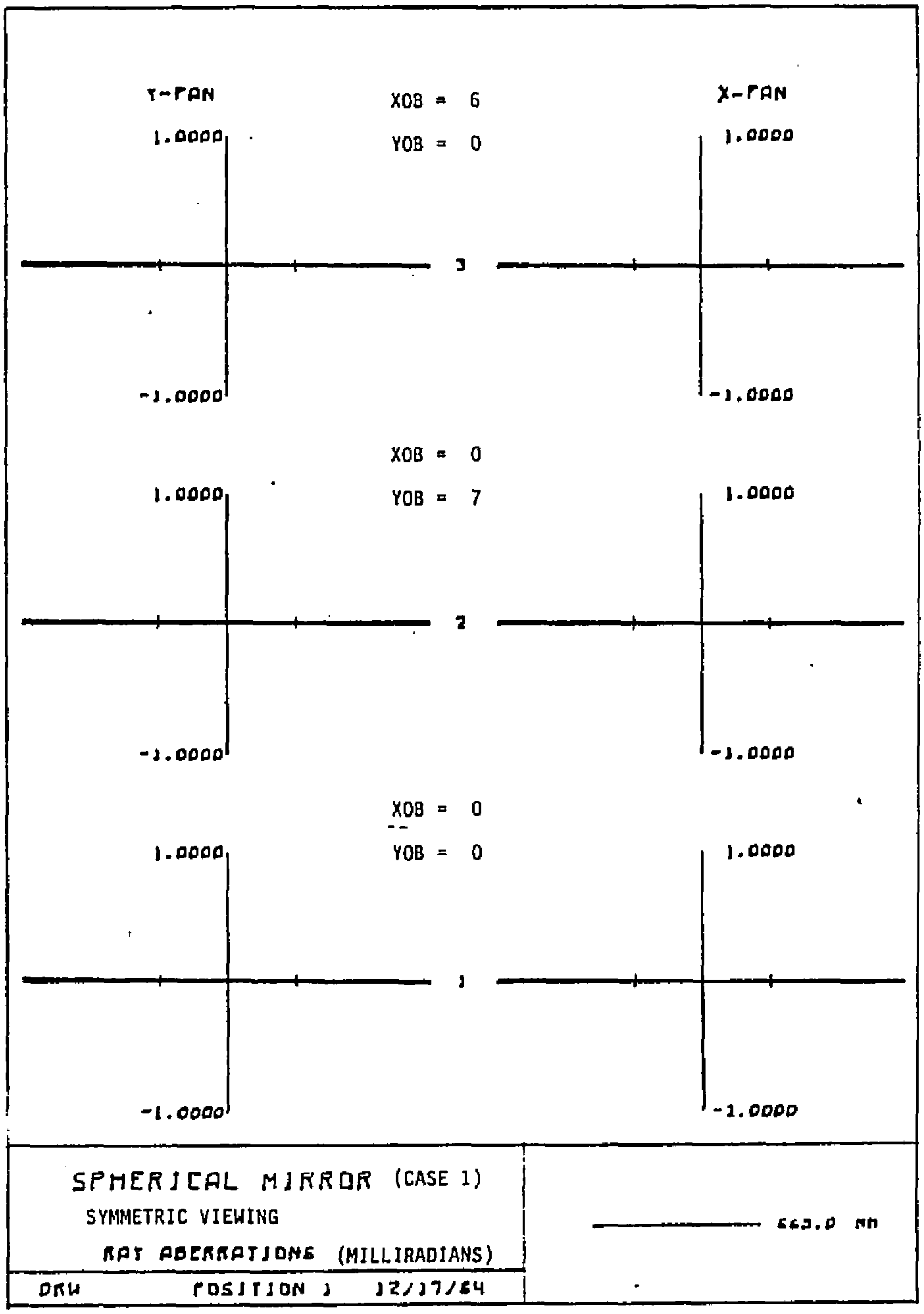
B.3. Object points and eyebox location (Case 1).



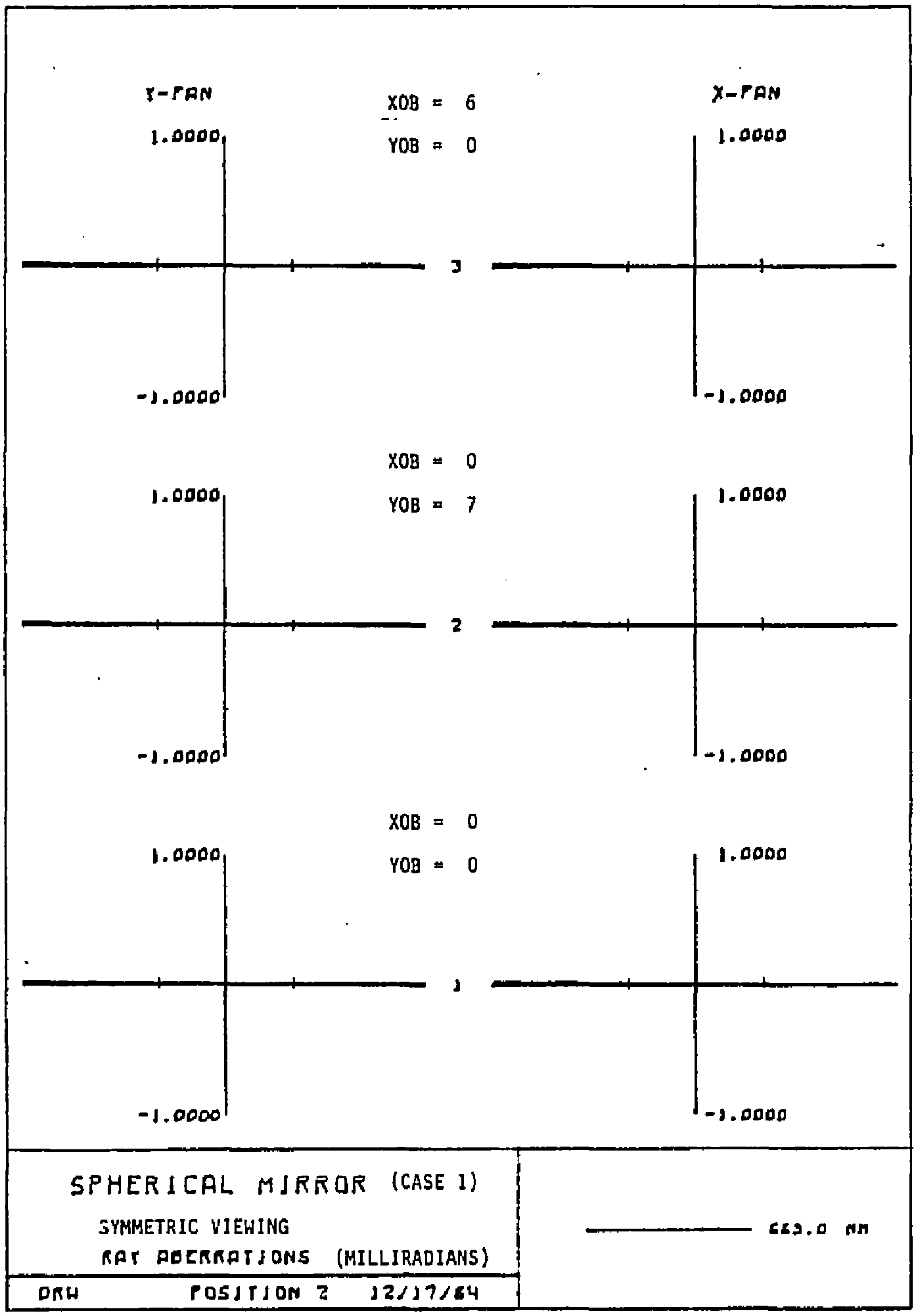
B.4. Key to ray fans for spherical mirror (Case 1).



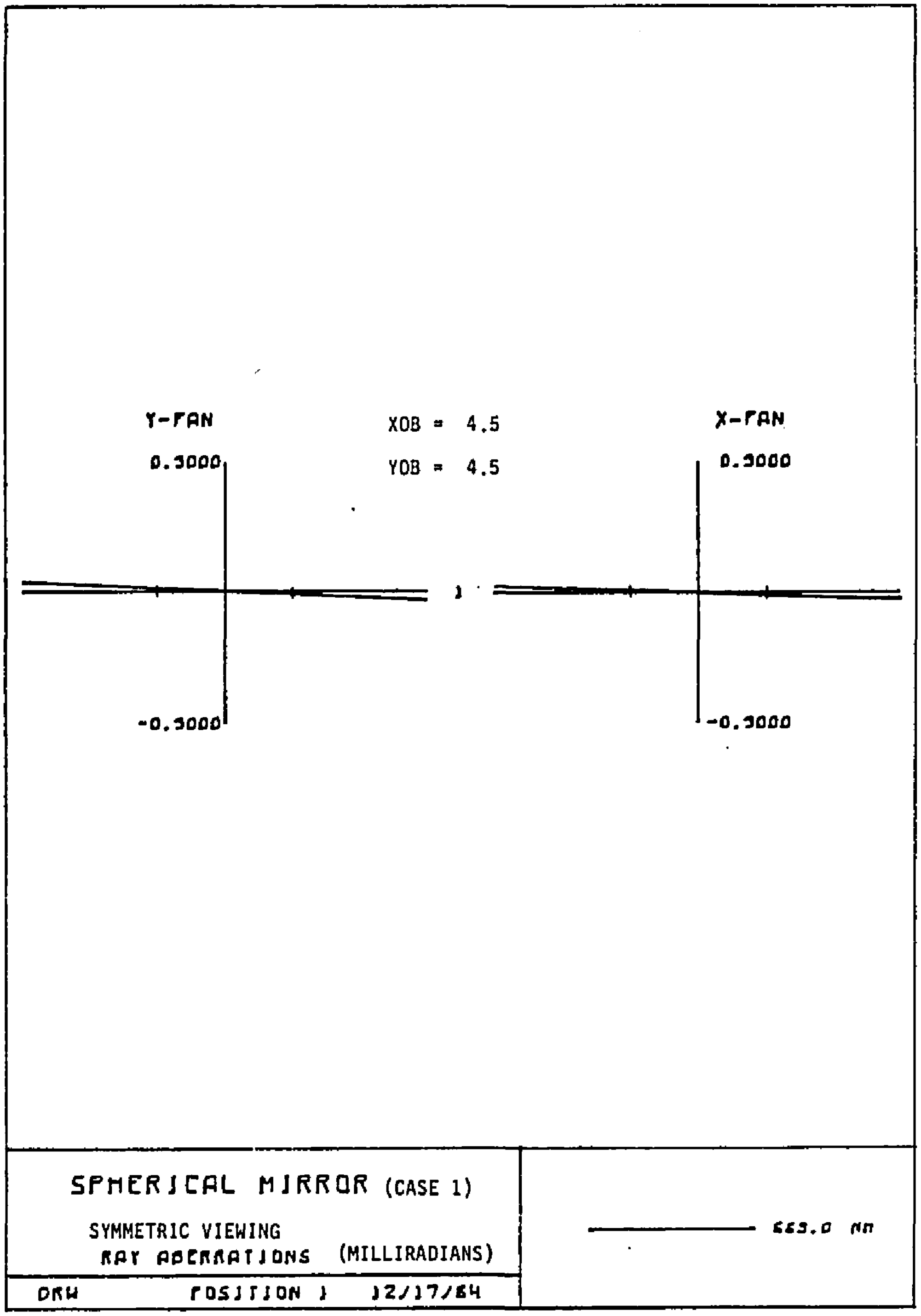
B.5. Key to ray fans for spherical mirror.


Y-FAN
XOB = 6
YOB = 0
X-FAN
1.0000
-1.0000
3
XOB = 0
YOB = 7
2
XOB = 0
YOB = 0
1
SPHERICAL MIRROR (CASE 1)
SYMMETRIC VIEWING
RAY ABERRATIONS (MILLIRADIANS)
DRW
POSITION 1
12/17/84
663.0 NM

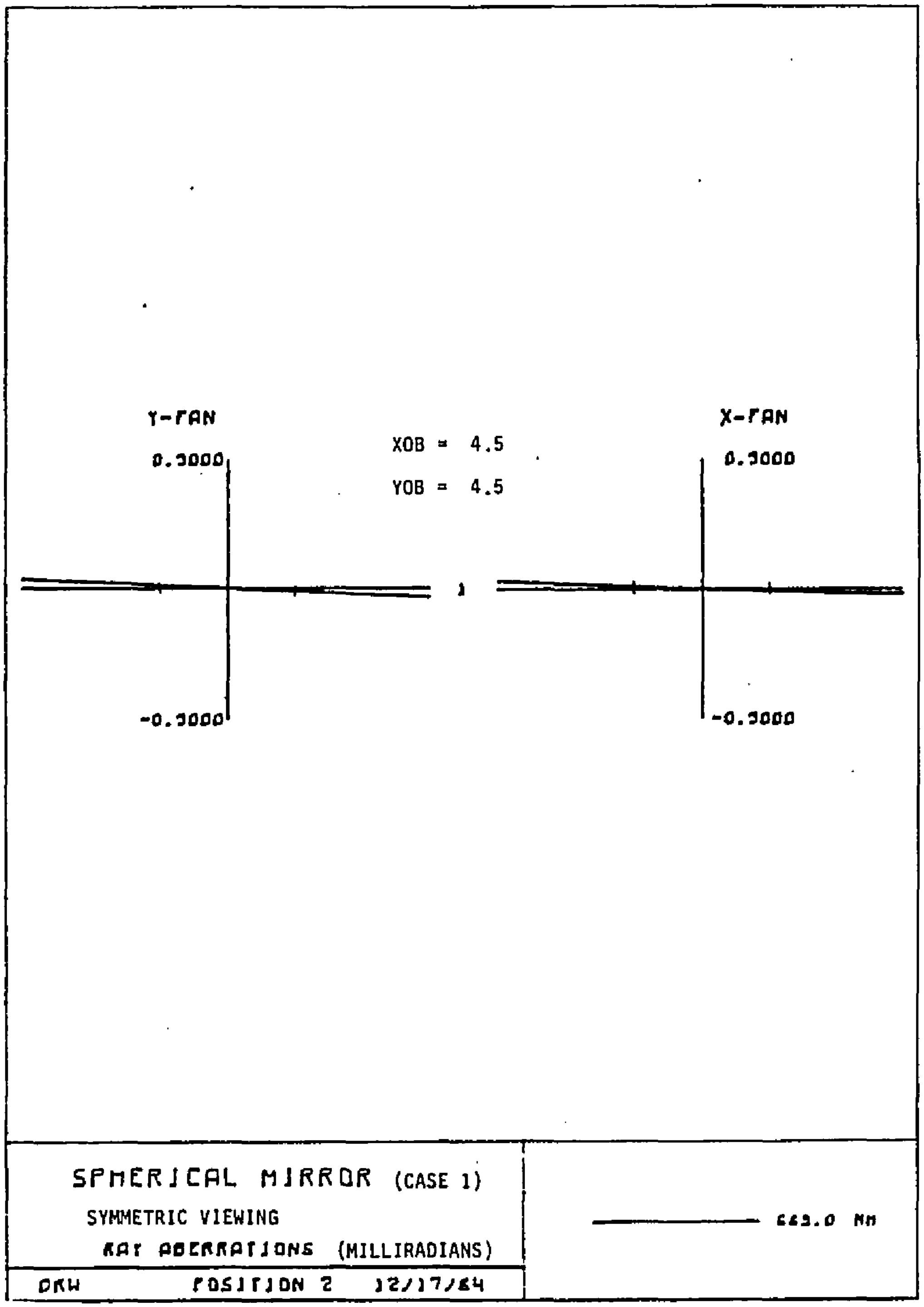
B.6. Right eye.


Y-FAN
X-FAN
XOB = 6
YOB = 0
1.0000
-1.0000
3
XOB = 0
YOB = 7
2
XOB = 0
YOB = 0
1
SPHERICAL MIRROR (CASE 1)
SYMMETRIC VIEWING
RAY ABERRATIONS (MILLIRADIANS)
DRW
POSITION 2
12/17/84

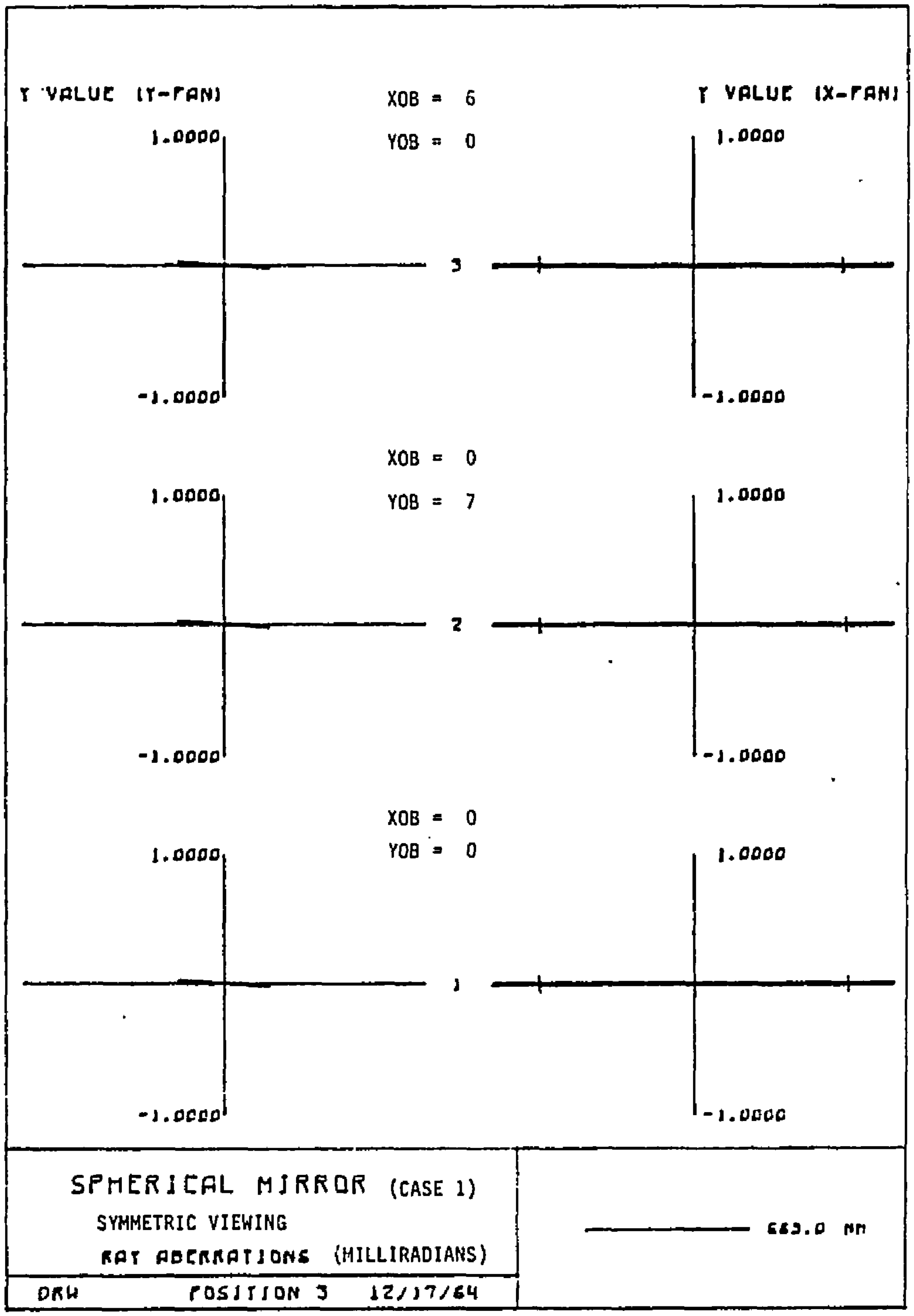
B.7. Left eye.


