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**AN OPTICAL ANALYSIS OF THE FARRAND
VCASS HELMET-MOUNTED DISPLAY**

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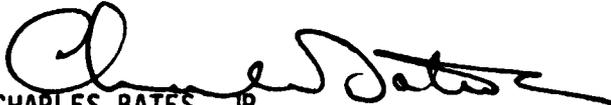
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CHARLES BATES, JR.
Director, Human Engineering Division
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20. Abstract--continued

Images for a panoramic display up to 140° wide by 60° tall. Each eye has its own 15-mm exit pupil and enough eye relief to allow ordinary eyeglasses to be worn. The display is permanently set at zero diopter focus to eliminate parallax. Interpupillary distance is adjustable, while accommodation for different head sizes is provided by altering the helmet liner with simple spacers. Optical quality would allow resolution of 2000 TV lines, and vignetting is nonexistent over most of the field of view. Although the optical design is difficult by conventional standards, optical tests made on the device prove the manufacturability of the optics.

SUMMARY

This report provides an indepth analysis and explanation of the Visually Coupled Airborne Systems Simulator (VCASS) helmet-mounted display (HMD) designed by the Farrand Optical Company, Inc., under Air Force Contract F33615-78-C-0512. The optical properties of the VCASS display are independently verified by the author and elaborated upon in more detail than that provided in Farrand documentation. In particular, much greater detail is provided concerning the Pancake WindowTM theory of operation, final design tradeoffs, acceptance test analysis, and the feasibility of design enhancements. The report concludes that further evolution and refinement of the VCASS HMD is possible and establishes the general tradeoffs that must be made between image quality, field-of-view, exit pupil, and the overall size of the optical system.



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PREFACE

This report was prepared under the direction and sponsorship of the Aerospace Medical Research Laboratory, Human Engineering Division, Visual Display Systems Branch of the United States Air Force as part of Project 71842601. Mr. Dean F. Kocian was the program technical monitor. The impetus for this study arose from developmental work and testing performed with this unique two-eye display as part of the VCASS system. The goal of this work was to insure that underlying technical principles were clearly understood and to promote an efficient design development process if display design changes were implemented as a result of VCASS testing.

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1. INTRODUCTION

This report provides an overview of the optical system performance of the Visually Coupled Airborne Systems Simulator (VCASS) helmet-mounted display (HMD) designed by the Farrand Optical Company, Inc., under Air Force Contract F33615-78-C-0512. The optical properties of VCASS have been independently verified by the author¹ for this report, and some points that were beyond the scope of Farrand's work have been examined and explained.

The Farrand VCASS HMD is based on the principle of overlapping the fields of view of two wide-angle monocular magnifiers.² Farrand has also developed a wide-angle display with the trade name "Pancake WindowTM," on which they hold at least one patent (USP 3,940,203). VCASS is the first application of the Pancake WindowTM to a miniature eyepiece version.

Further evolution and refinement of the VCASS HMD, which utilizes two 80° field of view monoculars and a large, 15-mm exit pupil, is possible, but first experience must be gained with the Farrand prototypes to improve our understanding of this complex display.

1. R. A. Buchroeder et al., "Design of a Catadioptric VCASS Helmet-Mounted Display," AFAMRL-TR-81-133, Air Force Aerospace Medical Research Laboratory, Wright-Patterson Air Force Base, Ohio, November 1981.

2. M. Shenker, J. LaRussa, R. R. Yoder, Jr., and W. H. Scidmore, "Overlapping Monoculars--An Ultrawide-Field Viewing System," Appl. Opt. 1, 399 (1962).

2. DESIGN CONSIDERATIONS

2.1. Helmet

The visor and related fixtures of the HGU-22/P extra large helmet were removed, and fixtures to connect the display were added (see drawings in Appendix). Farrand measured the weight of the modified helmet, without display, at 0.7 kg (24.5 oz), with center of gravity located at $\bar{X} = +1.16$ cm (0.46 in.) and $\bar{Y} = +1.72$ cm (0.68 in.) relative to the helmet centerline shown on AFSC ASD Drawing No. 65D1581, Rev. G.

2.2. Limitations on Size of Display

VCASS is intended to serve as an engineering research tool to explore the utility and applications of visually coupled systems technology.

The VCASS HMD will be worn by an observer seated in a cockpit. It may later be modified to be used in an actual aircraft cockpit with the canopy down. Thus vertical protrusions from the display, such as the "rabbit ears" of top-mounted CRTs cannot be included and weight/size should be kept to a minimum.