Y-FAN
XOB = 4.5
YOB = 4.5
X-FAN
0.5000
-0.5000
0.5000
-0.5000
SPHERICAL MIRROR (CASE 1)
SYMMETRIC VIEWING
RAY ABERRATIONS (MILLIRADIANS)
DRW
POSITION 1
12/17/84
653.0 NM

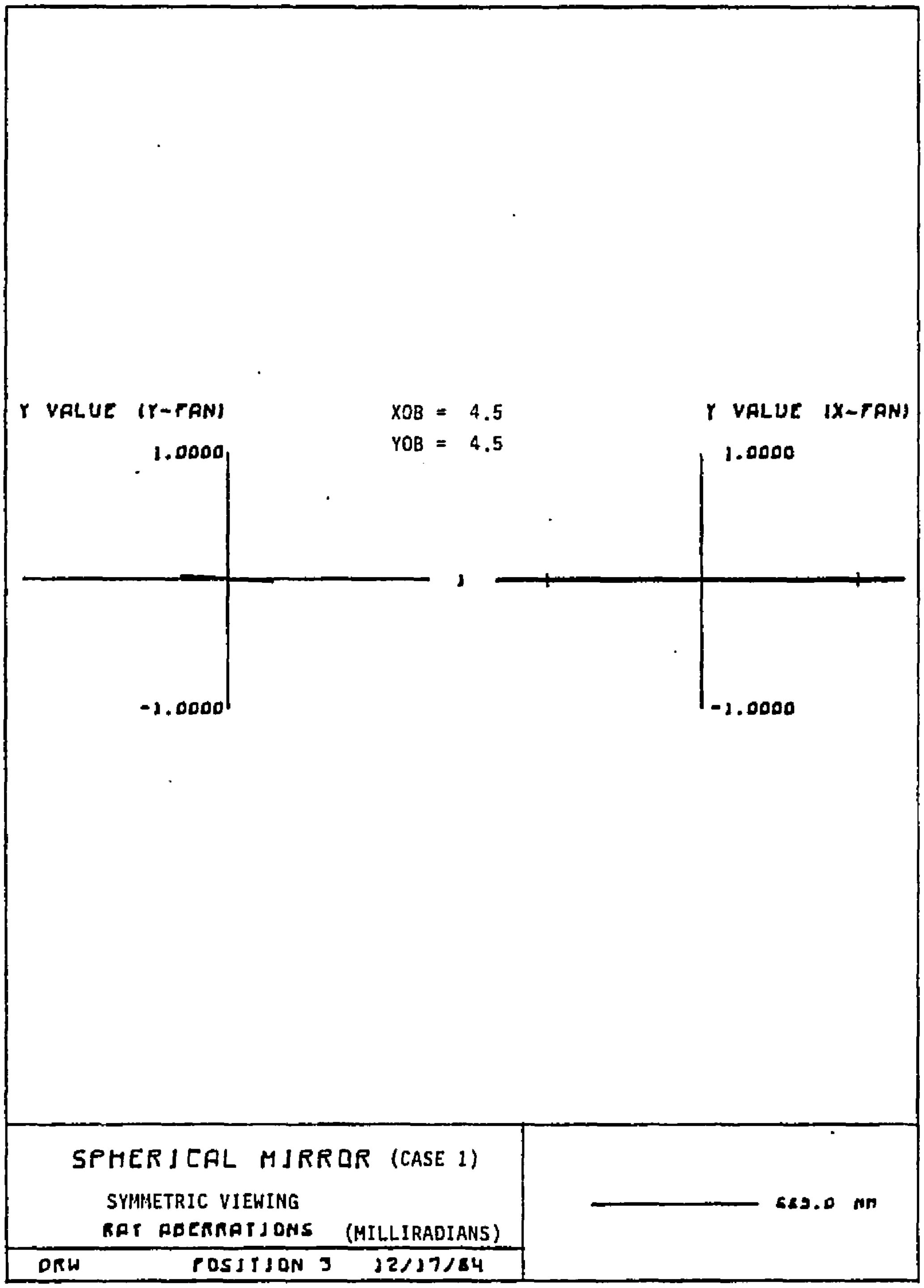
B.8. Right eye.


Y-FAN
X-FAN
XOB = 4.5
YOB = 4.5
0.5000
-0.5000
0.5000
-0.5000
SPHERICAL MIRROR (CASE 1)
SYMMETRIC VIEWING
RAY ABERRATIONS (MILLIRADIANS)
DKW
POSITION 2
12/17/84
663.0 NM

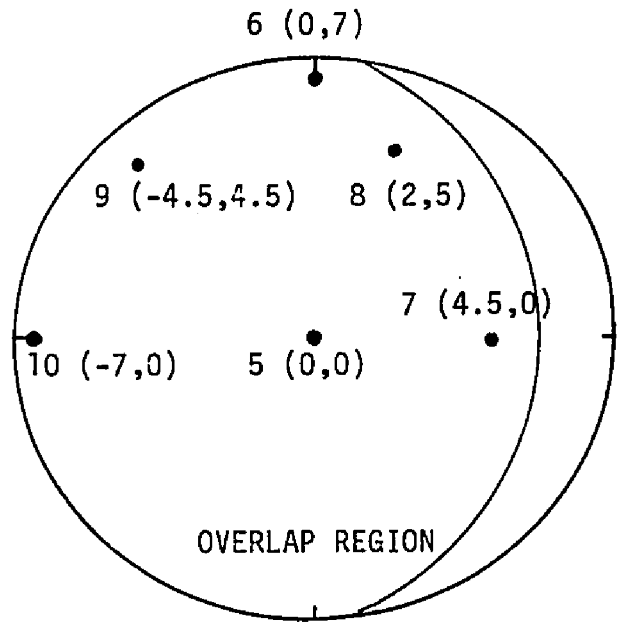
B.9. Left eye.

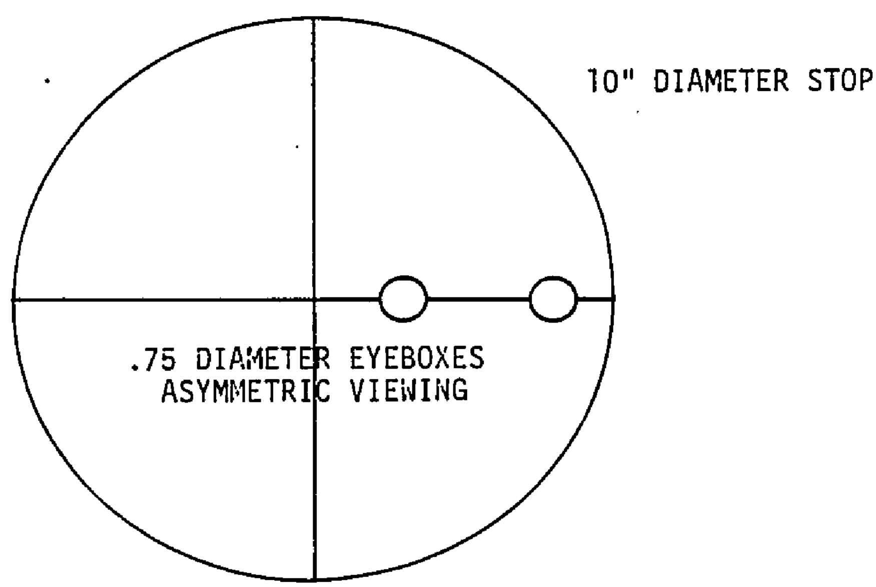


B.10. Dipvergence.

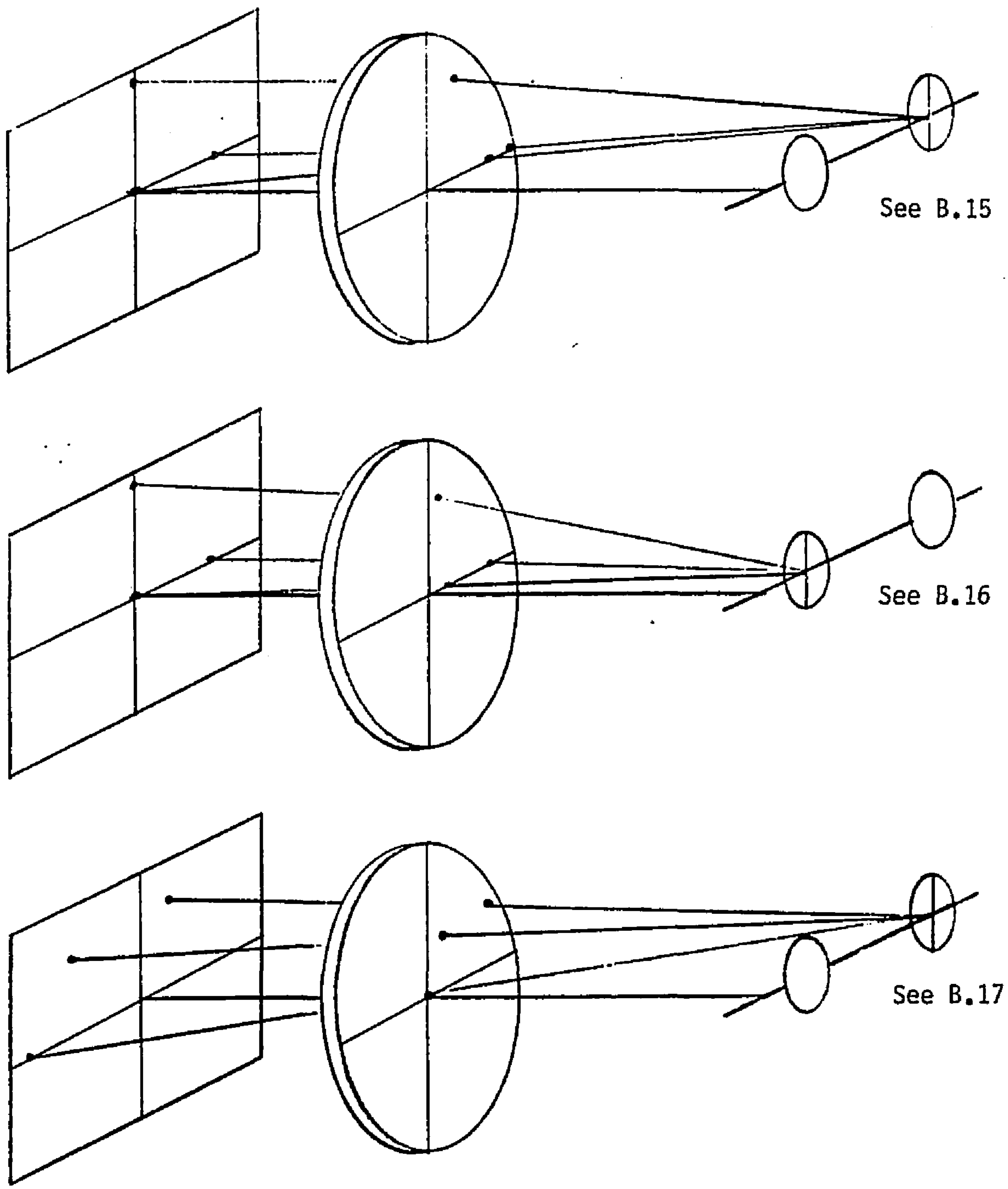


B.11. Dipvergence.

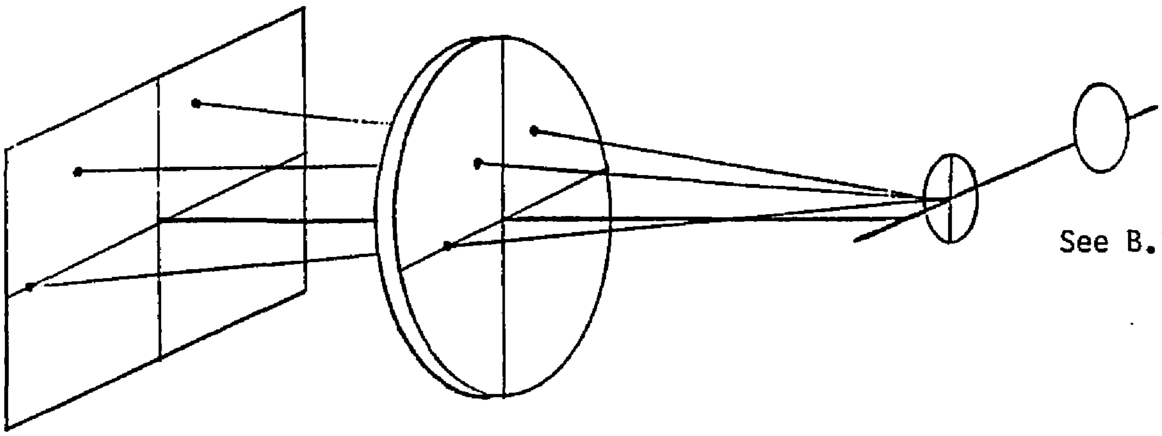


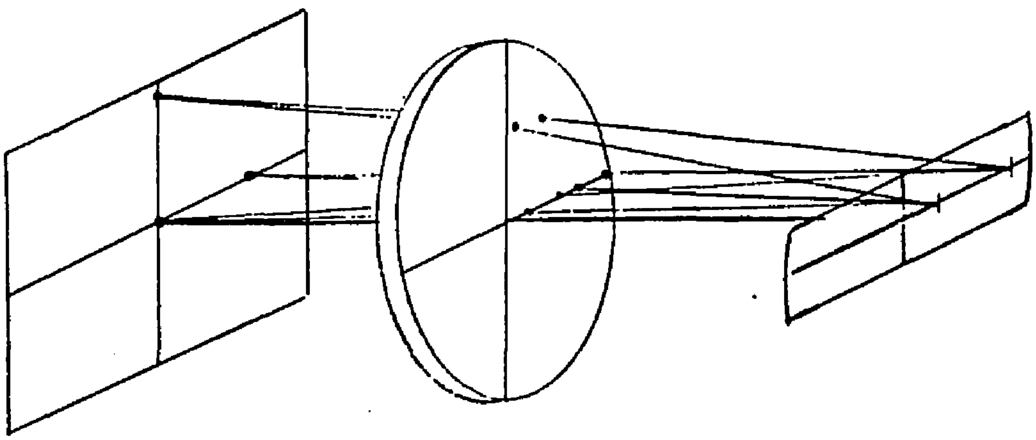


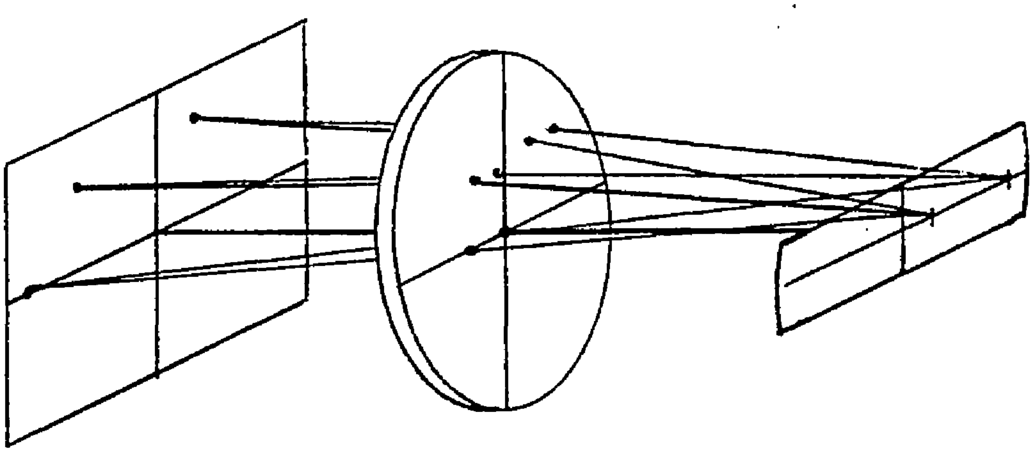
B.12. Object points and eyebox locations (Case 1).



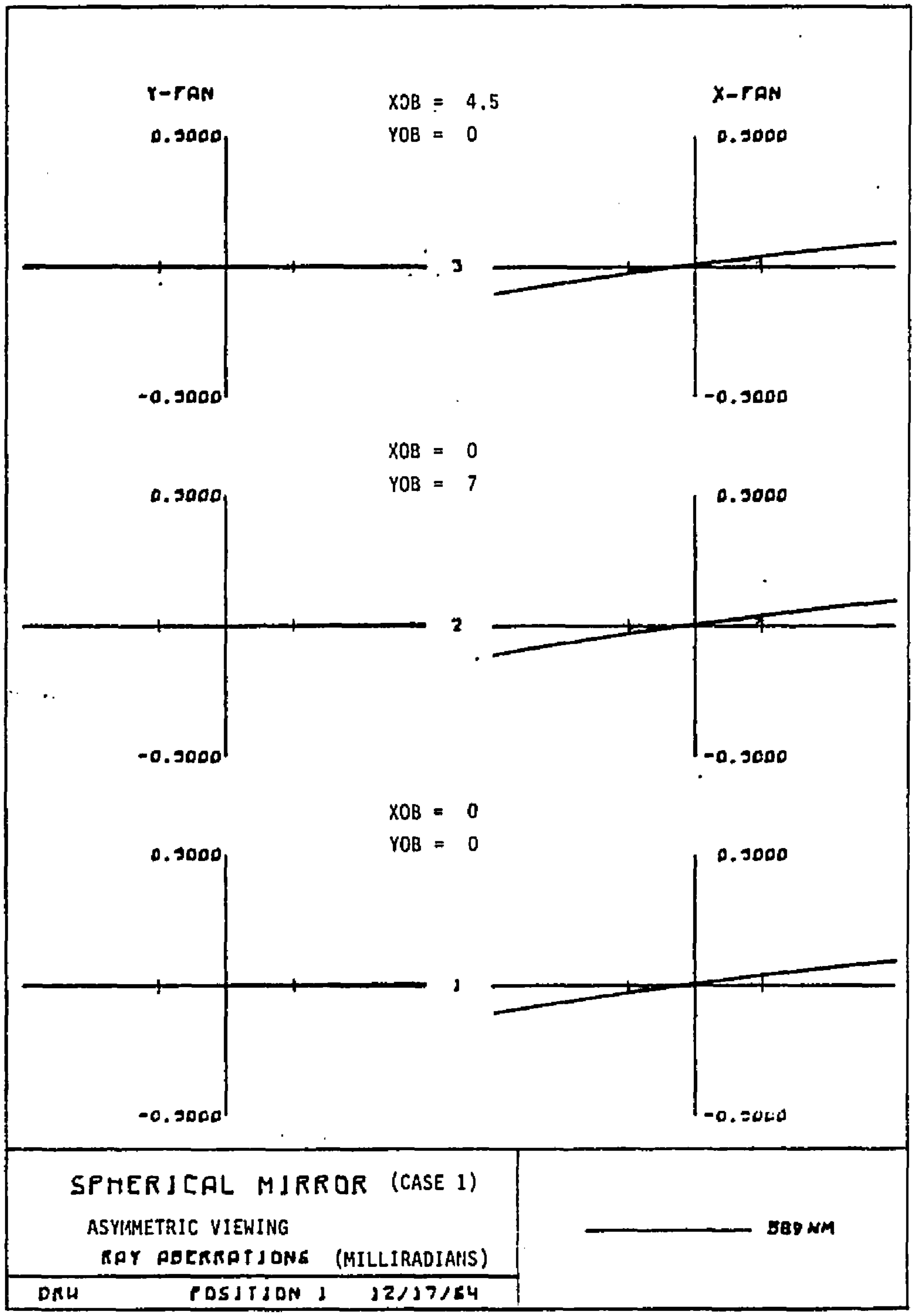
B.13. Key to ray fans for spherical mirror (Case 1).



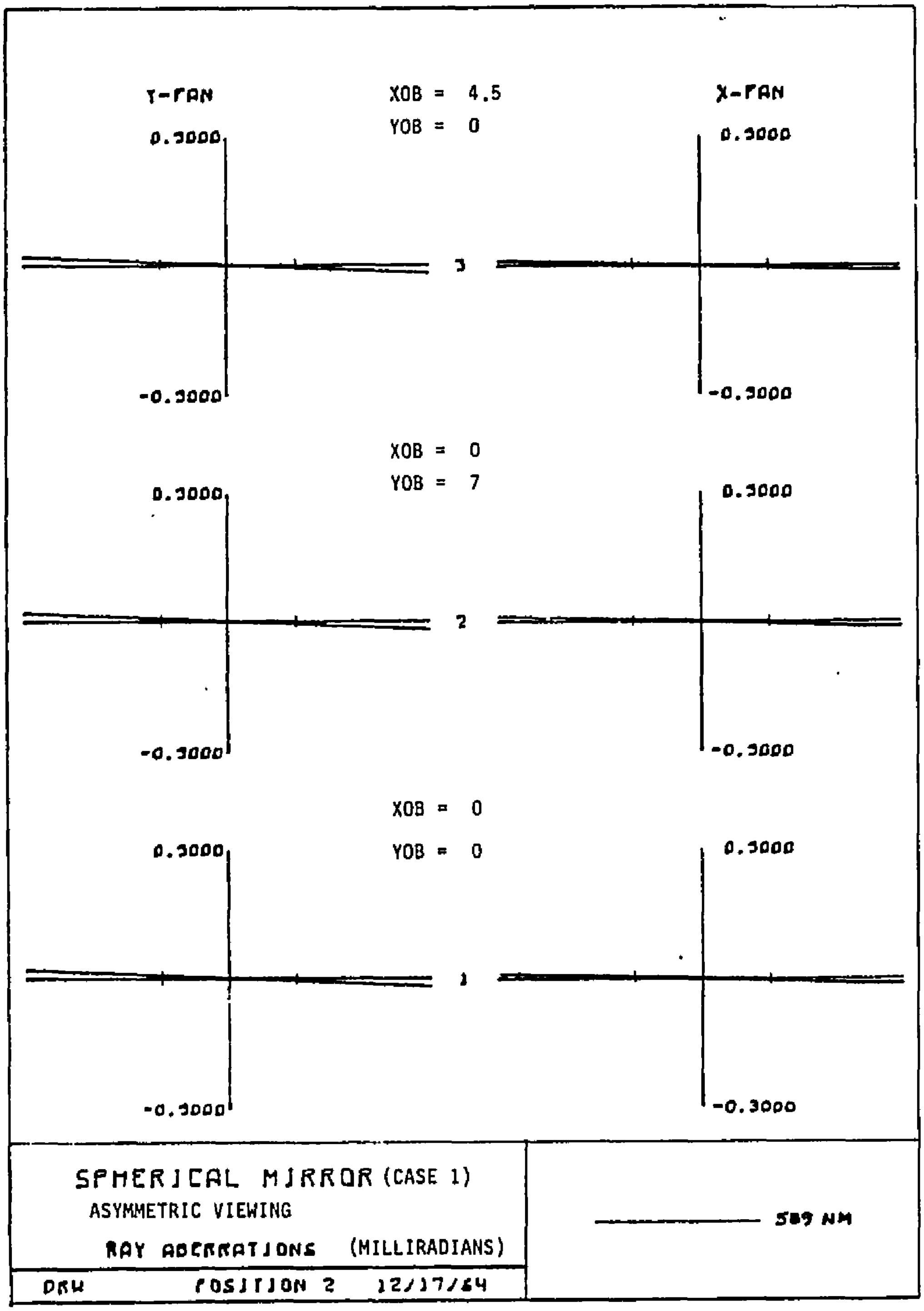




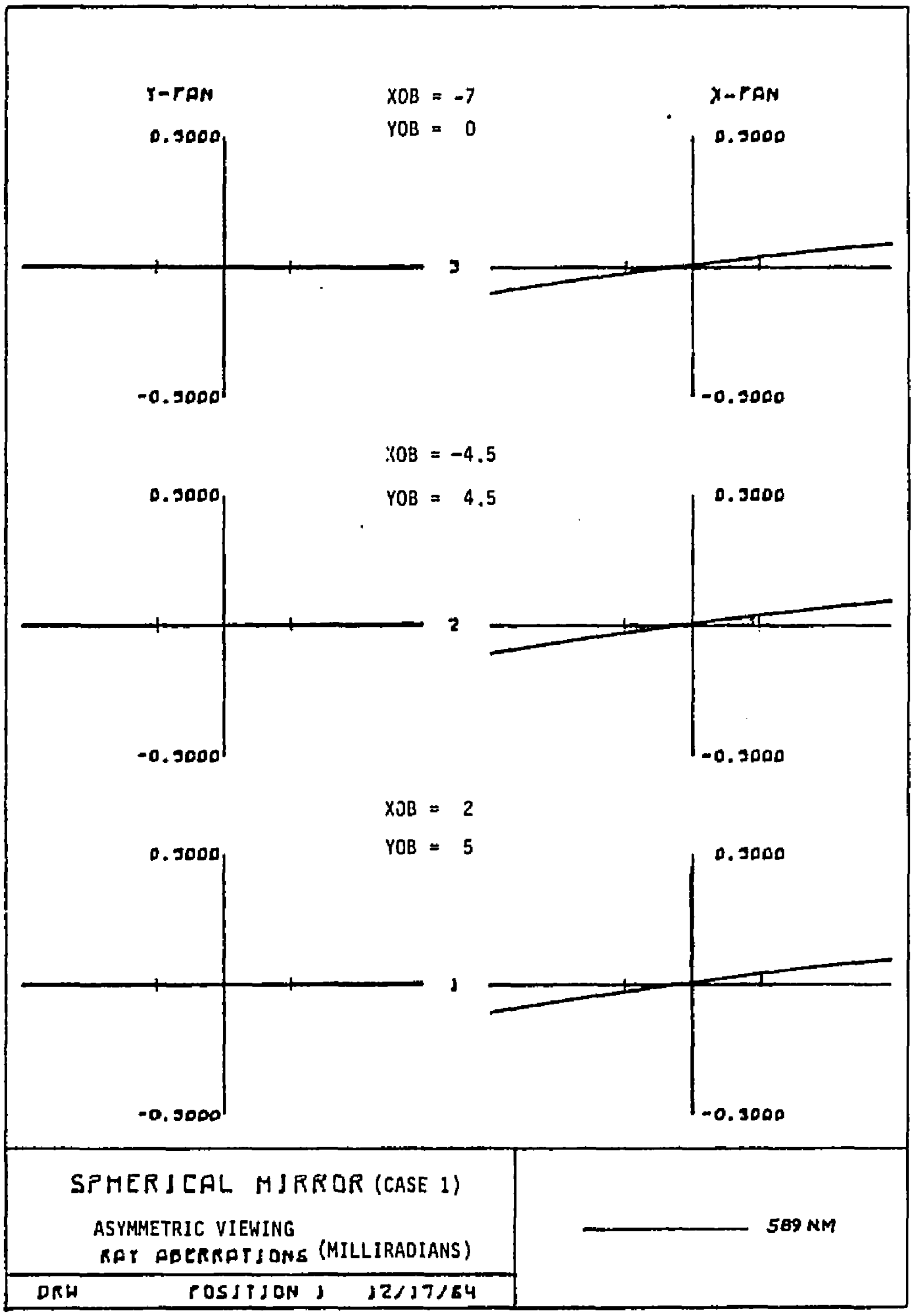
B.14. Key to ray fans for spherical mirror (Case 1).



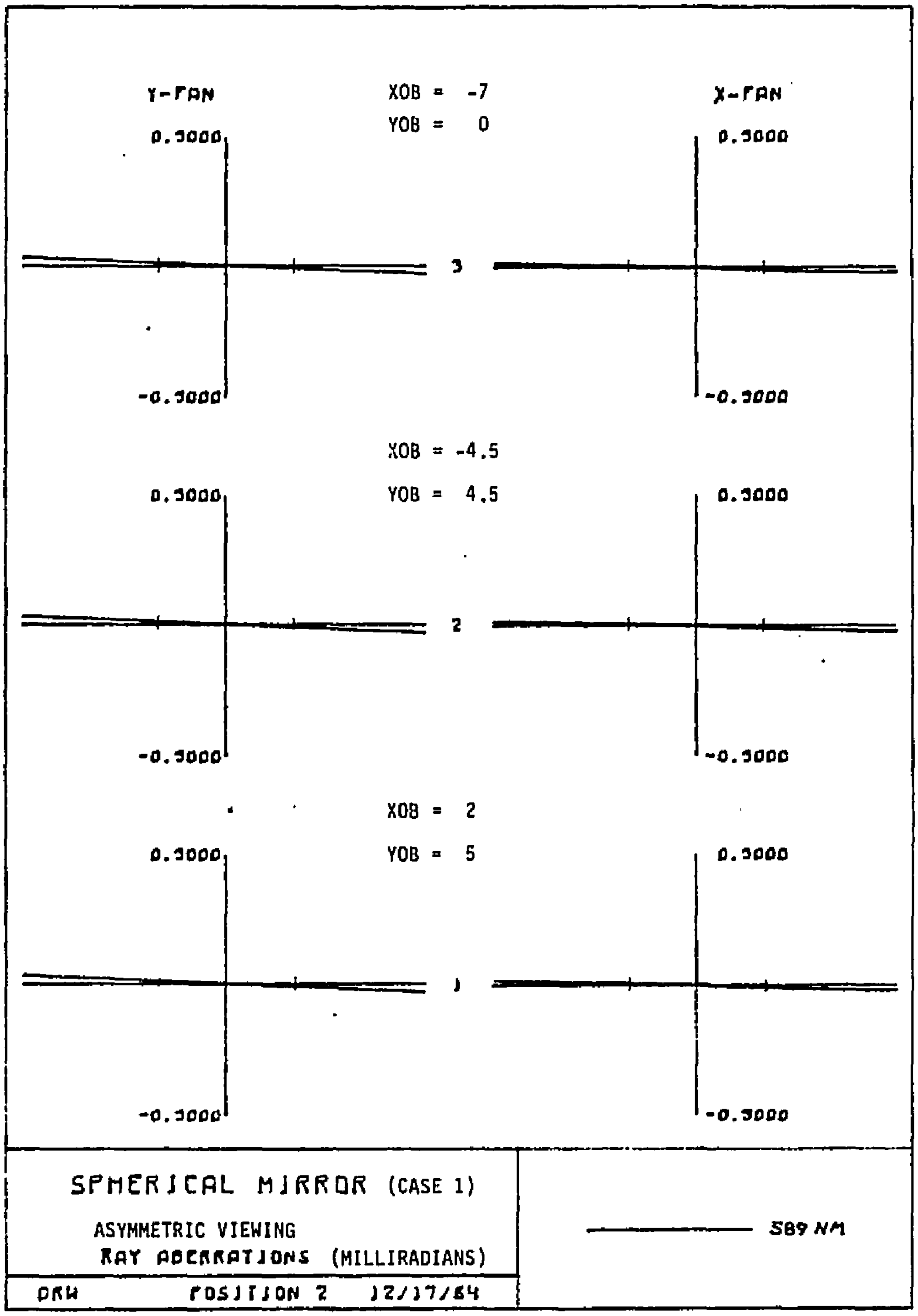
B.15. Right eye.


Y-FAN
XOB = 4.5
YOB = 0
X-FAN
0.3000
-0.3000
3
XOB = 0
YOB = 7
2
XOB = 0
YOB = 0
1
SPHERICAL MIRROR (CASE 1)
ASYMMETRIC VIEWING
RAY ABERRATIONS (MILLIRADIANS)
DRW POSITION 2 12/17/84
589 NM

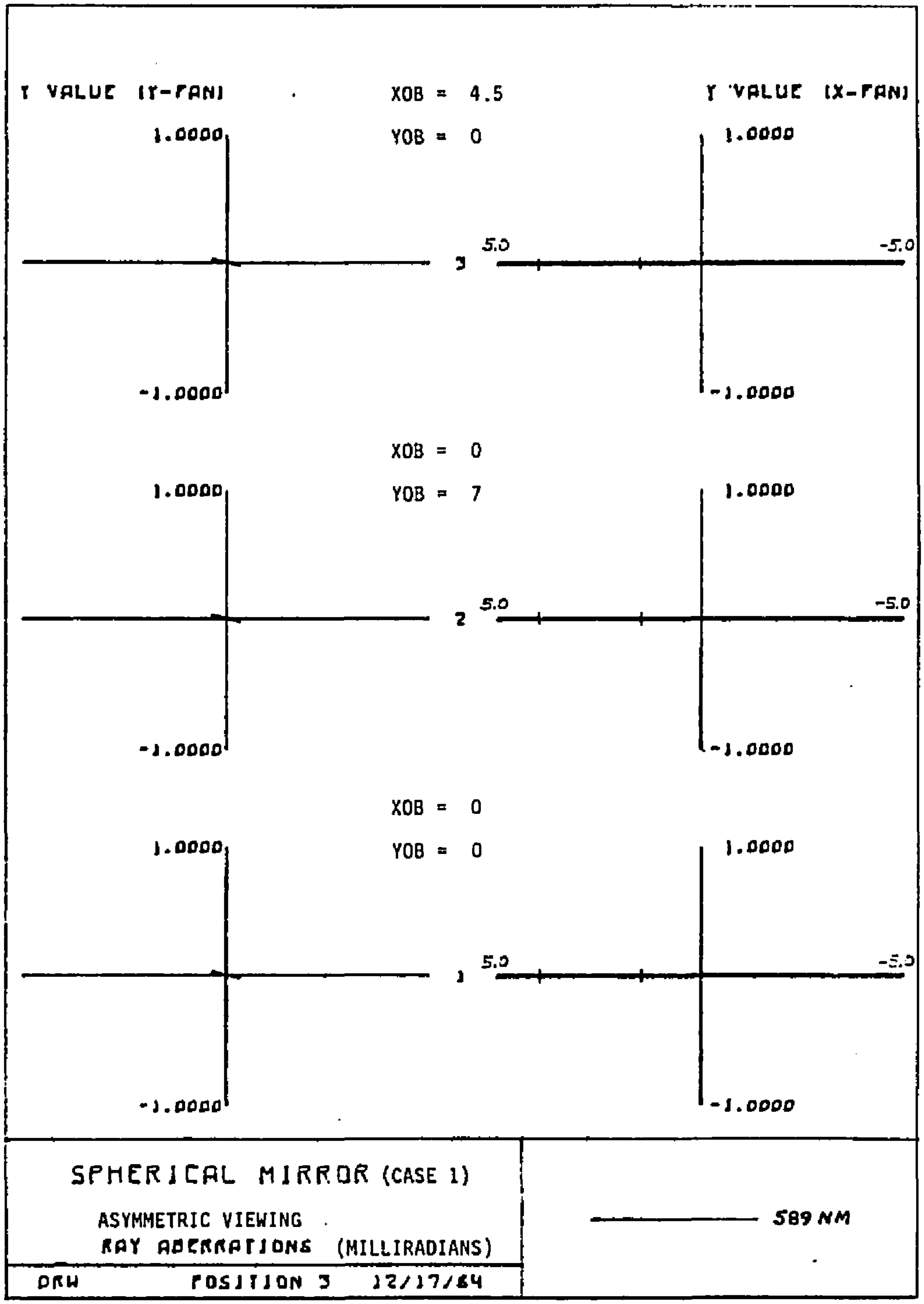
B.16. Left eye.



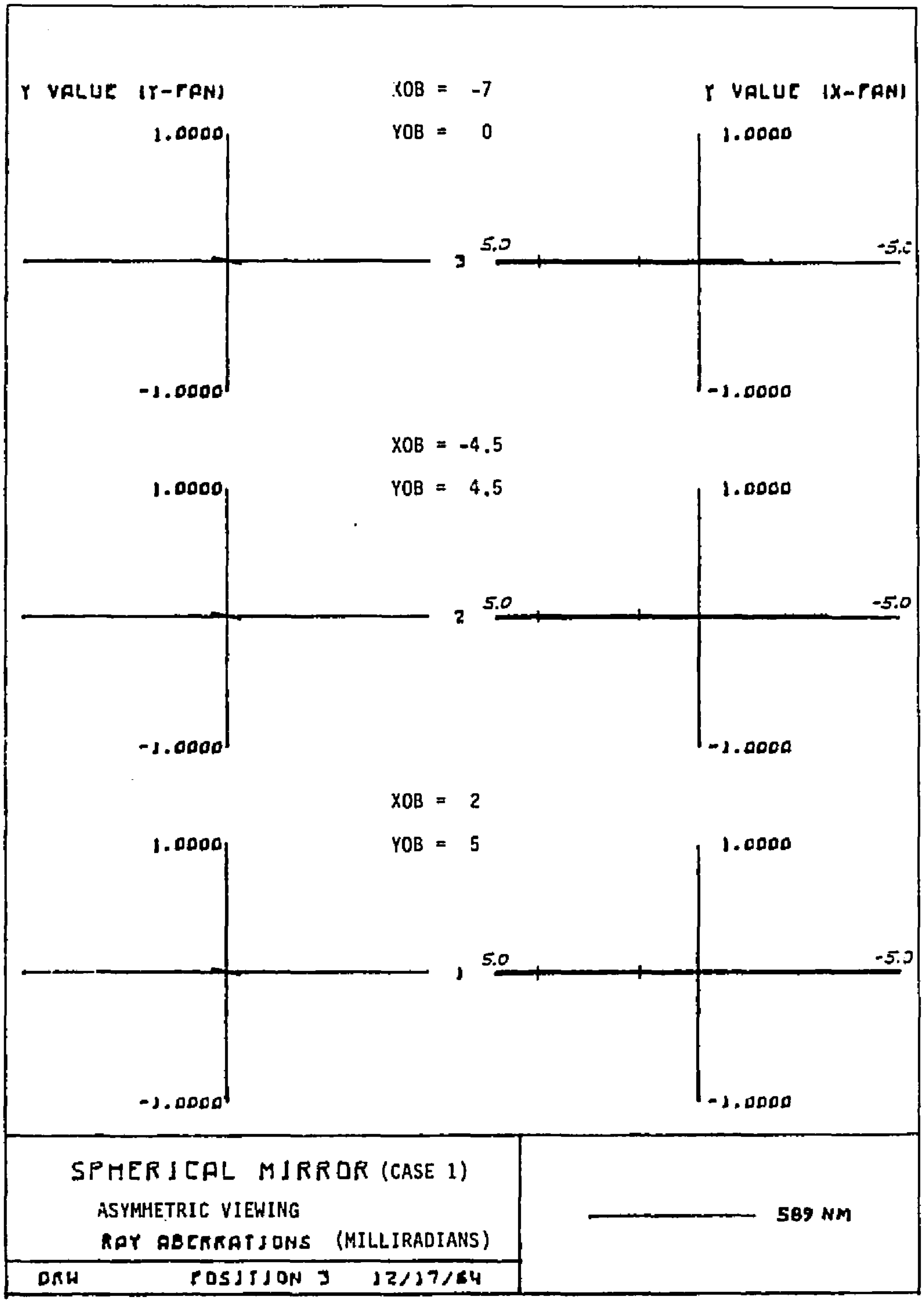
B.17. Right eye.


Y-FAN
XOB = -7
YOB = 0
X-FAN
0.5000
-0.5000
3
XOB = -4.5
YOB = 4.5
2
XOB = 2
YOB = 5
1
SPHERICAL MIRROR (CASE 1)
ASYMMETRIC VIEWING
RAY ABERRATIONS (MILLIRADIANS)
DRW POSITION 2 12/17/84
589 NM

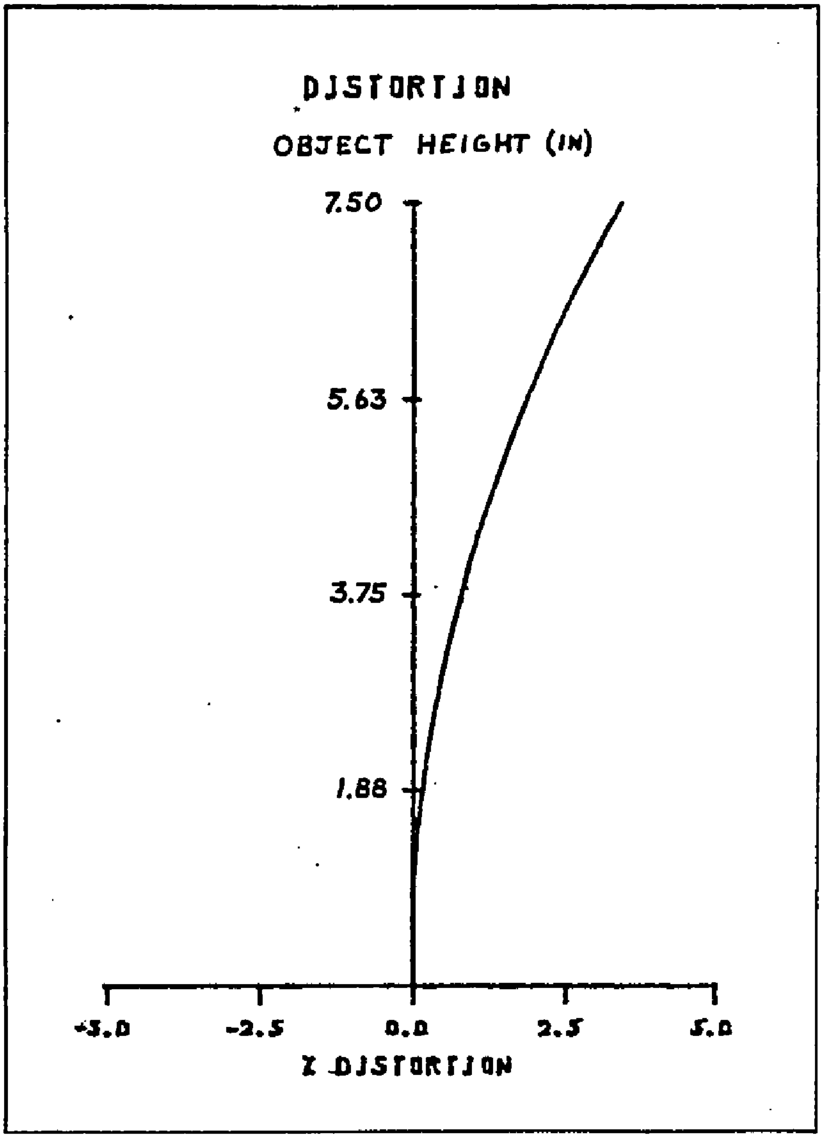
B.18. Left eye.