Weight and moment of inertia should be minimized to allow free movement of the head.

2.3. Head Position Sensing

Currently, a magnetic helmet sensing transducer is used to sense helmet position and orientation. The use of metallic materials in the display must be kept to a minimum to avoid interference with the magnetic transducer system.

2.4. Image Generator

2.4.1. Miniature CRTs on Helmet

A CRT of high resolution, at least 1000 TV lines, is required because of the high magnification needed to produce a wide-angle display. Image brightness depends only on the luminance of the CRT and the transmission of the optical system, provided the exit pupil completely fills the eye.

The prototype display uses a Thomas Electronics, Inc. miniature CRT. Its image area is approximately 19 mm in diameter, truncated top and bottom for a vertical dimension of about 15 mm. The present design uses a nearly monochromatic P53 green phosphor. The tube has a fiberoptic faceplate that has a concave radius of 150 mm to permit optimum focus with the optical system.

2.4.2. CRTs Off the Helmet with FFOB

The high-voltage leads to the helmet-mounted CRTs pose a potential safety consideration that is eliminated by using CRTs coupled to the helmet with flexible fiberoptic bundles (FFOB). Additionally, a FFOB can be arranged to optimize weight distribution on the helmet, while minimizing the size of the display.

Luminance is the property of an illuminated surface or self-luminous source that is perceived as brightness, measured in foot-Lamberts. Larger CRTs can be driven with higher beam currents without losing the requisite number of TV lines, thereby allowing luminance to be increased severalfold. However, the CRT image must be transferred through the fiberoptics to the HMD optics which leads to losses in resolution and luminance.

The fiber optic image fibers are covered with a lower refractive index material, called cladding, to prevent light transference, or crosstalk,

between fibers. The phenomenon of total internal reflection is required to achieve high transmission; no metallic coating would suffice. Curiously enough, there is an electromagnetic field surrounding the fiber, called an evanescent wave that dies out fairly quickly. The cladding itself must be nonabsorbing, and sufficiently thick to prevent this wave from interacting with adjacent fibers. A cladding thickness of about 2 waves, or $1 \mu\text{m}$, is preferred. It is apparent that if the fibers are $10 \mu\text{m}$ in diameter, a clad diameter of $12 \mu\text{m}$ is required. The area comprising the cladding is 30%, and if the fibers are packed as closely as possible, the unfilled areas (interstices) between clad fibers cause another 10% loss in image area. Therefore, a $10\text{-}\mu\text{m}$ fiber bundle will in general never be more efficient than 60%. If bundles of different sizes are coupled together, then the transmission can be obtained as the product of their separate transmissions. Therefore, if two bundles are cemented together, a net transmission of around 36% can be estimated. Consequently, a beam of light needs to be approximately 3 times stronger to equal a beam not transferred through such fiber optics.

The matter of resolution is equally disturbing. To separate two points, the points must be apart by more than two fiber diameters. If $10\text{-}\mu\text{m}$ fibers are coupled to a 19-mm faceplate, it is possible to resolve no more than approximately 900 line pairs, at virtually zero MTF. When bundles of different fiber sizes are joined, the resolution drops empirically by an inverse square sum rule. Thus, if two bundles of the same fiber diameter are joined, the resolution drops by 30%, but when a fine bundle is joined to a significantly coarser bundle, the result is almost the same as that given by the coarser bundle.

A candidate optical conduit has the following dimensions. Its length, which is flexible, is 1.8 m. The bundle comprises 10- μ m fibers organized into rectangular or hexagonal matrices of 25 or 36 fibers to fill a circular format 19 mm in diameter. The end connecting to the display is fixed in epoxy and ground and polished to the shape required by the optical design. The other end is likewise fixed in epoxy and either bonded or placed in close contact with the fiberoptic faceplate of a 2.54-cm miniature CRT, with 3- μ m fibers. As explained in the previous paragraph, the net transmission of such a configuration would be lower than that from a CRT directly connected to the display. However, the 3- μ m faceplate exists in either event, so the reduction in transmission compared with a helmet-mounted CRT is only approximately 40%. The resolution, however, is now limited by the 10- μ m fiber to about 900 line pairs.

The weight of a 1.8-m bundle would be about 1.3 kg.

2.4.3. Light Valve and FFOB

Probably the brightest projected television image that can be achieved at the present time is with the General Electric "light valve." The General Electric Company has supplied us with information about the principle of their version, which is used extensively for large screen projection.

The GE projectors weigh approximately 68 kg and typically require from 1000 to 1600 W of power, most of which is used to drive a xenon arc. Prospective users should not forget that the heat from these projectors must be vented.