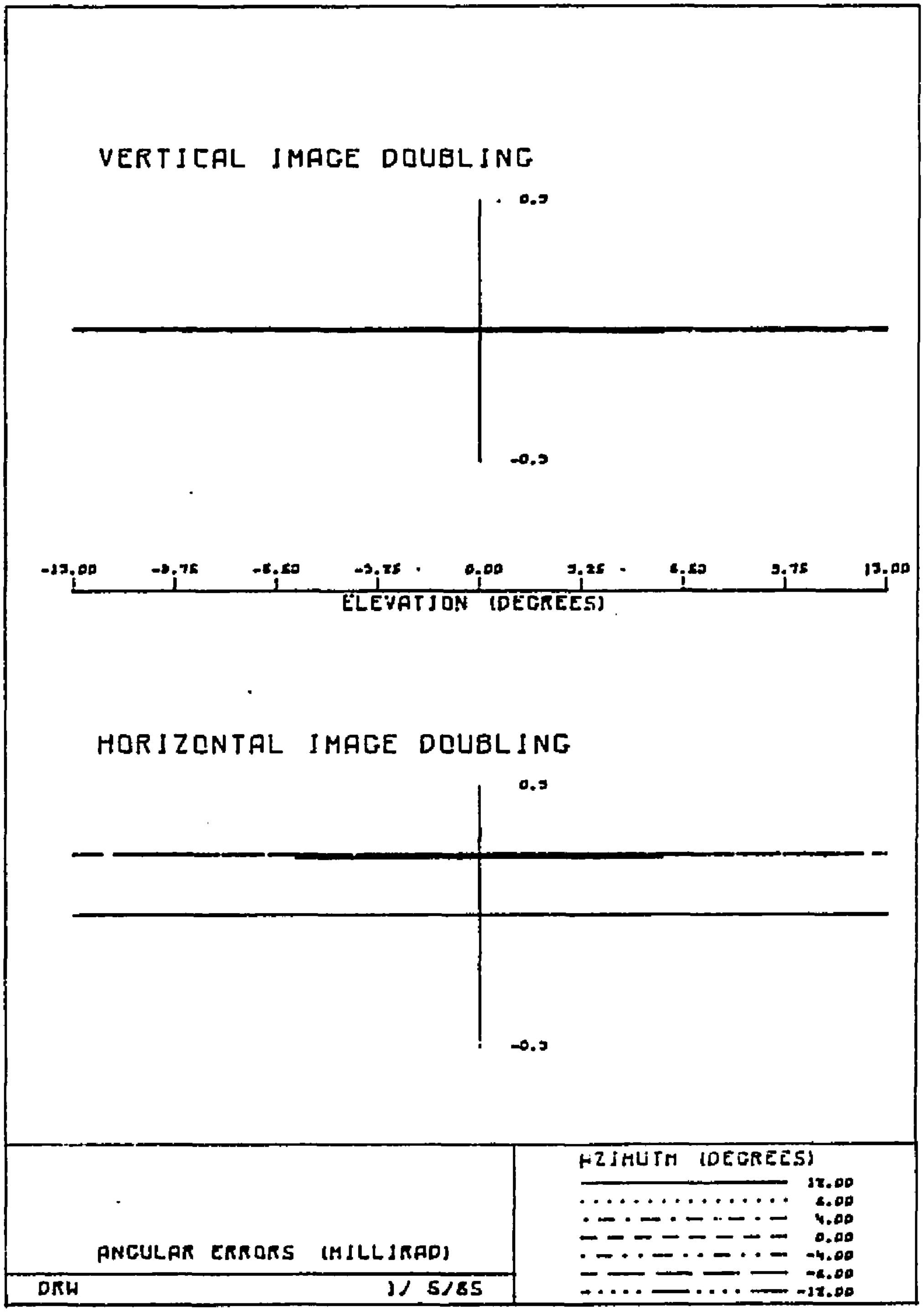
B.19. Dipvergence.



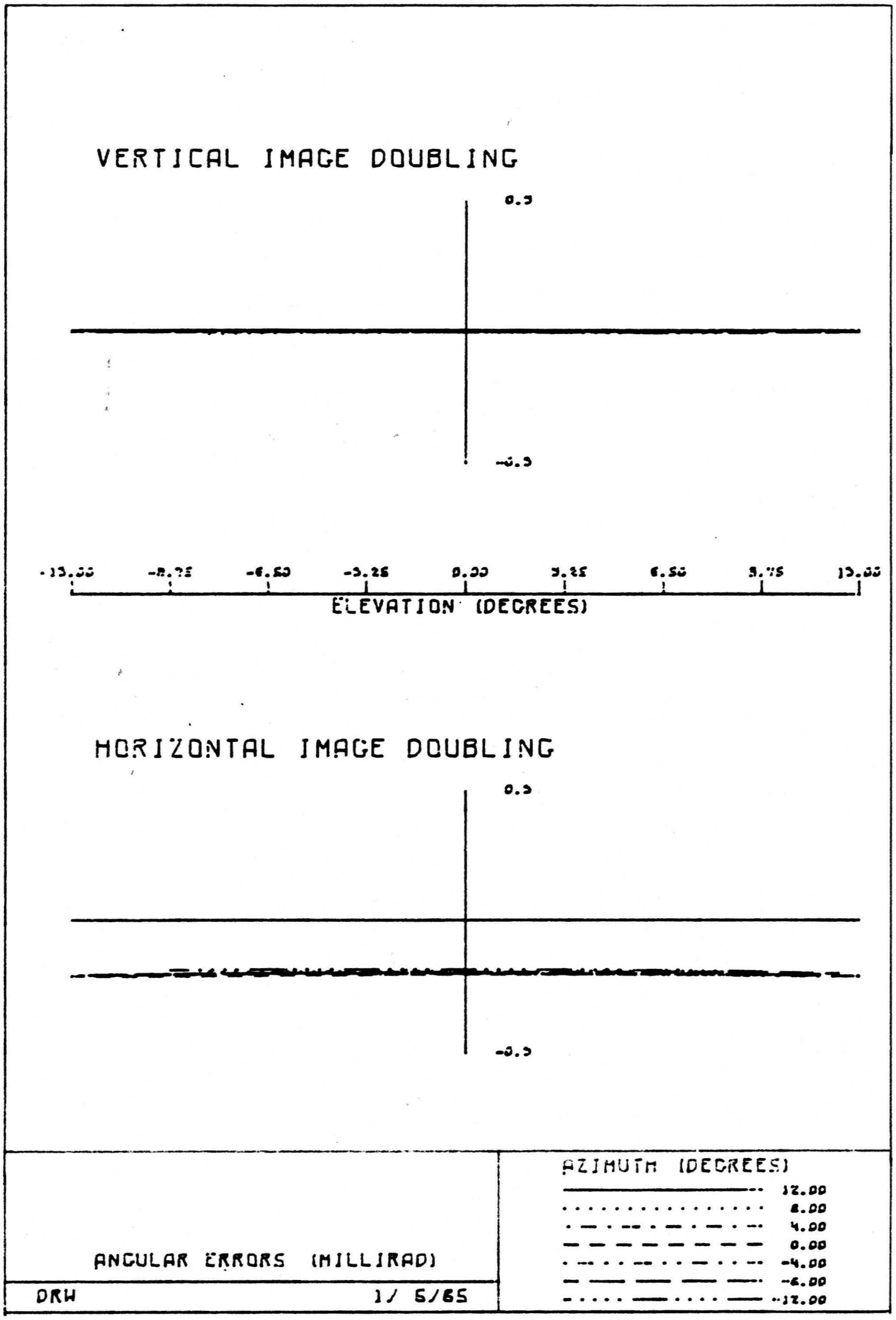
B.20. Dipvergence.



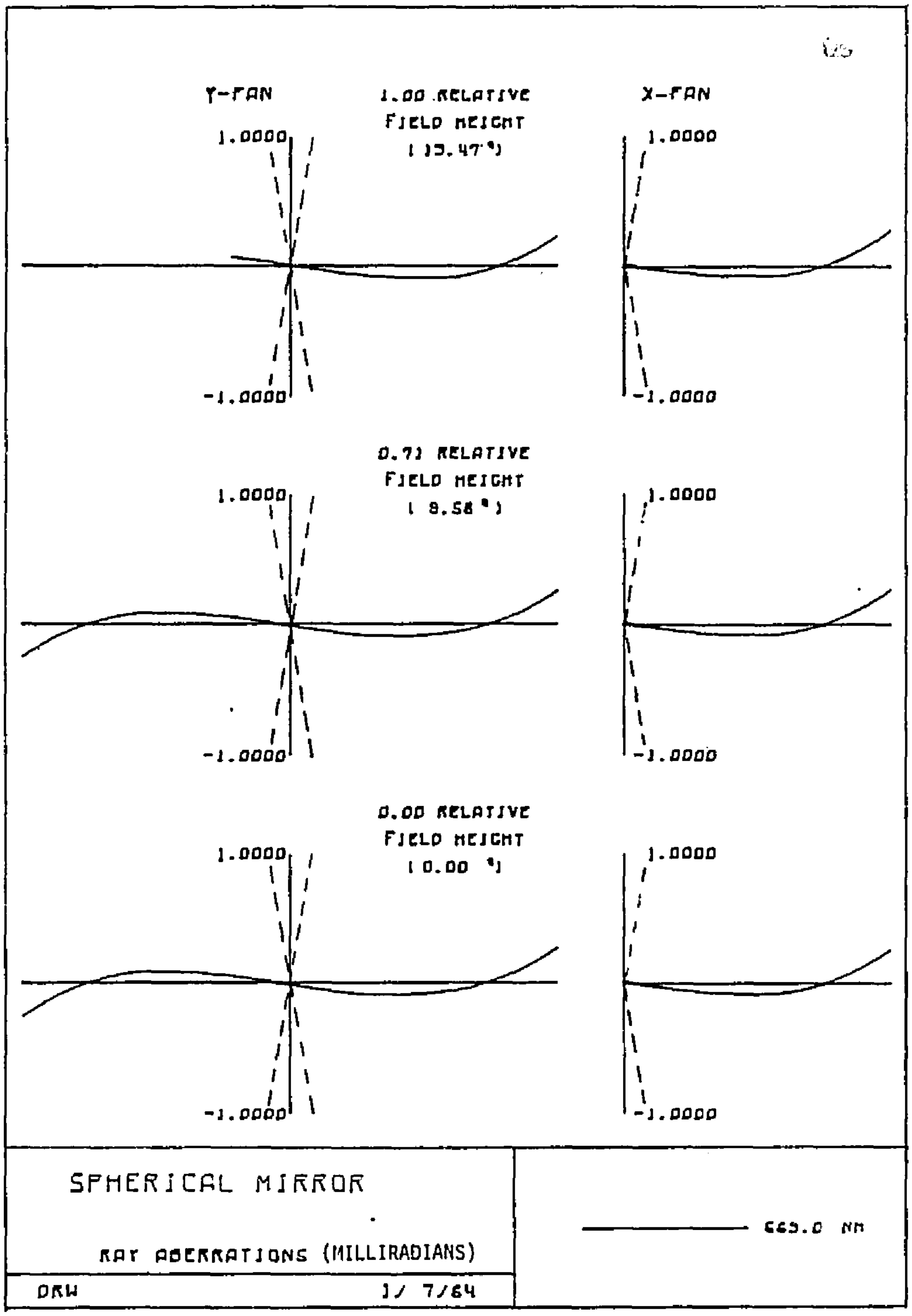
B.21. Distortion.



B.22. Image doubling (Symmetric view, Case 1).



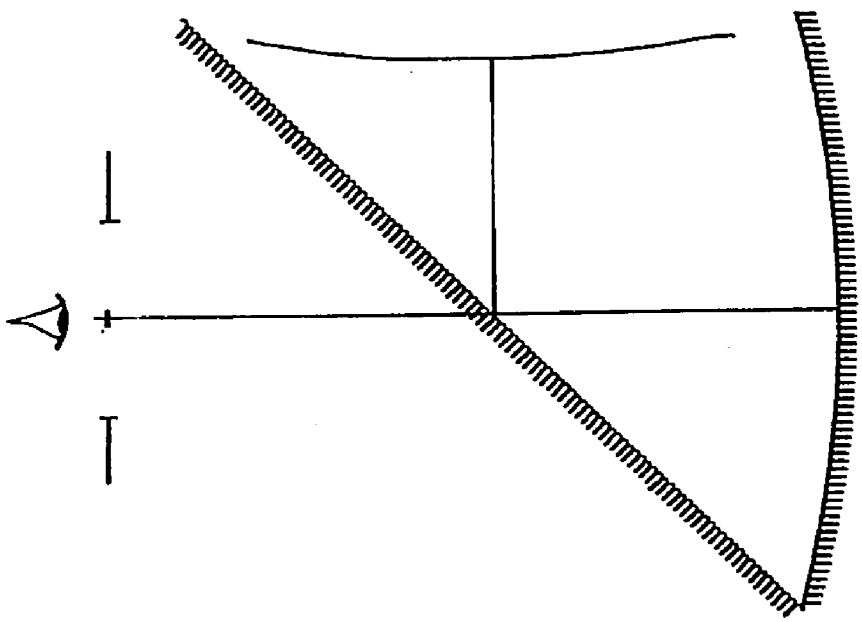
B.23. Image doubling (Asymmetric view, Case 1).



B.24. Blur size, Case 1.

APPENDIX C

ANALYSIS OF SPHERICAL MIRROR (CASE 2)



C.1. Spherical mirror (Case 2).

SPHERICAL MIRROR

SURFACE DATA

	RADIUS	CCY	THICKNESS	THC	GLASS	GLC	GCH	STOP
OBJ	-59.94602	300	12.944588	100		100		
1	1.0000E+18	300	0.000000	100		100		
2	DECE	0.000000	0.000000	-45.000000	0.000000	0.000000	BEND	
	DECC	100	100	100	100	100		
	1.0000E+18	300	-17.000000	100	REFL	100		
3	60.00000	300	36.000000	100	REFL	100		
4	1.0000E+18	300	0.000000	100		100		
5	DECE	1.250000	0.000000	0.000000	0.000000	0.000000		
	DECC	100	100	100	100	100		
	1.0000E+18	300	0.000000	100		100		
6	1.0000E+18	300	0.000000	100		100		S
7	DECE	-1.250000	0.000000	0.000000	0.000000	0.000000		
	DECC	100	100	100	100	100		
	1.0000E+18	300	0.000000	100		100		
8	1.0000E+18	300	1000.000000	100		100		
9	1.0000E+18	300	0.000000	100		100		

ZOOM DATA

			POS 1	POS 2	POS 3
EPD			3.760409	3.760409	16.269095
STO			6	6	6
VUY	1		0.002013	0.002013	0.769488
VLY	1		0.002013	0.002013	0.769488
VUY	2		0.064409	0.064409	0.783908
VLY	2		0.063977	0.063977	0.783807
VUY	3		0.009013	0.019920	0.772359
VLY	3		0.009013	0.019920	0.772359
VUX	1		0.001251	0.000002	0.000000
VLX	1		0.000002	0.001251	0.000000
VUX	2		0.016087	0.014898	0.014778
VLX	2		0.014898	0.016087	0.014778
VUX	3		0.052298	0.053743	0.053082
VLX	3		0.050738	0.054531	0.051373
XDE	5		1.250000	-1.250000	0.000000
XDC	5		100	100	100
XDE	7		-1.250000	1.250000	0.000000
XDC	7		100	100	100
CIR	5		0.375000	0.375000	5.000000
CIR	6		0.375000	0.375000	5.000000
CIR	6	A	-0.010000	-0.010000	-0.875000
REX	4		1.625000	1.625000	1.625000
REY	4		1.625000	1.625000	0.375000

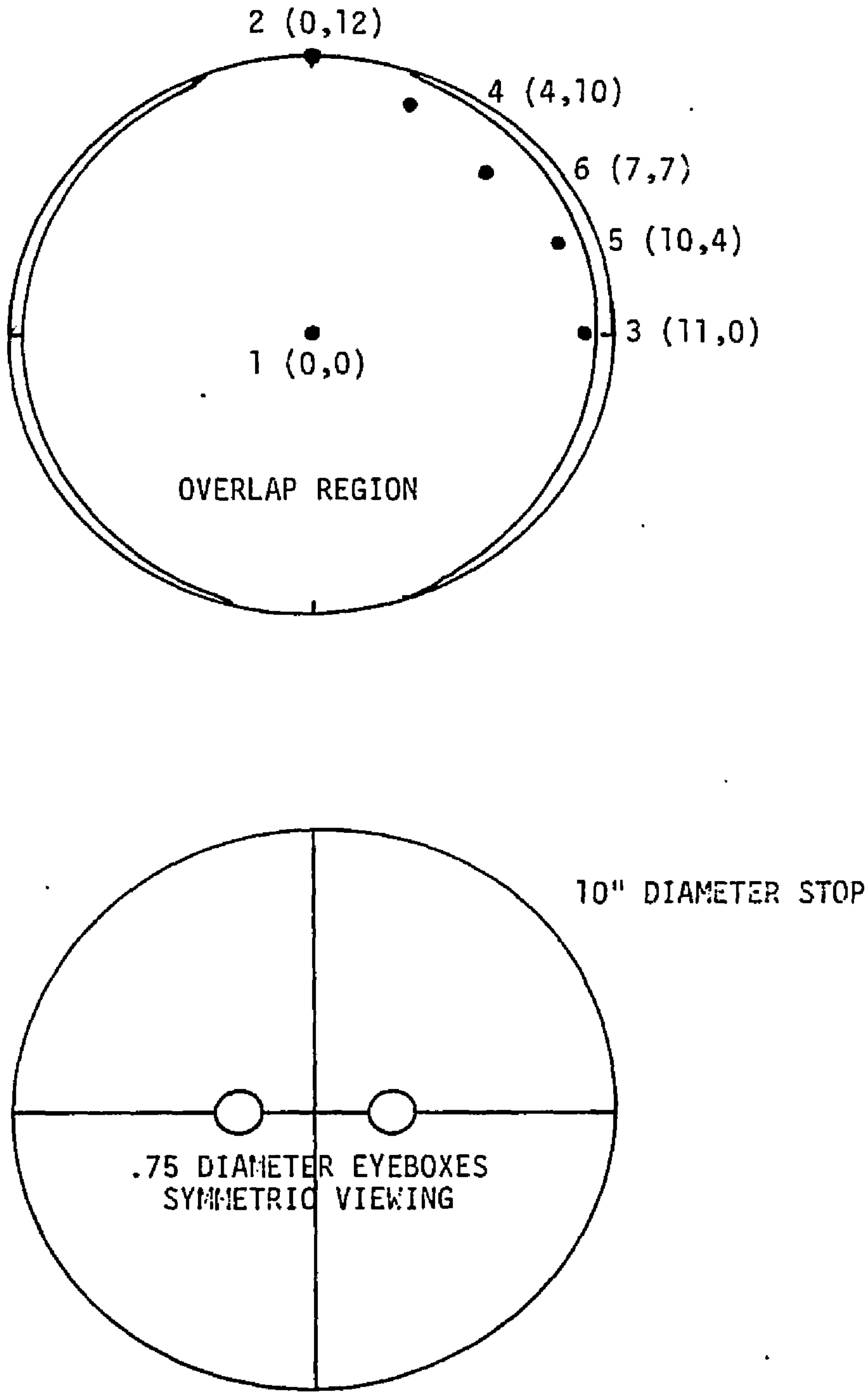
SPECIFICATION DATA

EPD	3.76041
AFO	
DIM	I
WL	589.00
WTW	1
REF	1

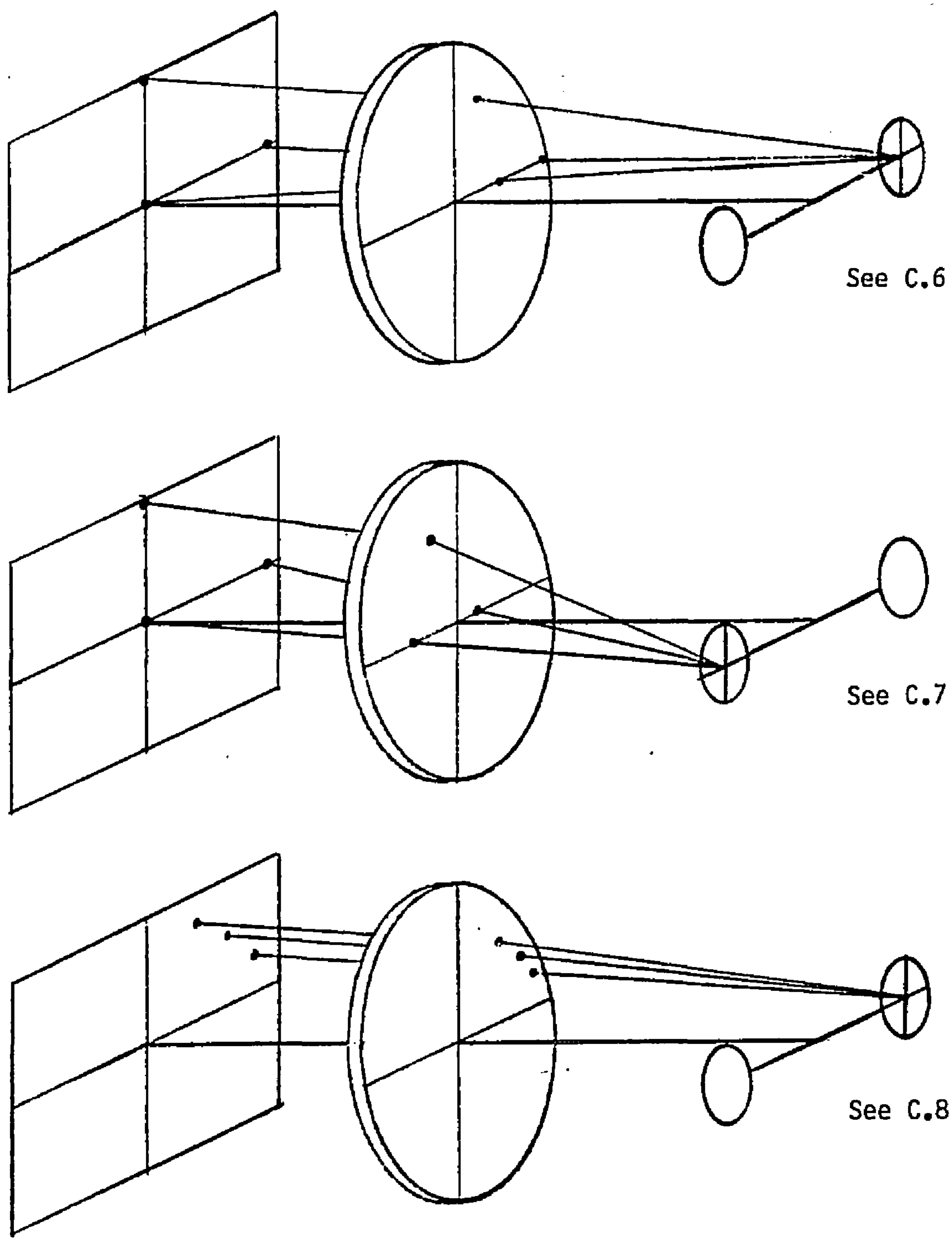
APERTURE DATA

CIR	3		14.999985
REX	4		1.625000
REY	4		1.625000
CIR	5		0.375000
CIR	6		0.375000
CIR	6	A	-0.010000

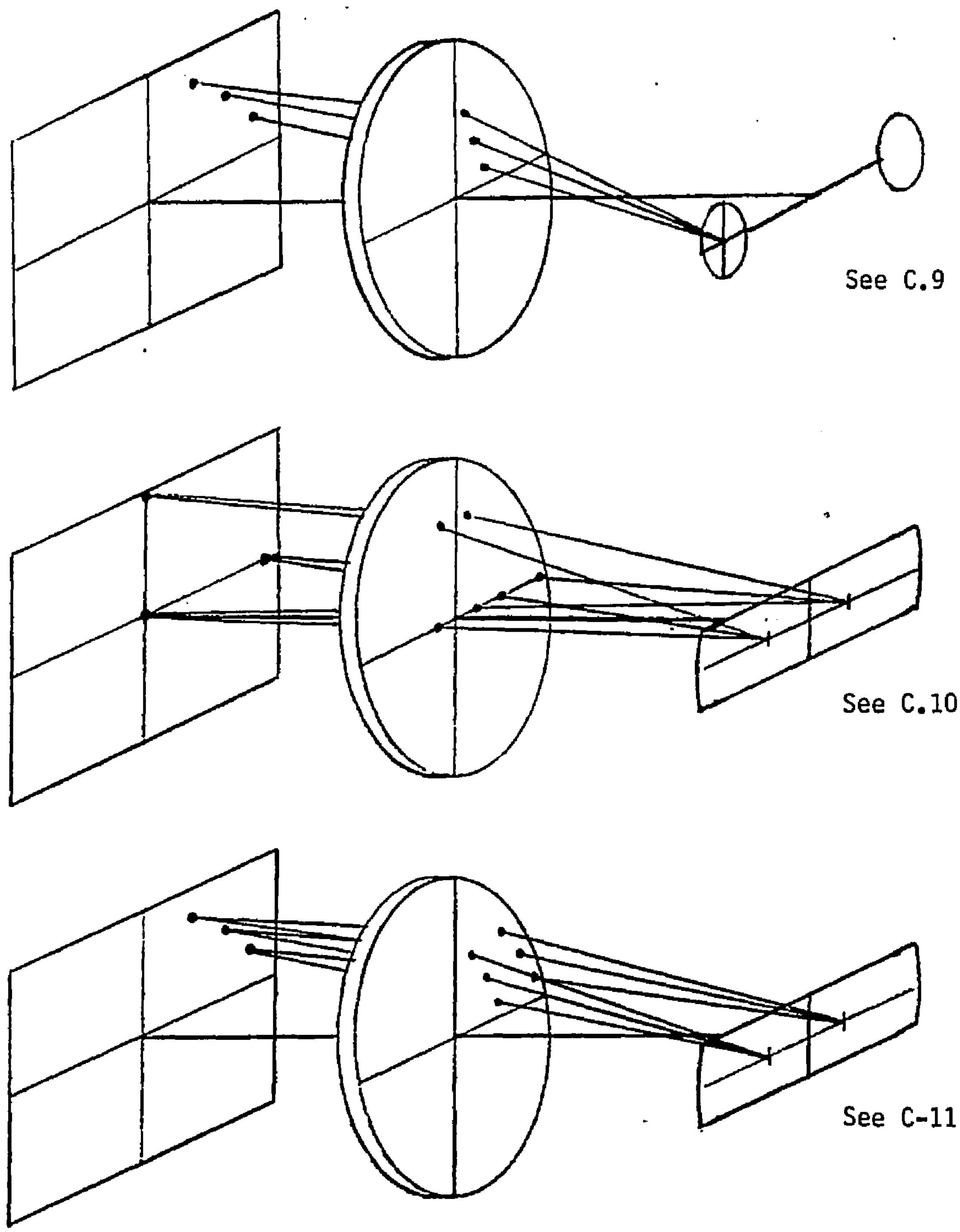
C.2. Spherical mirror (Case 2).



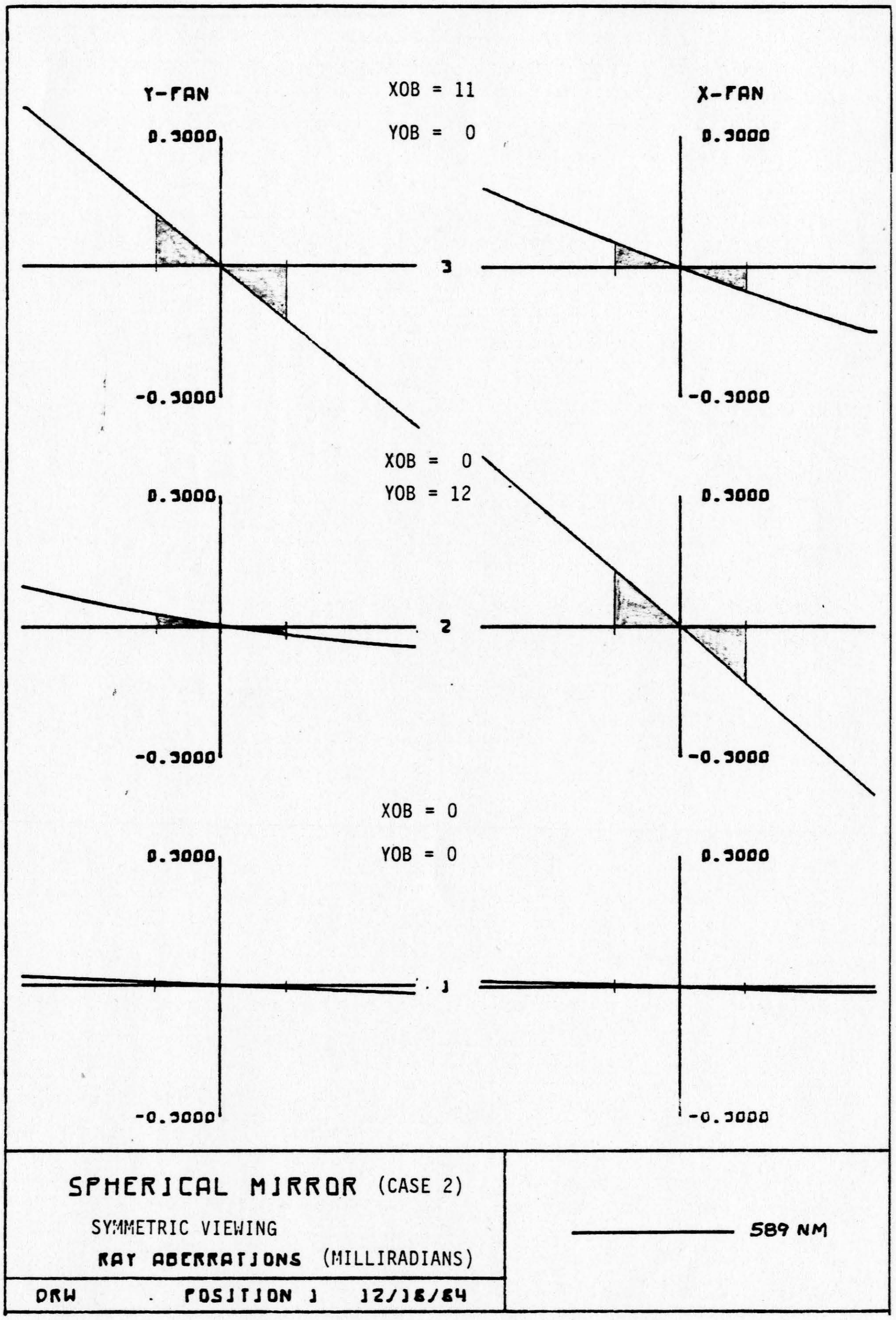
C.3. Object points and eyebox location (Case 2).



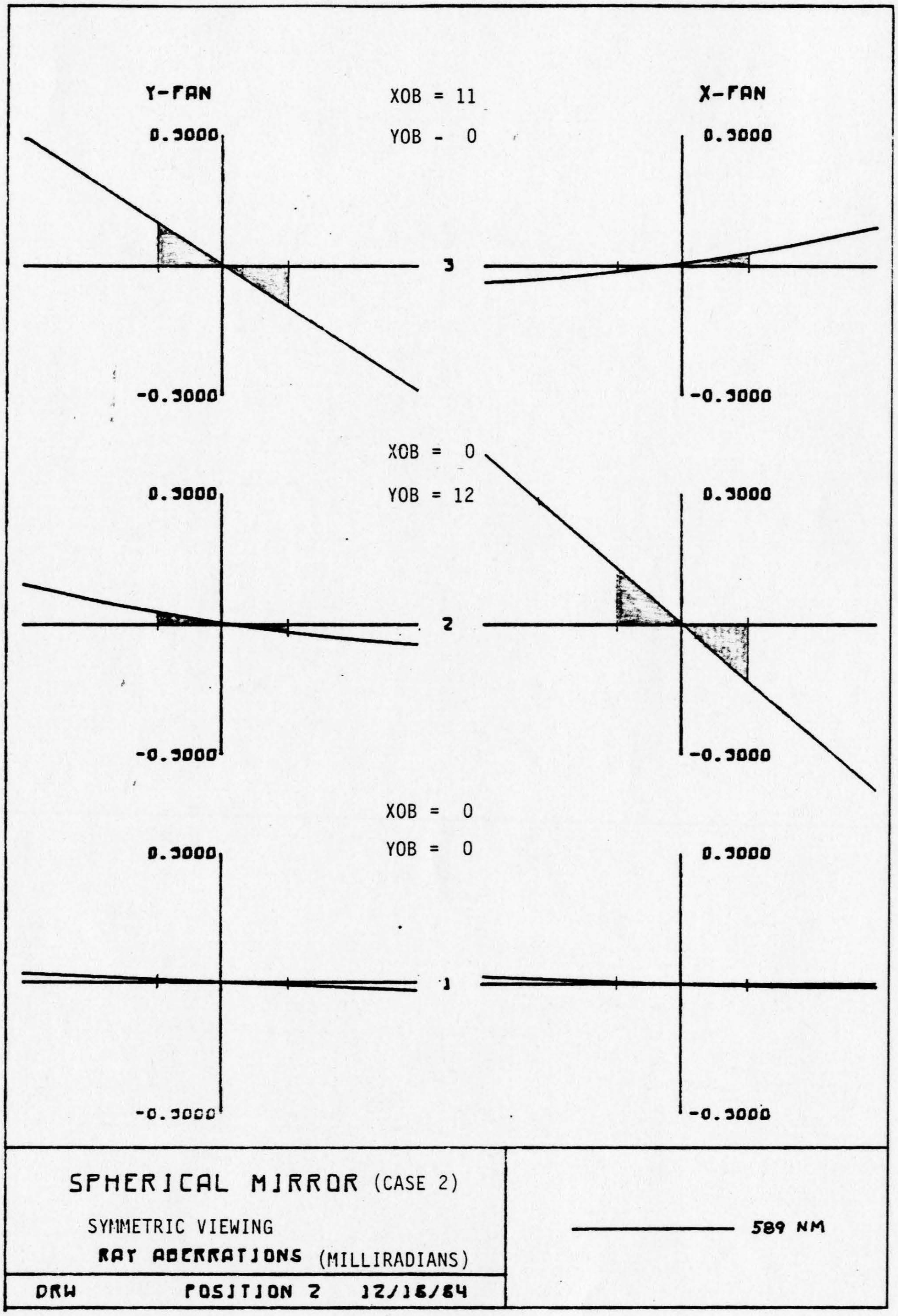
C.4. Key to ray fans for spherical mirror (Case 2).



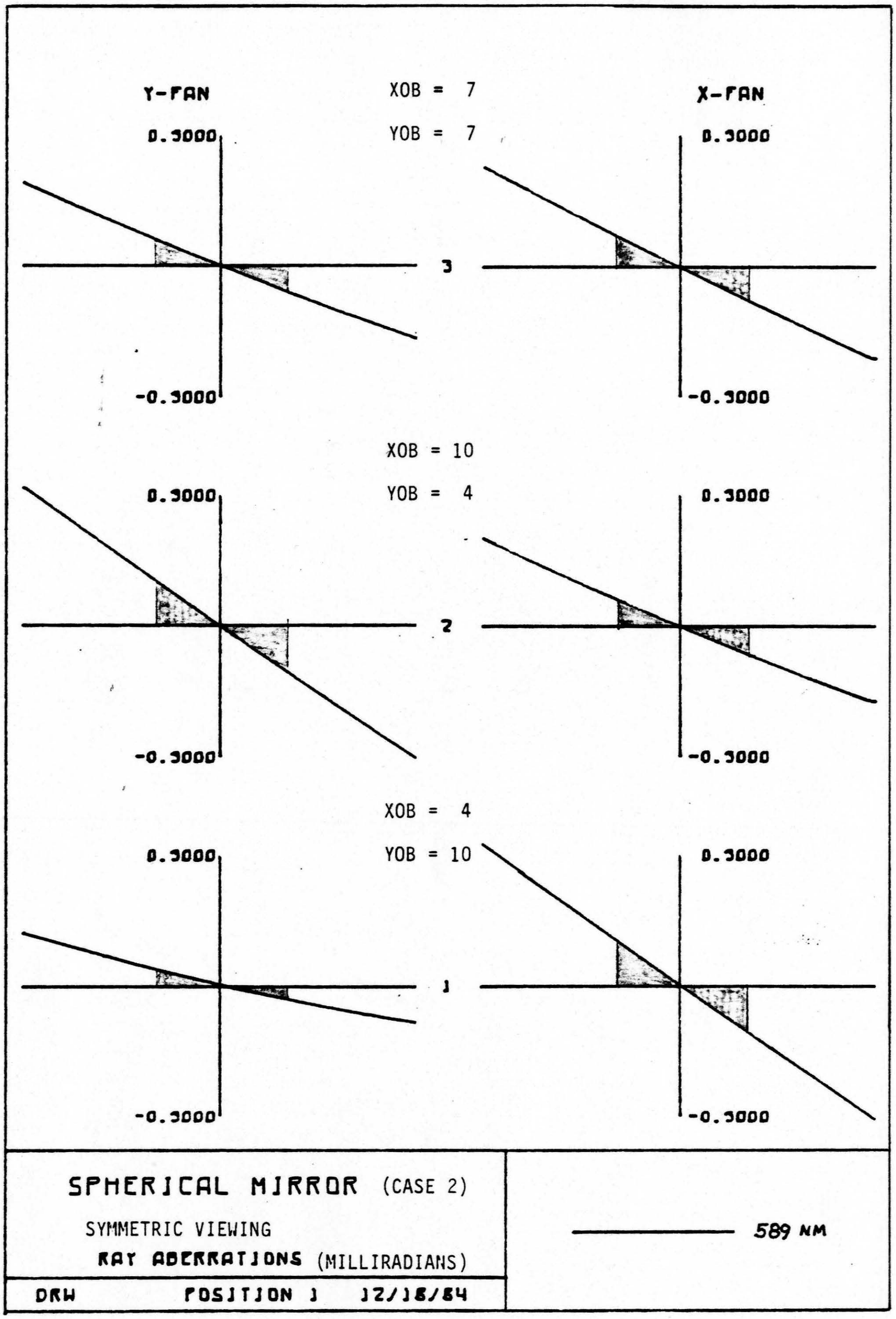
C.5. Key to ray fans for spherical mirror (Case 2).