The manner in which the GE light valve works is illustrated in Figure 1. Illumination from a white-light xenon arc at the left passes through a

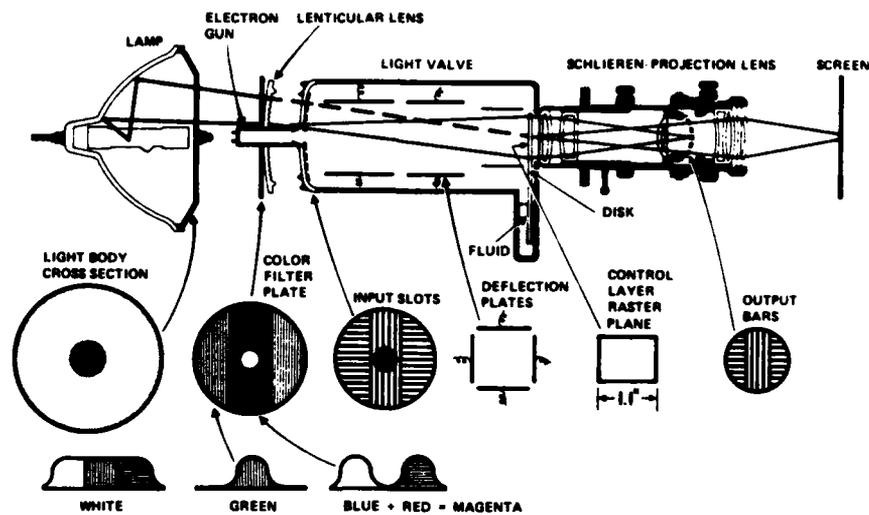


Figure 1. Operating principle of the General Electric light valve projector (courtesy of General Electric and Proc. SPIE).

color filter plate that has two green stripes and one magenta stripe. A lenticular plate enhances the transmission by directing the arc light to the input slot mask, which corresponds spatially to the initial color filter plate. This mask acts as the effective light source, much like the filaments in an ordinary projector. The mask is then reimaged by a set of lenses near the control layer raster plane to form a real exit pupil near a second set of lenses that project an image of the control layer raster plane. At the real exit pupil is placed a second output bar mask. The clear parts on this mask correspond to the blocked parts on the input mask and vice versa. Now, when the control layer, which is created by revolving a clear disk into a pool of high-viscosity transparent fluid, is undisturbed, all the light that passes through the input slot mask is completely blocked by the output bar mask. If we disturb the shape of the

control layer, light is diverted from its normal path and escapes through the output bar mask. The next step is to generate red, blue, and green images.

The chamber of the light valve is evacuated and held at a vacuum by a pump, which is needed since the fluid slowly volatilizes. A single electron beam is generated by the electron gun and is deflected by two sets of deflection plates. As in normal television, horizontal and vertical sweep voltages are applied to the deflection plates to produce a raster. The light valve modulates the horizontal sweep with two carrier frequencies, inversely proportional to the wavelength of the light being coded, one at 16 MHz for red, the other at 12 MHz for blue light.

The revolving disk, which is covered with an oil film, has a thin transparent conductive coating that attracts the electron beam, which then produces transient grooves similar to those in a diffraction grating. Note that when there is no modulation of the carrier frequency, no light diffracts from the zero or direct order. As the modulation increases, the grooves become deeper, and more light is diffracted into the various orders to the left and right of center. To obtain color images, all but the red and blue diffracted images are blocked off; this is accomplished with the output bar mask. The brightness of each color is therefore controlled by adjusting the carrier modulation.

The green image is produced differently. The vertical sweep is modulated at 48 MHz, which is unrelated to the wavelength of green. The pre-existing raster lines form a diffraction grating. These lines can be eliminated by moving them vertically until they spread out enough to touch each other, producing a uniform (green) field that will not diffract and

therefore not transmit through the output bar mask. Thus the green signal information is inversely proportional to the modulation of the 48-MHz carrier. Since all three images share a common axis of symmetry, there are no oblique color effects as occur with multiple-lens projectors. The colors here are spectral and thus capable of a richness not possible with CRT phosphors.

Obviously a light valve projector is too large and too hot to be mounted in a cockpit, so the image must be delivered through a FFOB. A problem arises with fiberoptics coupled to the light valve, evidently one serious enough that a solution is still being sought by Farrand with the assistance of the American Optical Company, which makes fiberoptics.