Y-FAN
XOB = 11
YOB = 0
X-FAN
0.3000
-0.3000
3
XOB = 0
YOB = 12
2
XOB = 0
YOB = 0
1
SPHERICAL MIRROR (CASE 2)
SYMMETRIC VIEWING
RAY ABERRATIONS (MILLIRADIANS)
DRW . POSITION 1 12/18/84
589 NM

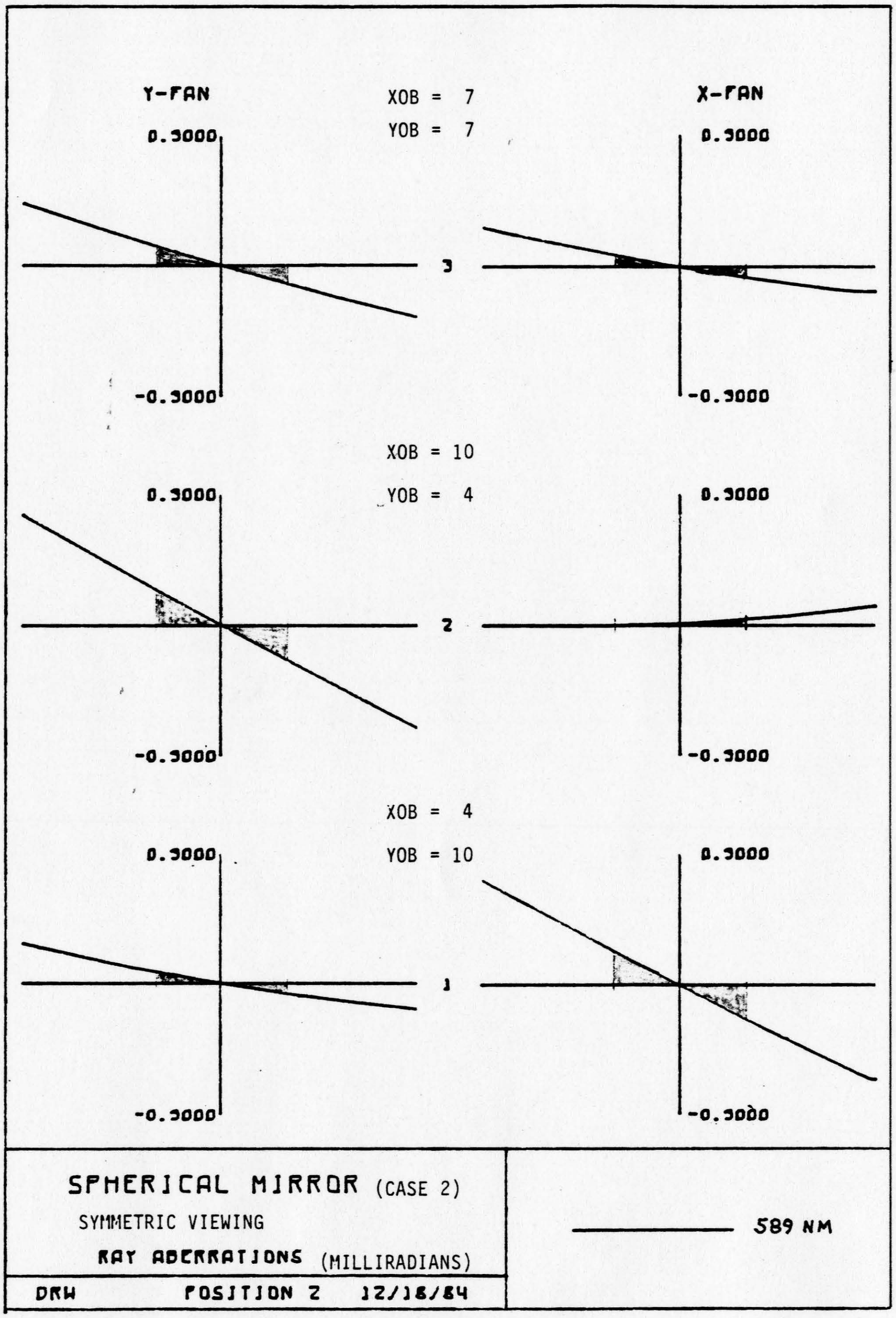
C.6. Right eye.


Y-FAN
XOB = 11
YOB - 0
X-FAN
0.3000
-0.3000
3
XOB = 0
YOB = 12
2
XOB = 0
YOB = 0
1
SPHERICAL MIRROR (CASE 2)
SYMMETRIC VIEWING
RAY ABERRATIONS (MILLIRADIANS)
DRW
POSITION 2
12/18/84
589 NM

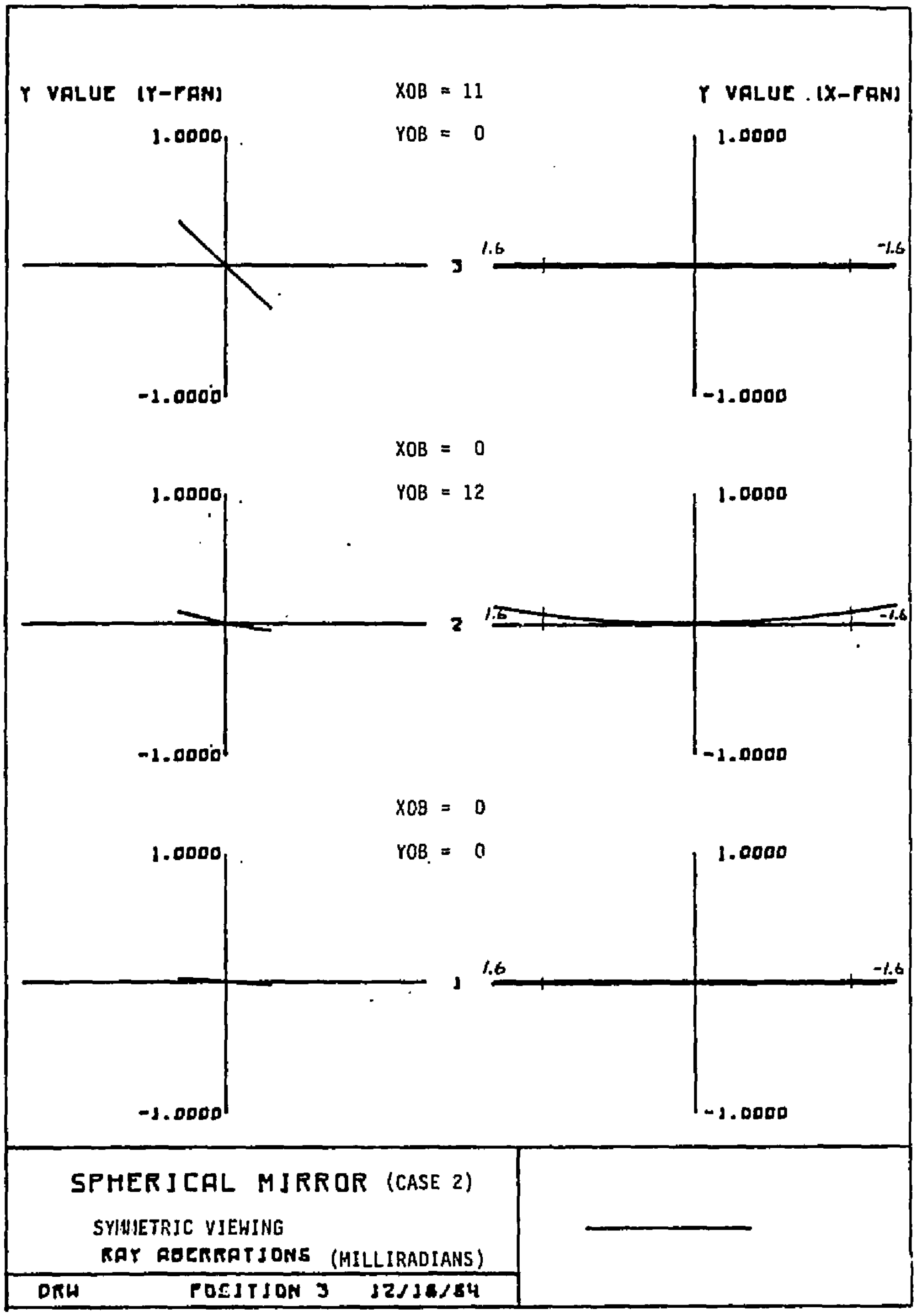
C.7. Left eye.


Y-FAN
X-FAN
XOB = 7
YOB = 7
0.3000
-0.3000
3
XOB = 10
YOB = 4
2
XOB = 4
YOB = 10
1
SPHERICAL MIRROR (CASE 2)
SYMMETRIC VIEWING
RAY ABERRATIONS (MILLIRADIANS)
DRW
POSITION 1
12/18/84
589 NM

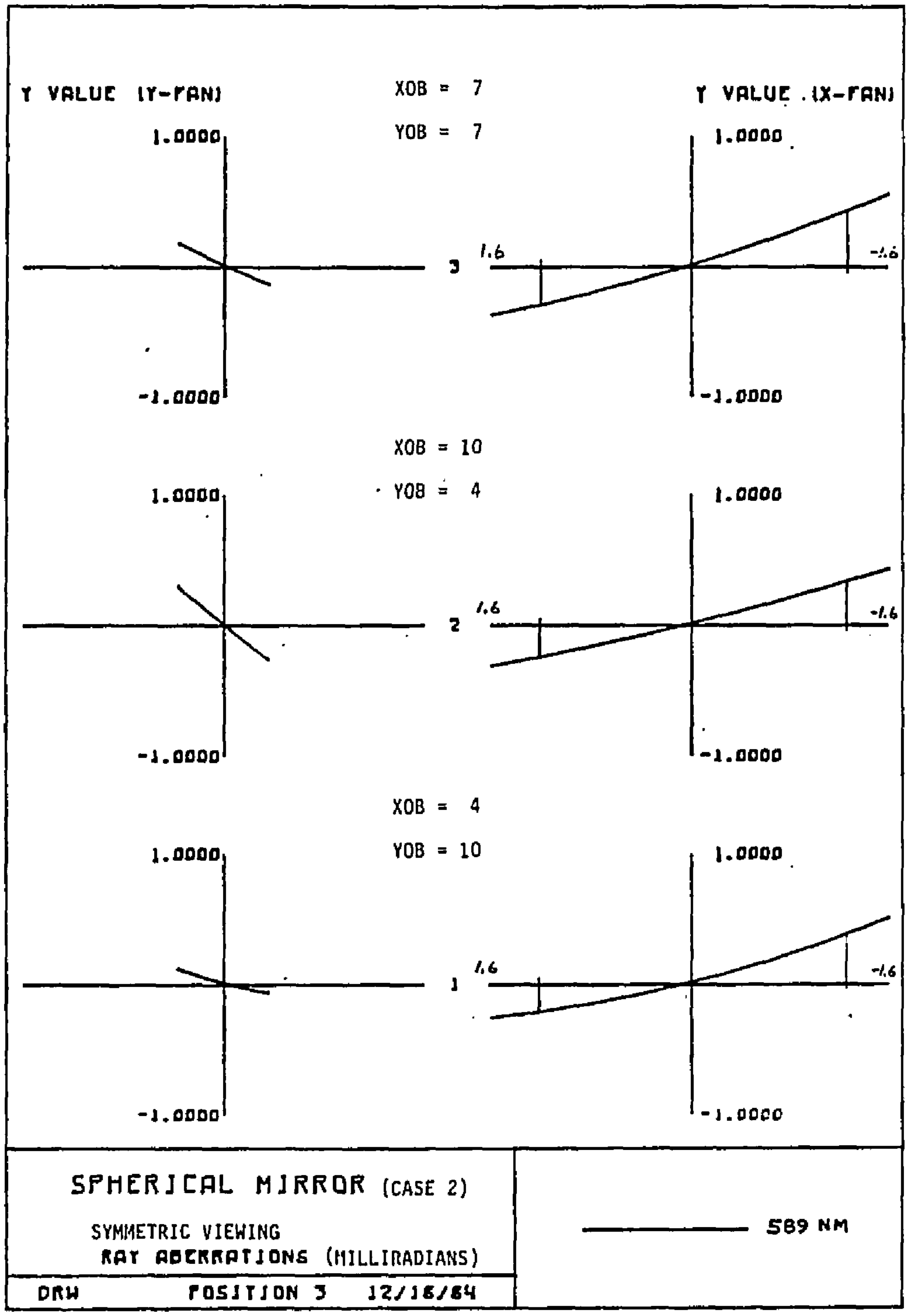
C.8. Right eye.


Y-FAN
XOB = 7
YOB = 7
X-FAN
0.3000
0.3000
3
-0.3000
-0.3000
XOB = 10
YOB = 4
0.3000
0.3000
2
-0.3000
-0.3000
XOB = 4
YOB = 10
0.3000
0.3000
1
-0.3000
-0.3000
SPHERICAL MIRROR (CASE 2)
SYMMETRIC VIEWING
RAY ABERRATIONS (MILLIRADIANS)
589 NM
DRW
POSITION 2
12/18/84

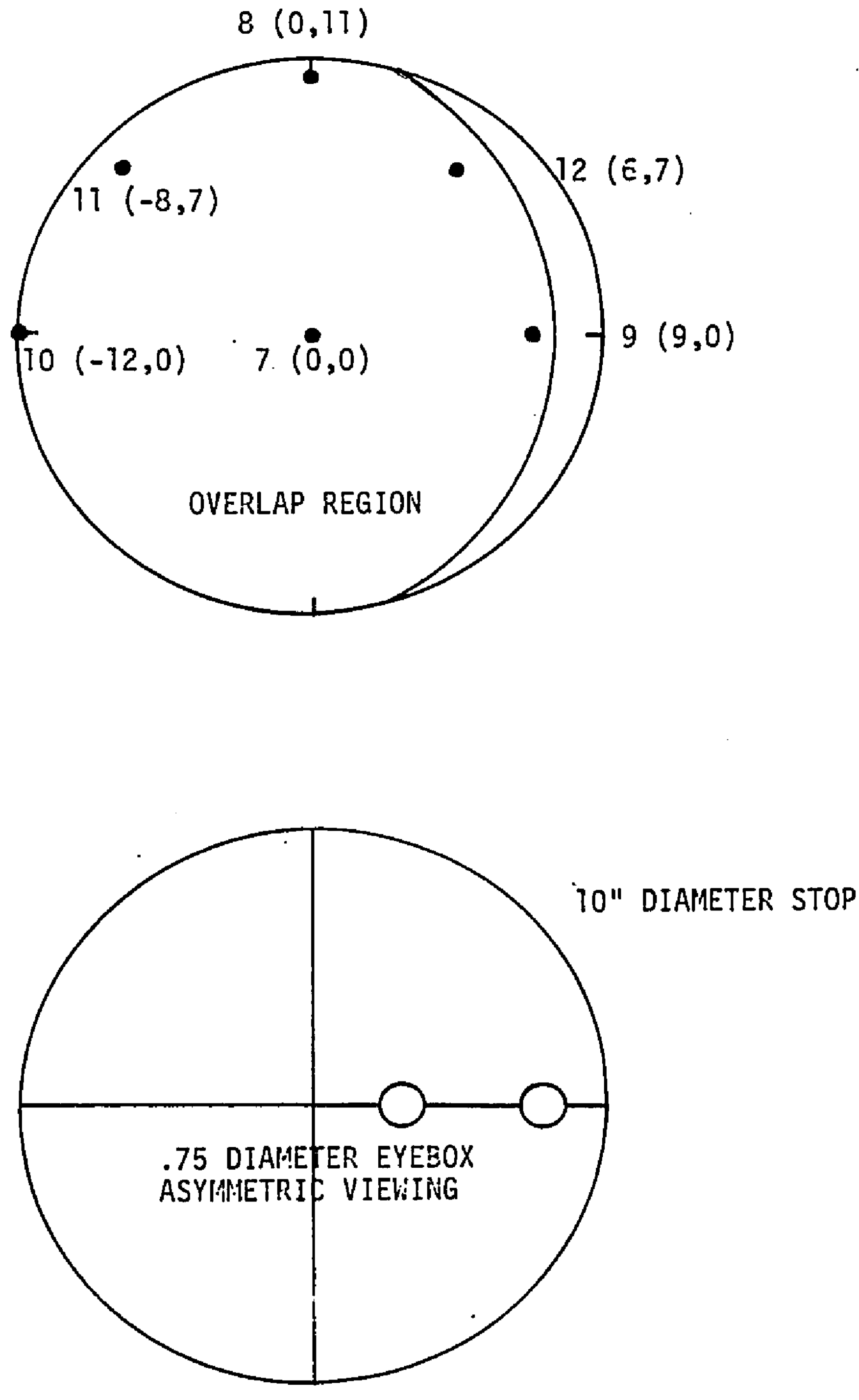
C.9. Left eye.



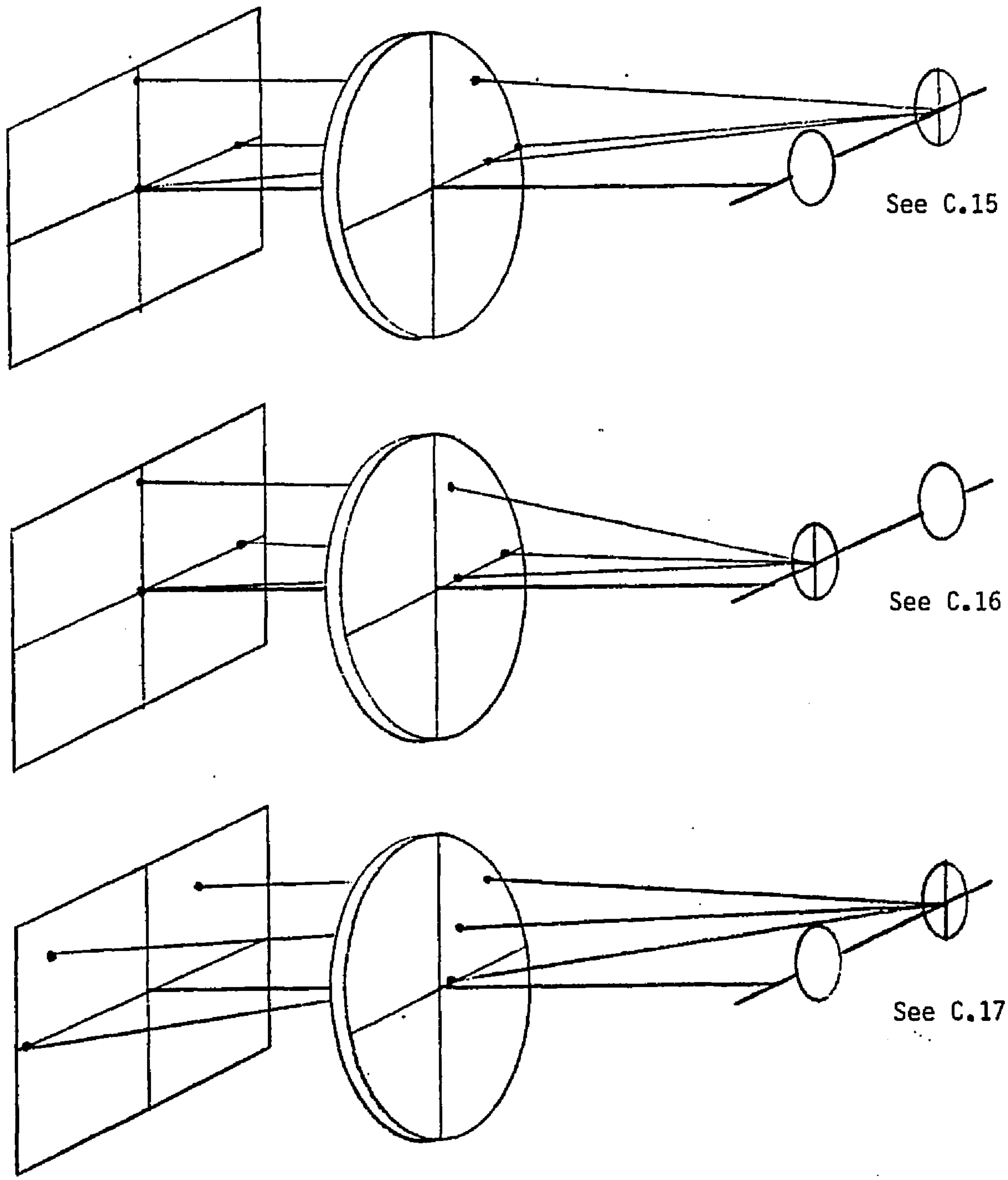
C.10. Dipvergence.



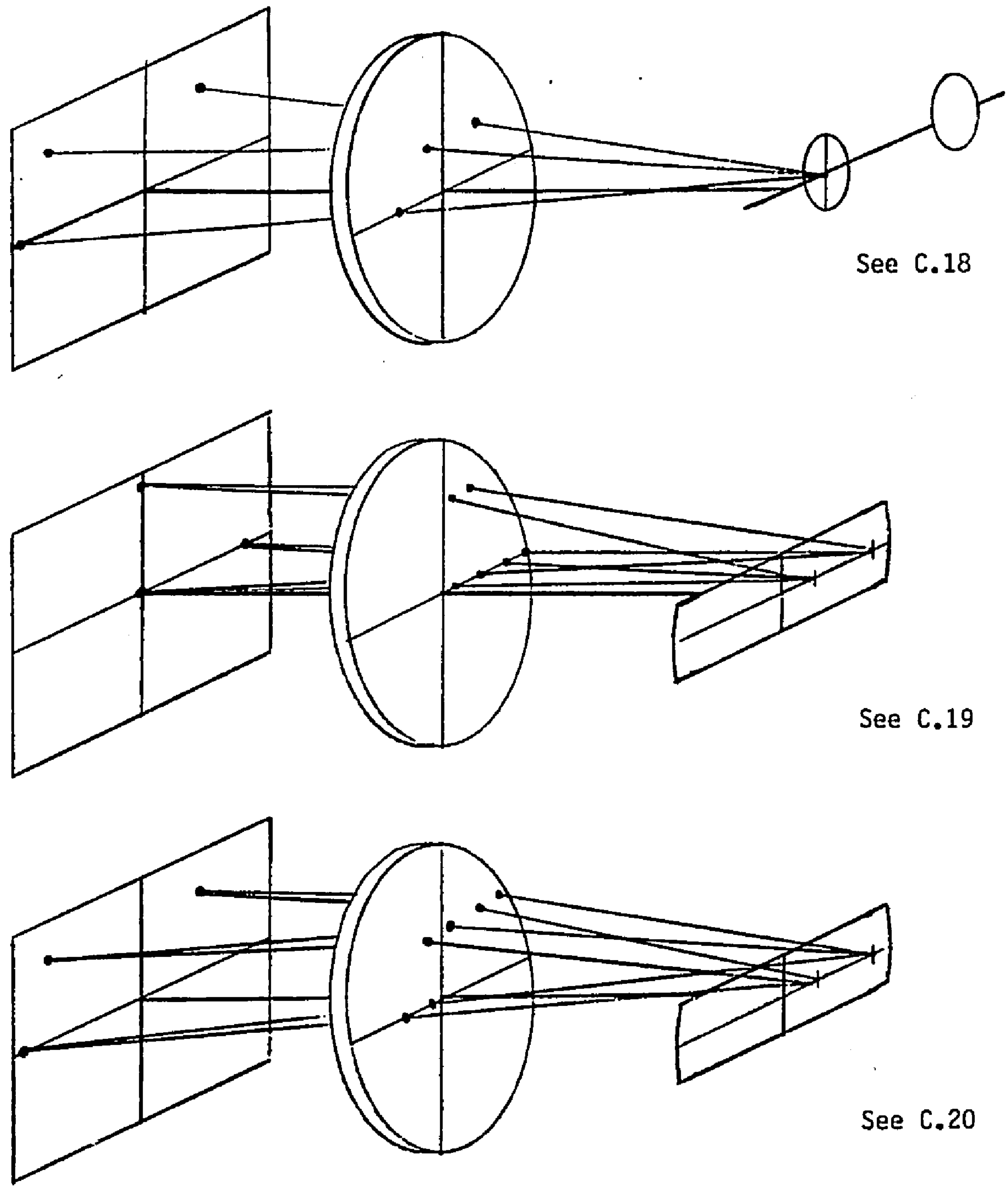
C.11. Dipvergence.



C.12. Object points and eyebox locations (Case 2).



C.13. Key to ray fans for spherical mirror (Case 2).

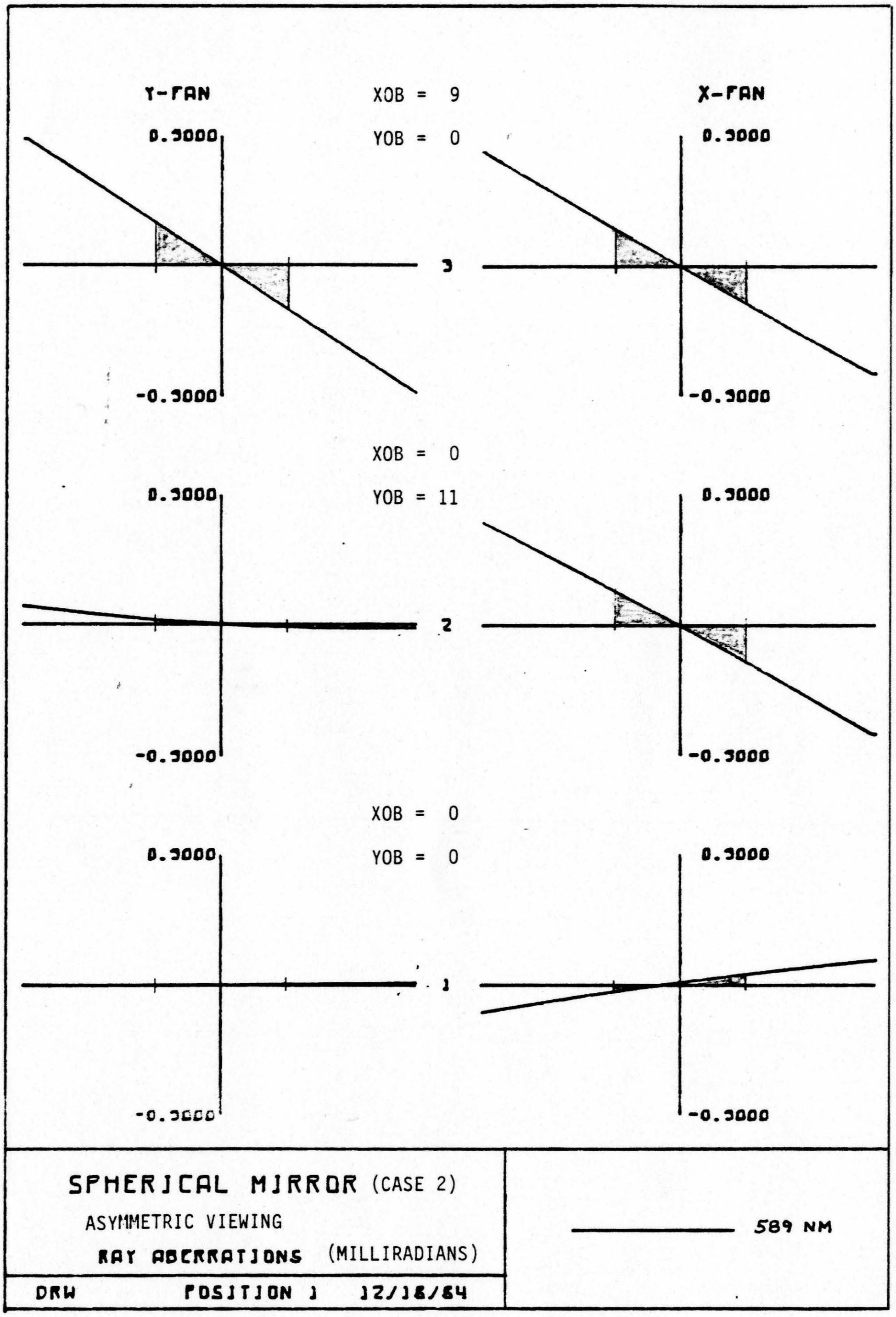


See C.18

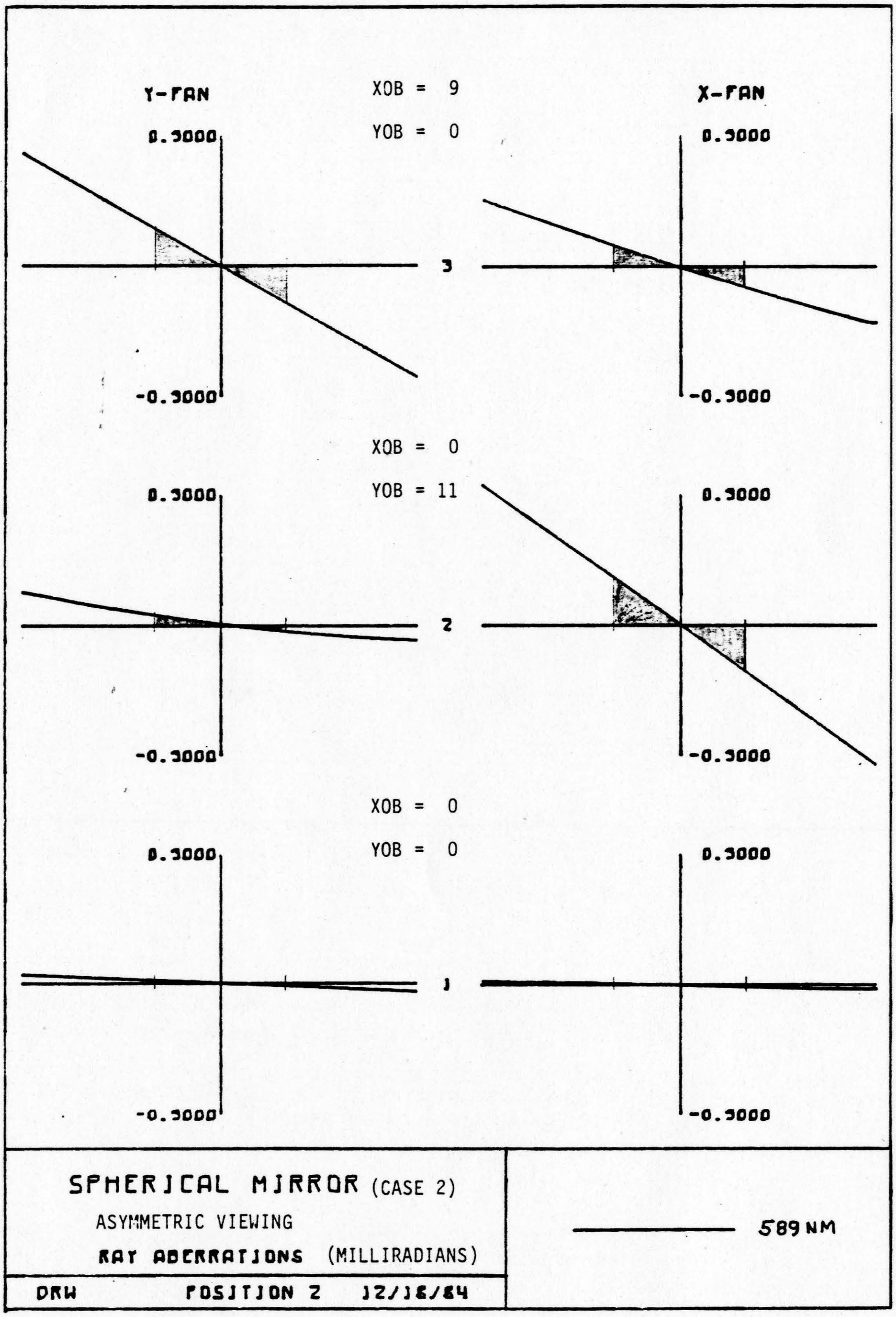
See C.19

See C.20

C.14. Key to ray fans for spherical mirror (Case 2).

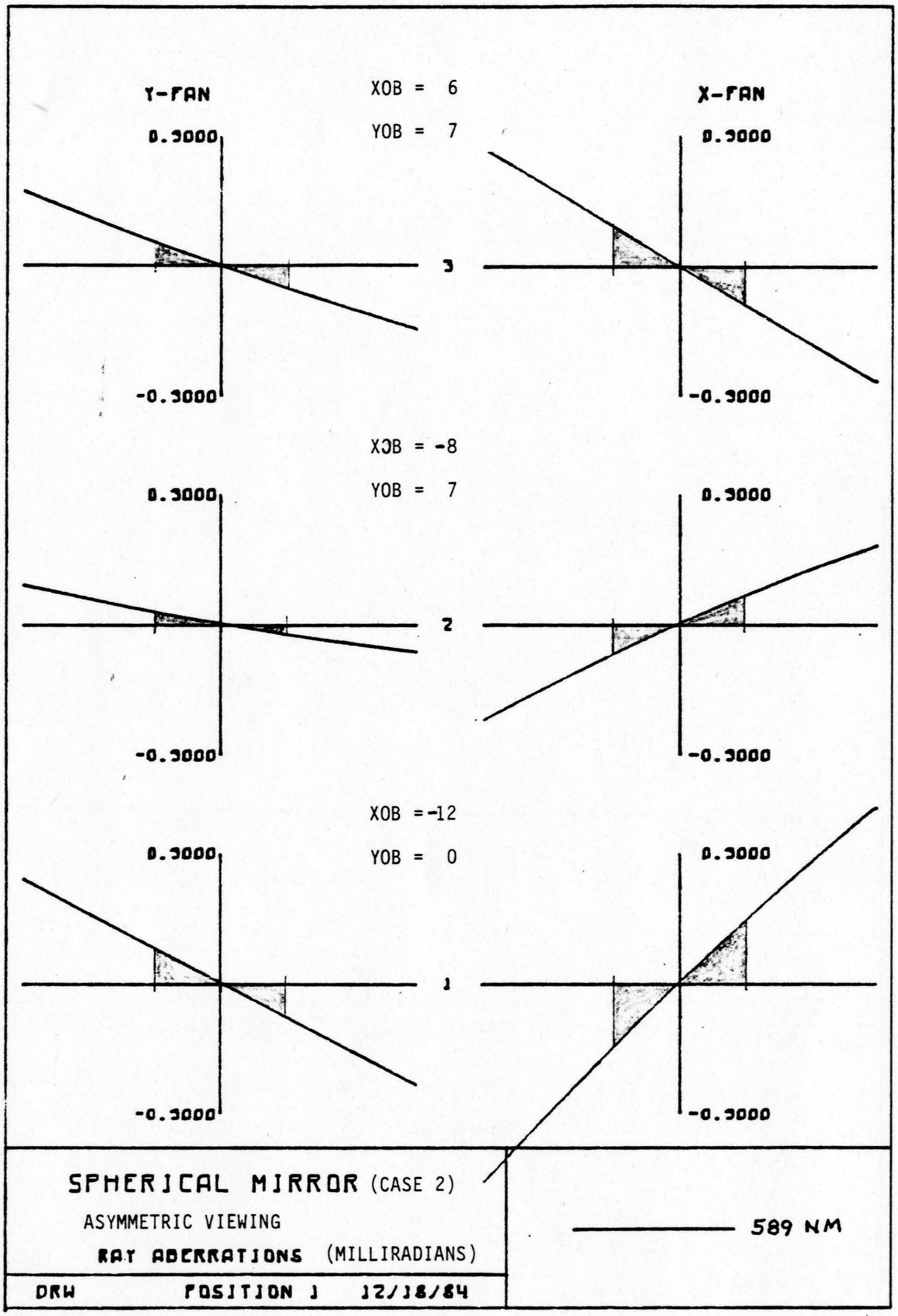


C.15. Right eye.

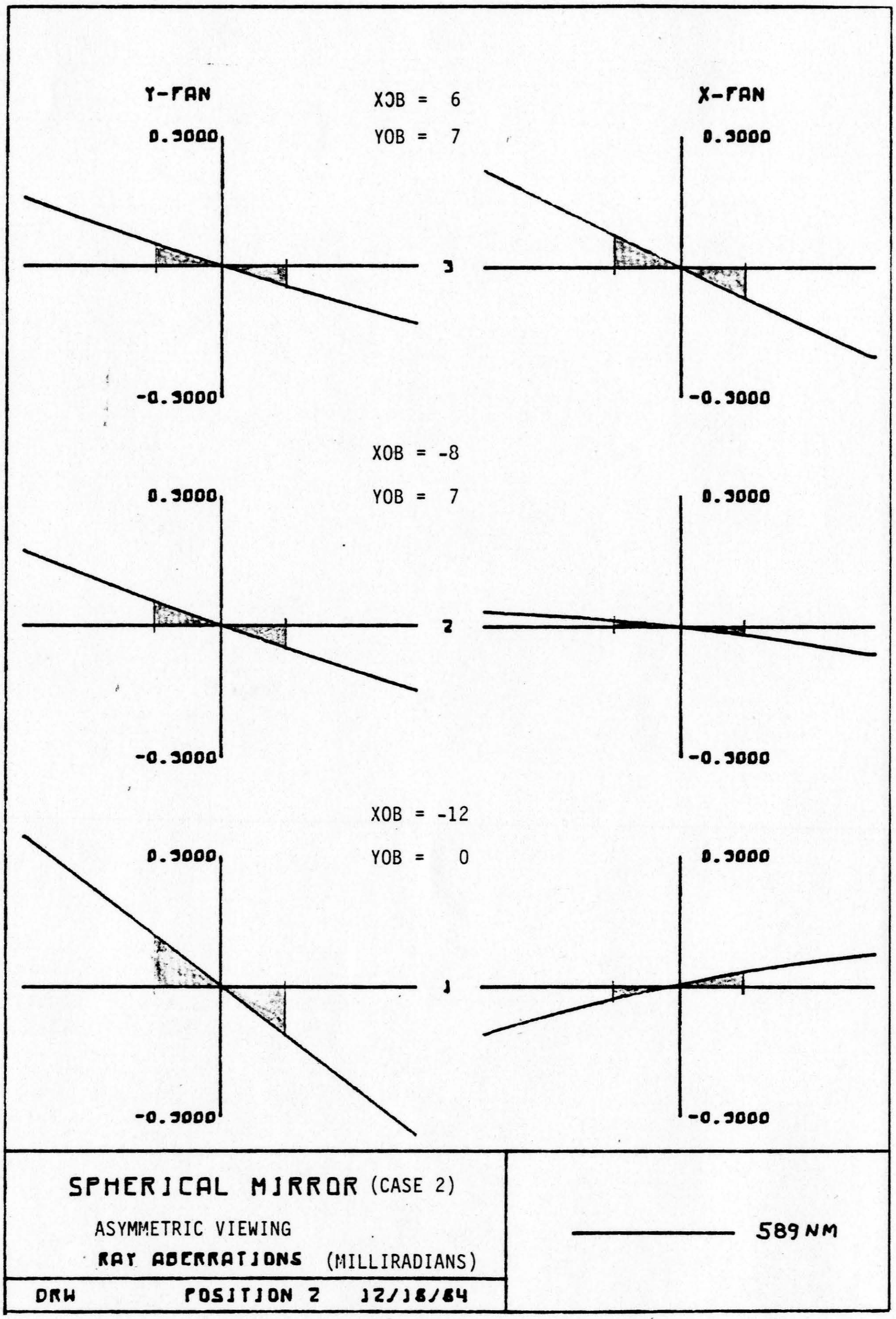


Y-FAN
XOB = 9
YOB = 0
X-FAN
0.3000
-0.3000
3
XOB = 0
YOB = 11
2
XOB = 0
YOB = 0
1
SPHERICAL MIRROR (CASE 2)
ASYMMETRIC VIEWING
RAY ABERRATIONS (MILLIRADIANS)
DRW
POSITION 2
12/18/84
589 NM

C.16. Left eye.

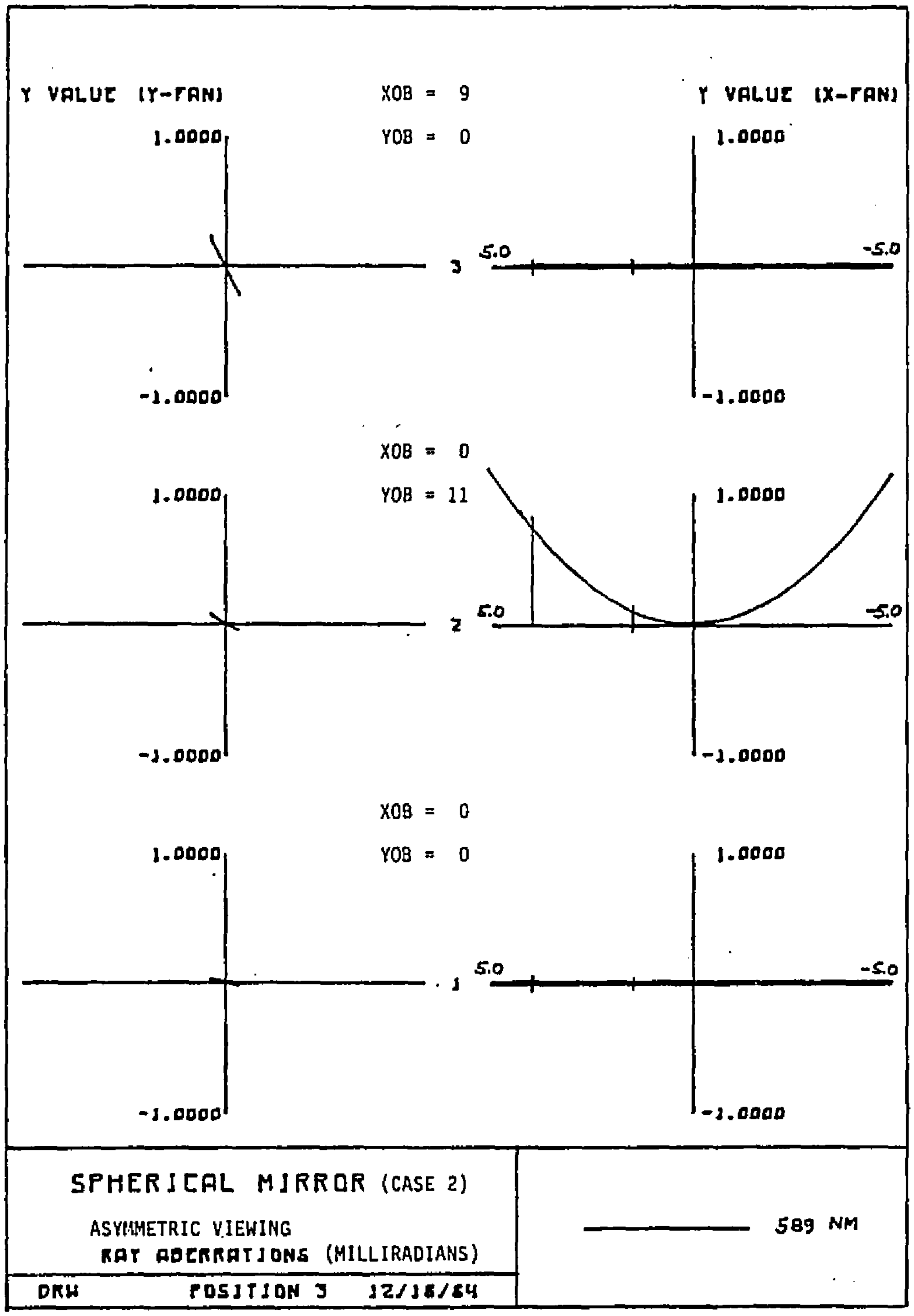


C.17. Right eye.