The exit pupil of the light valve consists of a bilaterally symmetric but not uniform pattern of vertical magenta bars and horizontal green bars. There is a sizable hole in the middle, which is due to the obstruction of the arc structure and electron gun.

As may be seen in Figure 2, a fiber preserves angular but not spatial information about a ray. A stripe of light will be transformed into a nonuniform ring of light. The light from the light valve will consequently be transformed from its striped pattern into a nonuniform ring pattern. The pattern produced in our exit pupil will be an image of this distribution, so it will be empty in the middle and green-rich toward its outer edge.

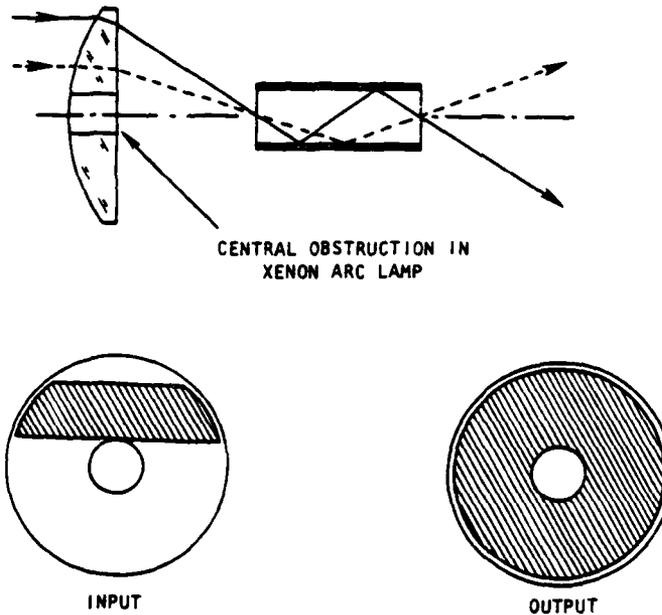


Figure 2. Fiberoptics conserve angular but not spatial distribution.

2.5. Optical Specifications

2.5.1. Field of View--Panorama Adjustment

The optical system for each eye is designed to have a field 80° wide by 60° tall, which is derived from a 19-mm diameter CRT image.

Conceptually, the optical axes of the two displays can be tilted outward by equal amounts from the forward line of sight to provide a wide-field panoramic image. The basic concept is illustrated in Figure 3. The amount of overlap is adjustable from 20° to 60° (axes tilted from 30° to 10°).

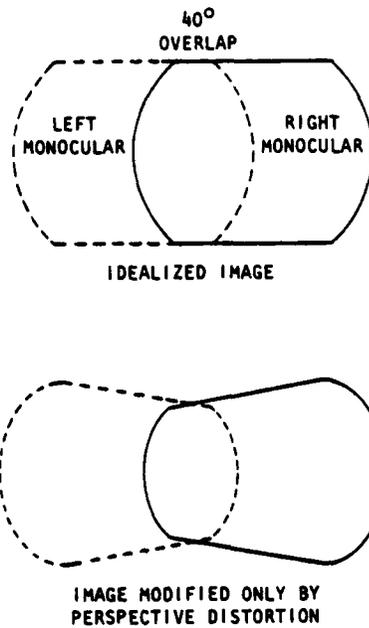


Figure 3. Panoramic display produced by overlapping monocular images.

2.5.2. Eye Relief

Nominal eye relief (axial separation to the nearest optical component measured from the exit pupil to the Pancake WindowTM) is 39.5 mm. Because the left eye display optics interfere with the right eye's optics, the smaller the eye relief, the greater can be the image overlap.

2.5.3. Exit Pupil Diameter

The nominal exit pupil diameter is 15 mm. Since there must be a hard aperture stop in the optical relay of the design, the actual shape and size will vary over the field of view because of pupil aberration.

2.5.4. Transmission

Original goals for transmission were waived to permit use of the Pancake WindowTM principle. Typical final transmissions are 0.7% for the CRT path and 2.3% for the see-through path. Special coatings cannot greatly enhance these values.

2.5.5 IPD and Focus Adjustment

The interpupillary distance (IPD) is adjustable from 62 to 72 mm. The smaller the IPD, the more restricted is the possibility for overlapping the two fields of view. If large exit pupil diameters could be achieved, we could dispense with IPD adjustment.

Focus adjustment for different states of accommodation is not provided. It may be unwise to allow focus adjustment in binocular displays because only when the displays are set for zero diopter focus does the line of sight remain independent of centering the eyes in the exit pupil. In VCASS, defocus would manifest itself as a dynamic parallax error.