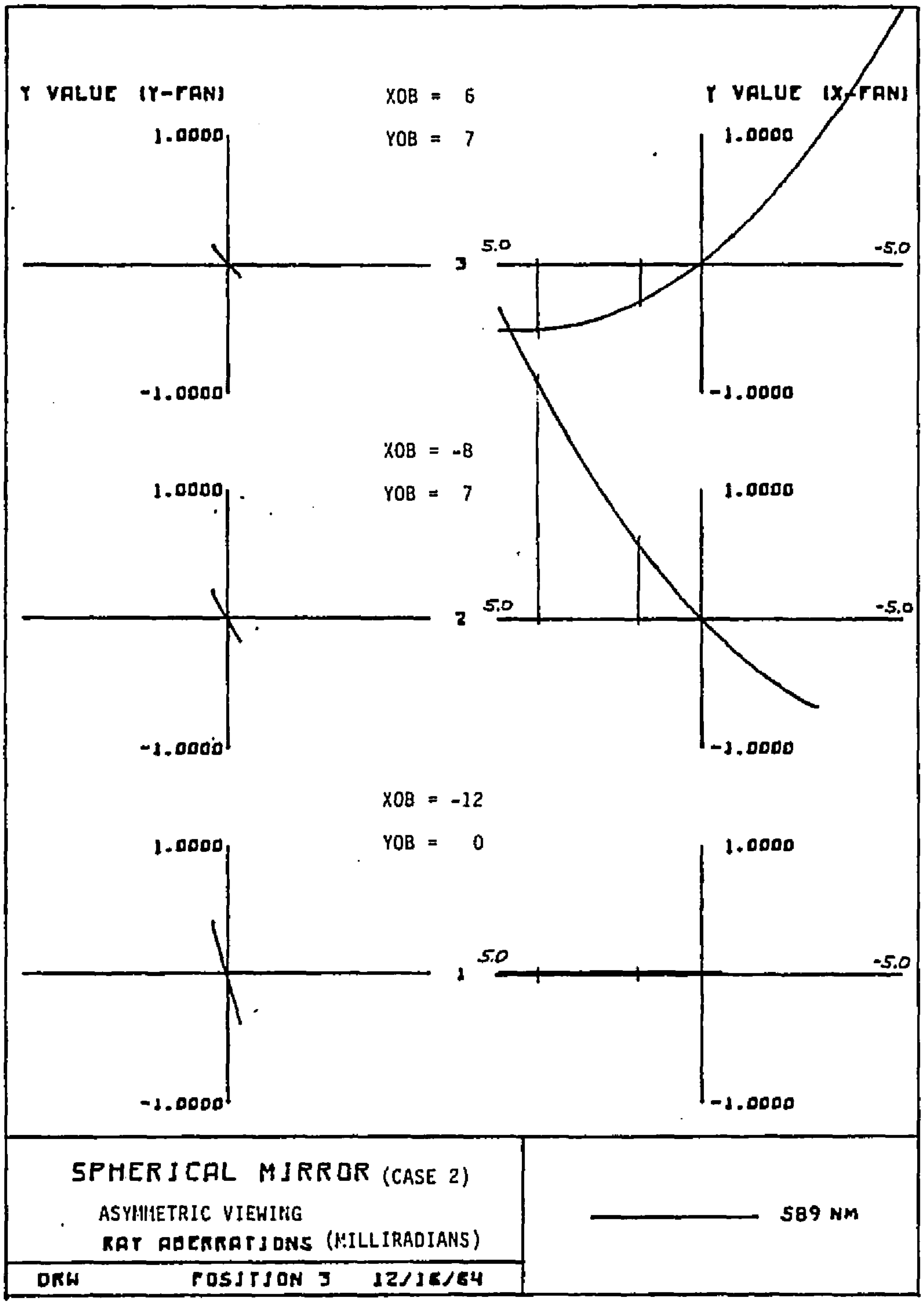


Y-FAN
X-FAN
XOB = 6
YOB = 7
0.3000
-0.3000
3
XOB = -8
YOB = 7
2
XOB = -12
YOB = 0
1
SPHERICAL MIRROR (CASE 2)
ASYMMETRIC VIEWING
RAY ABERRATIONS (MILLIRADIANS)
DRW
POSITION 2
12/18/84
589 NM

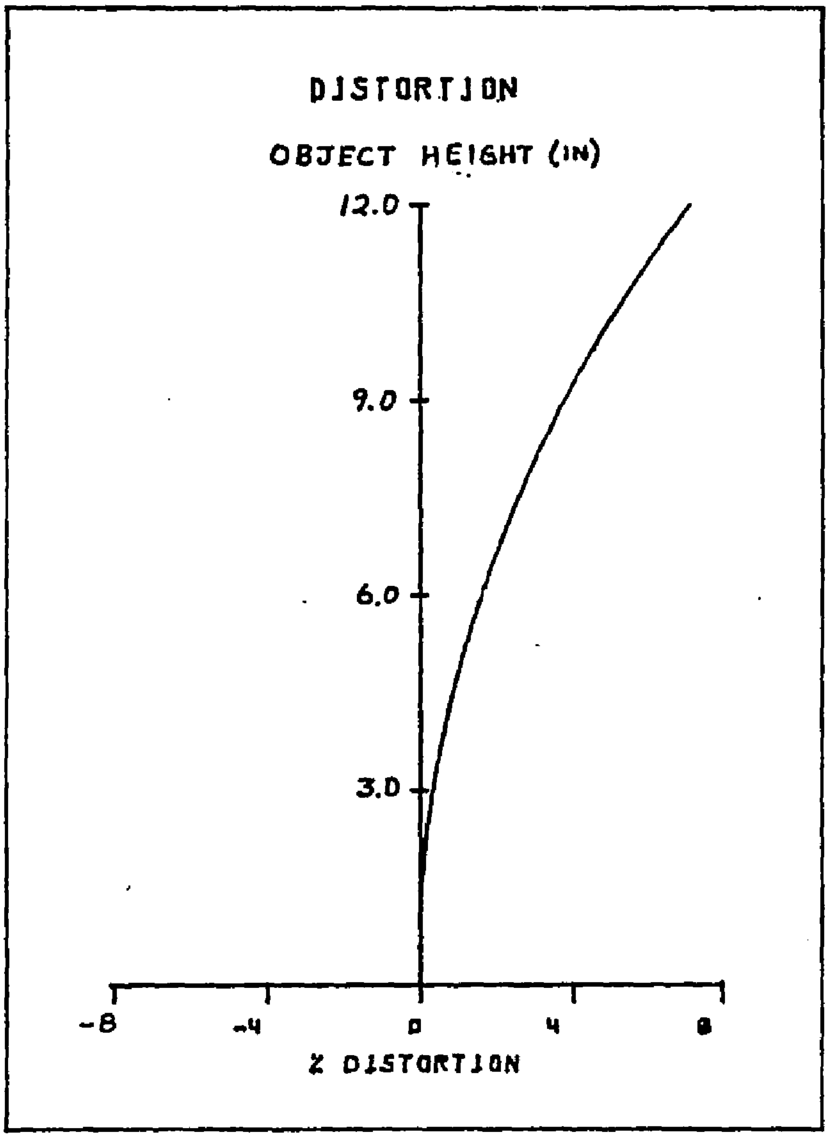
C.18. Left eye.



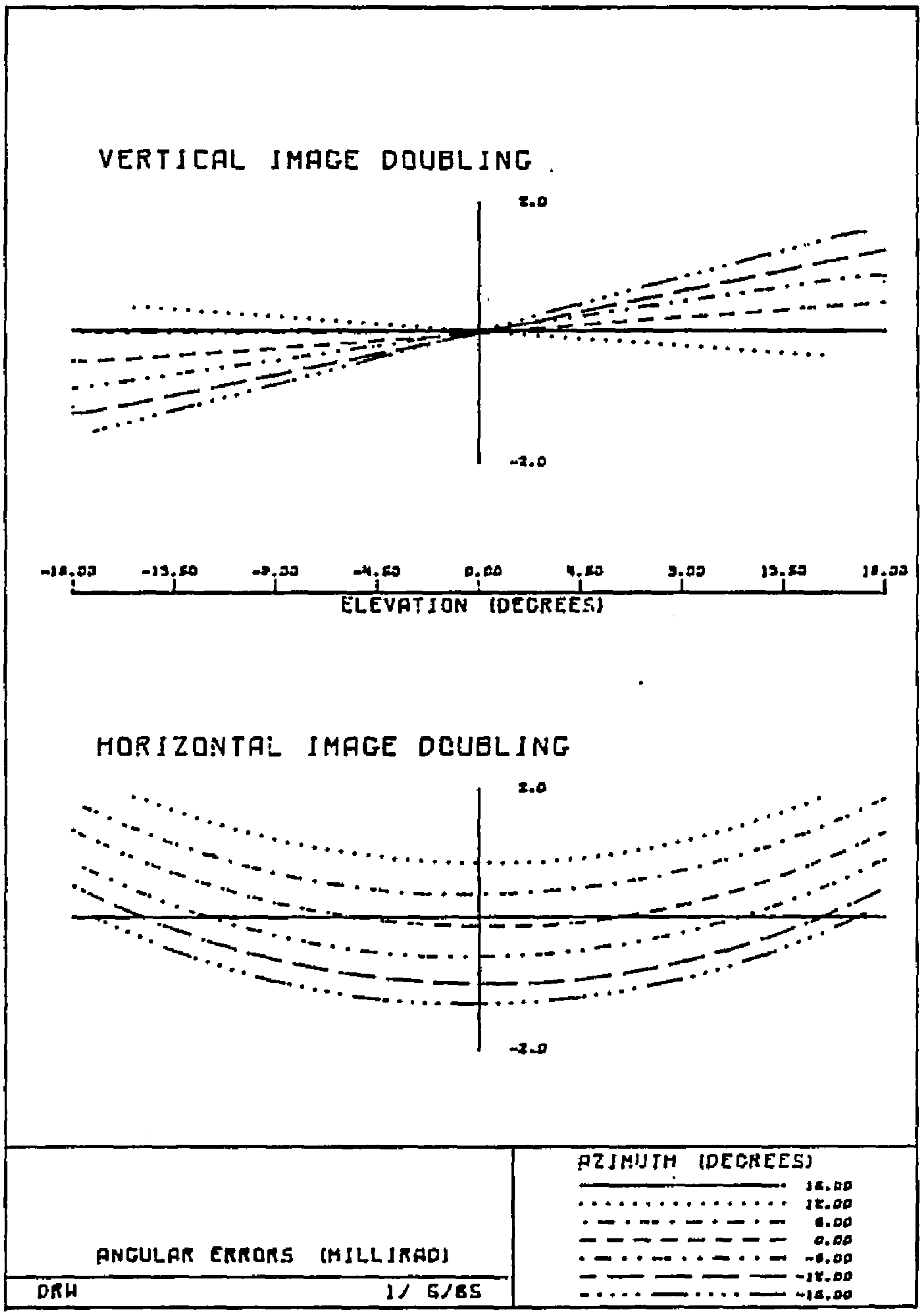
C.19. Dipvergence.



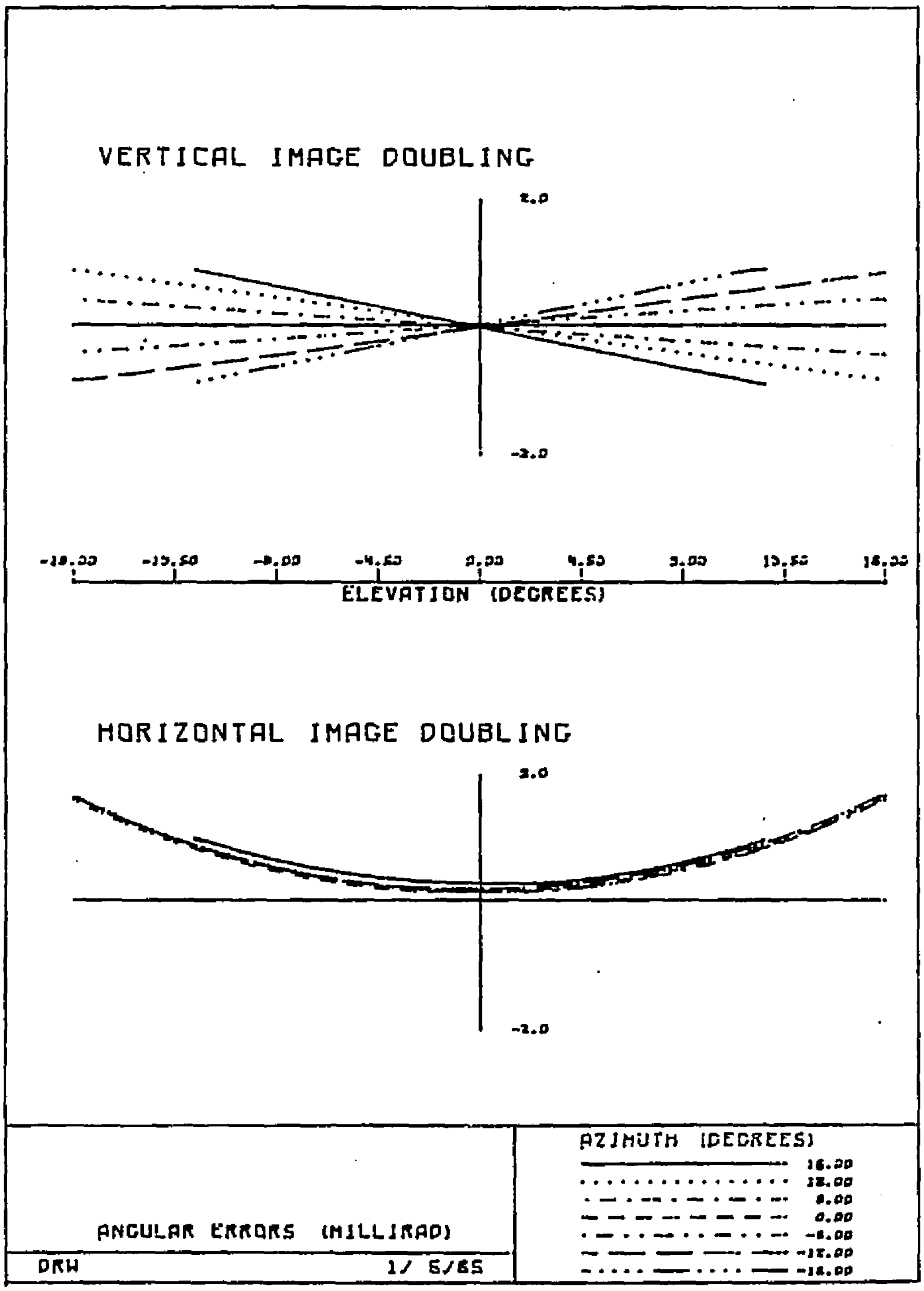
C.20. Dipvergence.



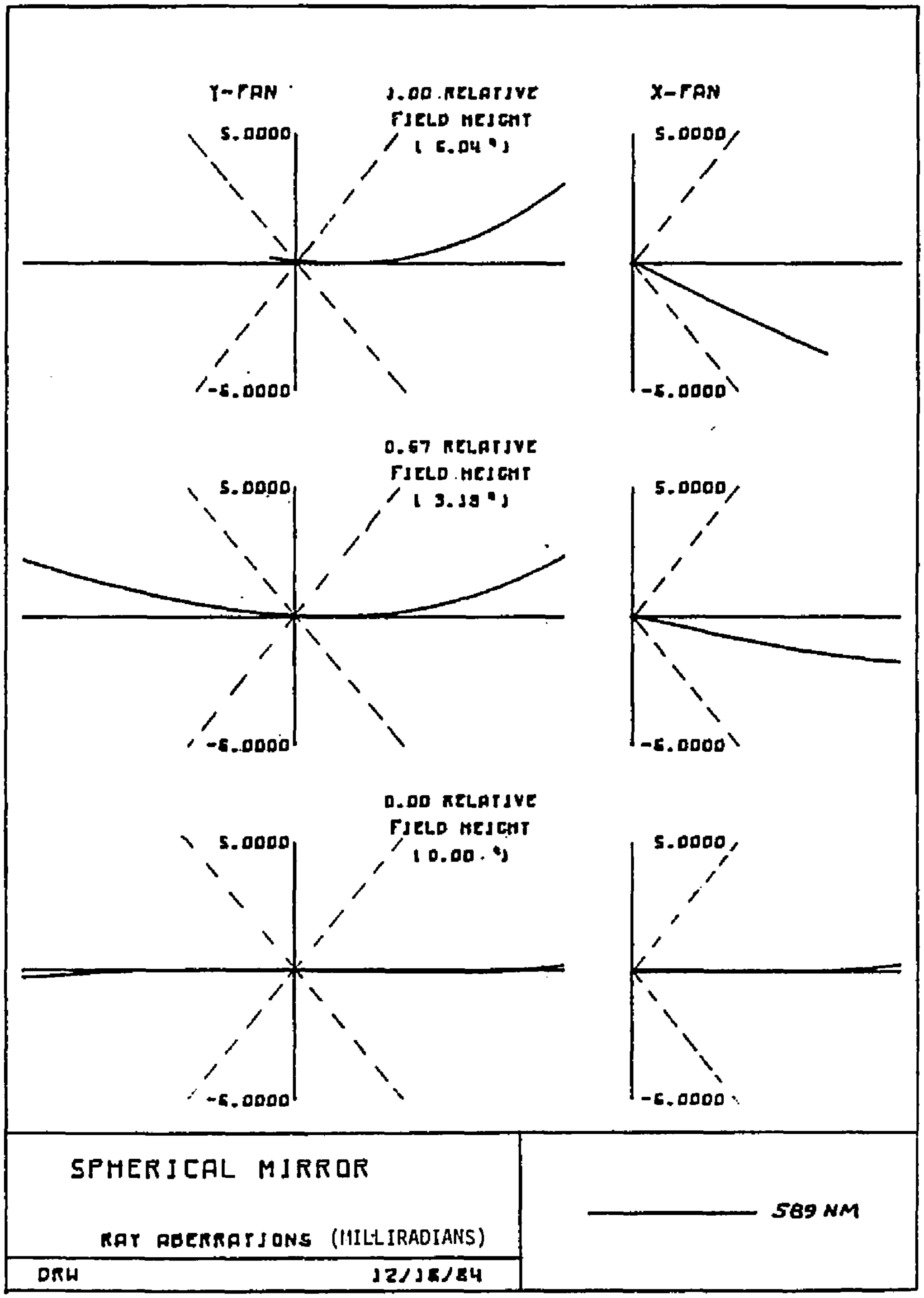
C.21. Distortion (Case 2).



C.23. Image doubling (Symmetric view, Case 2).



C.22. Image doubling (Asymmetric view, Case 2).



C.24. Blur size, Case 2.

REFERENCES

1. Shenker, M. Survey Paper on Biocular Systems. Presented at the annual meeting of the Optical Society of America (October 1972).

2. Cox, A. F. J., Dudley, R.C. Visual Comfort and Operator Performance with Low Light Level Imaging Devices. International Conference on Low Light Level and Thermal Imaging Systems, London, England, pp. 106-111 (March 1975).

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