Nominal focusing is achieved by moving the miniature CRTs relative to the relay lens housing. The nominal focal length of the Farrand design is 13.67 mm, from which diopter calibration can be derived.

2.5.6. Collimation

The principal reason for overlapping the displays was originally to blend the two images together. Although stereoscopic vision would be possible, this was a secondary objective. The large field of image overlap would be more suited to stereoscopic display.

For the images to blend and for stereoperception to be possible, the two images must match to some precision. A requirement for 2% match in nominal magnification provides image similarity in shape. Divergence of 0

minutes and convergence of 8 minutes of arc have been set. The relative rotation of one image should be defined with respect to the other, and to the meridian, within typically 30 minutes of arc. Because apparent magnification in this kind of display is anamorphic, that is, not rotationally symmetric, finer details remain to be settled after experience with the prototypes.

2.5.7. MTF

The modulation transfer function (MTF) is a measure of image contrast at different spatial frequencies, and the performance of the optical design is prescribed in terms of MTF curves. These are shown, compared with the final design values, in Section 4.3.

2.5.8. Color Correction

The design must work well with a narrow spectrum phosphor such as the P53, and in addition, should be achromatic to permit use of the display with other image generators such as beam penetration phosphors and light valves. The chromatic MTF of the final design is only slightly inferior to the monochromatic MTF, and still exceeds the monochromatic MTF specification.

2.5.9. Distortion

Distortion is the combined eyes' perception of improper angular mapping of an object simulated to lie in the field of view. The intention is that the perceived mapping error will be less than 2%. Many wide-angle binoculars have distortion in excess of 10%.

3. DESIGN DEVELOPMENT

3.1. Refractive Helmet Mounted Displays

Refractive HMDs have the advantage of high transmission, and fields up to 40° have been achieved. However, limits on the field of view and the exit pupil are imposed optically by oblique aberrations as well as in a more subtle sense by chromatic aberration of the exit pupil. Additionally, from a practical standpoint the size, thickness, and consequent weight of certain glass elements become excessive. For the present application, see-through requirements seriously inhibit the maximum field that can be achieved with a refractive display.

3.2. Folded Catadioptric Displays

Some of the possibilities with this form of display for VCASS were extensively explored and reported in AFAMRL-TR-81-133, "Design of a Catadioptric VCASS Helmet-Mounted Display," where a design with a field of 70° and an exit pupil of 12 mm was achieved only with difficulty.

Catadioptric displays have an inherent advantage over refractive displays: one element acts both as a transmitter and a reflector, so the see-through field of view can be large. No thick lens elements, as would be needed for a refractive display, are involved in a catadioptric display.

3.3. Farrand Pancake WindowTM Display

Farrand Optical Company, Inc., has made extensive use of the Pancake WindowTM concept for magnifying large CRTs in aircraft simulators. The principle of operation is described in U.S. Patent 3,940,203 for a holographic version. The principle is the same for the catadioptric form used in VCASS and can be explained with Figure 4. Consider that there is a

light source, either a CRT phosphor or, as in the present case, the intermediate image formed by the relay optics. The goal is to form a magnified virtual image at infinity by using the concave mirror of the Pancake WindowTM as an eyepiece. This is accomplished with partially reflective coatings as shown. However, at this point the unmagnified image is superimposed on the magnified image. This must be eliminated for the Pancake WindowTM to be useful. To achieve this, the light from the source is polarized. Figure 4 shows the polarizer in front of an image source. In the Farrand design it is enclosed in the cell holding the relay optics.

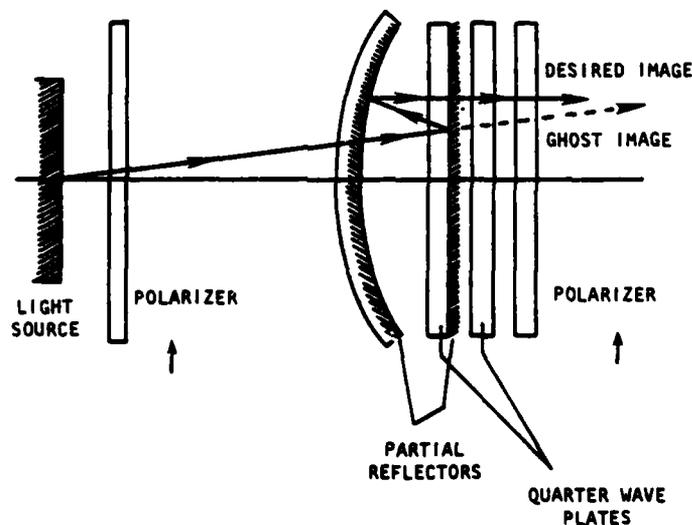


Figure 4. Principle of the Pancake WindowTM

The spherical reflector is ordinary except for its 50:50 coating. Next, a quarter-wave plate with a 50:50 coating on its second surface is placed in position. Now, half the light passes through the coating and must be eliminated before reaching the eye. This is done by using a second

quarter-wave plate, and finally a polarizer whose axis is aligned with that of the first polarizer. The reflected light, meanwhile, has passed back through the first quarter-wave plate, thus giving one-half wave retardation to the beam. It reflects off the concave reflector and is collimated, then goes back through the partially reflective quarter-wave plate, through the second quarter-wave plate, and up to the last polarizer.

How does this beam differ from the straight-through beam? The effect of one-half wave of retardation is to turn the plane of polarization of the input beam by 90° , so that its plane of polarization is at right angles to that of the output polarizer. This theoretically eliminates the unwanted beam. The doubly reflected beam, however, passes through a quarter-wave plate four times, so that it experiences a full wave of retardation. The first half-wave turned it 90° , the second one turned it another 90° , so it once again has its plane of polarization aligned with that of the output polarizer and is therefore visible to the eye. Unfortunately, the transmission of this system is inherently low, and there seems to be no way to avoid this problem.

3.4. Two Forms of the Pancake WindowTM Display

The low transmission of the display led Farrand to explore an alternative form. As shown in the right-hand sketch of Figure 5, the need for a flat beam-combining plate causes a significant loss both in the CRT image path and in the see-through path. Farrand therefore explored a modification of the design that eliminates the beam combiner, as shown in the left-hand sketch. This form, which also leads to good imagery, was rejected because, as may be observed, it intrudes on the available eye relief.

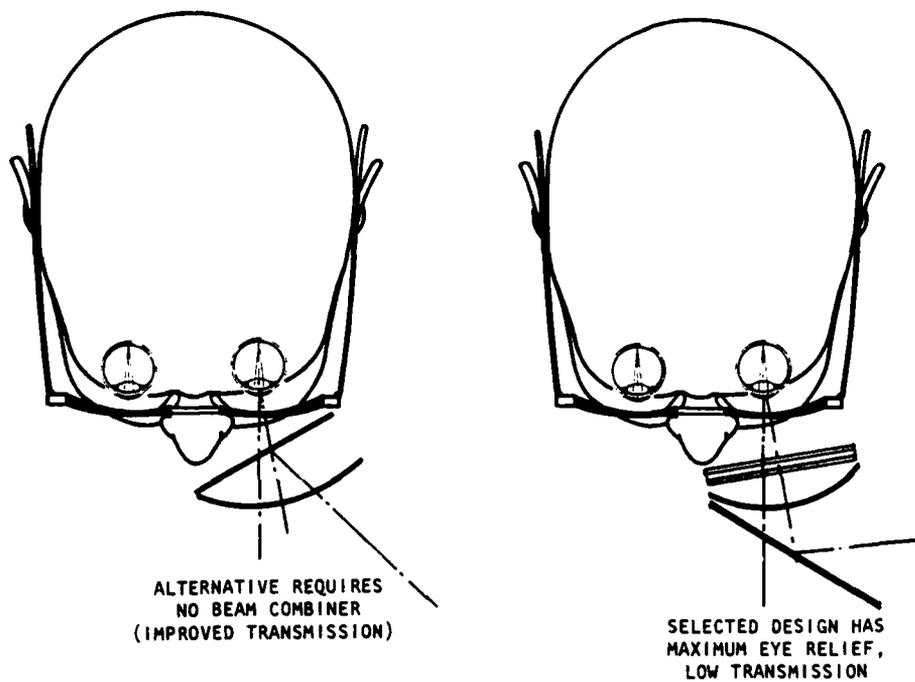


Figure 5. Two distinctive embodiments of the Pancake Window™ principle.

This second form is similar to that of conventional folded catadioptric displays; however, in wide angle embodiments the pancake's quarter-wave plates and polarizers are necessary to avoid unwanted nonfocussed images.

3.5. Some General Optical Design Tradeoffs

The imaging problem is involved in a very complicated way with mechanical problems associated with assembling two bulky wide-angle monoculars to form a binocular HMD. The optical designer has a variety of compromises to make, and the choices made by a team at the University of Arizona were different from those made by Farrand.

Arizona elected to design for a flat field with zero optical distortion. The use of conventional catadioptric folding concepts led to a maximum monocular field of only 70°. Simplicity of the optical design, whose relay contains just five lens elements, restricted the pupil to 12 mm.

Farrand, in using its Pancake WindowTM, was easily able to obtain an 80° field of view. With a complex intermediate image relay group comprising 11 elements, they also achieved a very high-quality 15-mm exit pupil, but on a curved field. As a further aid to mechanical design and optimum image quality, the Farrand design allowed up to 17% optical distortion. This distortion was not mandatory, but its correction would involve major optical changes in the existing design. Likewise, field curvature could be eliminated, but only by an optical redesign.

The advantage of eliminating optical distortion and field curvature is that these problems do not need to be compensated by the computer or CRT electronics. Centration of the CRT image then becomes usable as a means

for collimation that is comparatively insensitive to focus and image tilt errors.

Therefore, it is possible to envision a Pancake WindowTM design with or without optical distortion, with or without a flat image field, and with a range of exit pupil diameters different from the present 15-mm value. This shall be discussed in greater detail, but first let us consider image overlap.

By making the optical axes of the two separate monoculars diverge, a wide-angle panoramic binocular was obtained, but at the same time only a limited area of overlapping images occurred in which redundancy or stereoscopic imagery was achieved. It is regarded as being desirable, at least as an option, to be able to sacrifice the wide field for an overlapping field. Basically, this depends on eyerelief and interpupillary distance (IPD) in an uncluttered Pancake WindowTM design. The numbers can be refined to include fractional vignetting of the pupil, but ignoring that calculation for clarity, the total angular overlap of monocular fields can be approximated as:

$$\text{Overlapping Field} \approx 2 \times \arctangent (1/2 \text{ IPD/Eyerelief}).$$

For a 62-mm IPD and a 40° semifield angle, this equation leads to an eyerelief of 37 mm. However, this value ignores the fact that vignetting would be 50% in the ideal case, that the Pancake elements have some thickness, and that allowance must be made for mounting them. Therefore, the eyerelief would be shorter. Since one eye must not see the other eye's image, schemes should be avoided that would allow overlapping images with leaks or ghosts.

To facilitate wearing the display, it is advantageous to have exit pupils much larger than the pupil of the eye. This allows the size of the helmet to be less critical and compensates for pupil shift caused by pivoting the eyes in their sockets.

Provided that the output numerical aperture of the relay does not exceed 1.0, it is not necessary to optically bond the relay to the image generator. It is assumed that the CRT size is unchanged, although increasing its diameter or increasing it optically with fiberoptic magnification or with a bonded magnifying lens is highly advantageous optically (but, unfortunately, not in terms of size and weight). Presently, the pupil is 15 mm in diameter with a numerical aperture (NA) of 0.55, so scaling yields $NA = 0.74$ at 20 mm and $NA = 0.92$ at a 25-mm exit pupil diameter. The 25-mm pupil would probably require bonded contact or a fiberoptic magnifier. The 20-mm pupil is probably realizable with a design modification.

The impact of this modification can be estimated. Although the use of aspheric surfaces is powerful, allowance should be made for some additional elements. To the level of third order aberration, spherical aberration will be the principal problem, and will increase at least as the third power of the increase in numerical aperture. However, dividing one element into two permits a reduction in the spherical aberration by a factor of eight. Therefore, the number of elements should probably increase at the same rate as the increase in speed to be safe. There should be allowance for three to four more elements in the relay section of the HMD. Alternatively the MTF specification can be reduced and more vigorous use made of the aspherics in the present design, or a different

configuration can be chosen.

The relay section will naturally increase in diameter at the same rate that the diameter of the pupil increases; the weight will rise more rapidly than the diameter.

If the field of view is reduced, a constant level of complexity is given approximately by the Lagrange invariant, $Q = (\text{pupil}/2)(\text{field angle}/2)$. A 60° field with a 20-mm pupil and a 50° field with a 24-mm pupil are likely to be similar in size and shape to the present design, which is intended for an 80° field with a 15-mm pupil. A 60° field with a 25-mm pupil requires an increase in optical complexity.

If 60° to 50° designs are desired with only 15-mm pupils, then the number of elements will be reduced, and the overall weight and complexity of the HMD will be more favorable. Since the existing Farrand design is capable of a 60° overlap, any modification of it should be able to achieve that overlap too, provided the pupil is allowed to vignette as it does now.

If a P53 monochromatic phosphor were used, the lenses could be non-achromatic. This would ordinarily reduce the complexity of any selected lens configuration. In the Arizona form, the five-element relay becomes a three-element design of even superior quality.

The Farrand relay is of Petzval lens form, and under less stringent MTF requirements would comprise only spherical lens elements. The design requires a large number of elements for monochromatic correction, thus color correction does not add a great burden. The aspheric surfaces of the design could probably be obviated by adding a few additional elements, which would add to the weight problem.

It is difficult to make generalizations about configurations that involve complicated packaging considerations. Perfectly sensible optical design solutions may be found useless for a HMD, and it is often advantageous to bend the rules in one area in order to obtain a greater mechanical advantage in another. Both Farrand and the University of Arizona worked diligently along similar but separate paths and came to many similar conclusions, even though each was unaware of the details of what the other was doing. The problems for a wide angle display were, on the whole, given a great deal of attention in these two studies, and of the two, the Farrand design represents a closer approach to optical perfection.

3.6 Image Orientation through Pancake WindowTM Display

Figure 6 shows corresponding images through the display. The Pancake WindowTM is equivalent to a single-lens magnifier. It produces a virtual image at infinity, and this image has the same orientation as the image at its focal plane. The effect of rotating the prism about the optical axis is to cause this image to rotate. Therefore, for any orientation of the prism, there is a suitable rotation of the CRT that will give a perfectly aligned apparent image at infinity.

The figure shows fold angles at 90°; however, the same result applies at any set of angles, and derives from the fact that there are two reflections and one image rotation from the relay optics. Therefore, regardless of the contortions through which the optical path is folded, rotating the CRT is always sufficient to produce an image right-side up with the proper handedness.

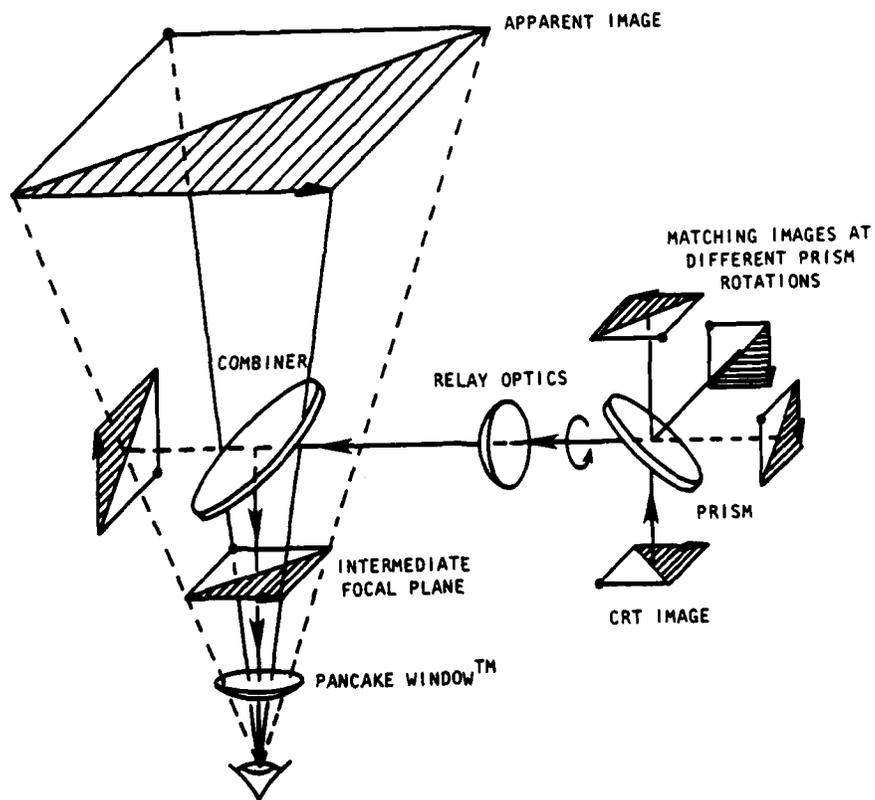


Figure 6. Image orientation through the optical system.

3.7. Image Mapping on the CRT

3.7.1. Lens Distortion

The optical system derived by Farrand uses a fiberoptic faceplate with a concave output curvature of 150 mm. This can complicate our definition of distortion. What is of concern here are the image dimensions on the input side of the CRT; that is, the image that must be introduced into the optical system. Farrand properly computes this distortion with a computer program called ACCOS, and it has been verified for this report with one called GENIL. Our subsequent analyses with the CODE V program computed distortion differently. Therefore, the results shown in Figure 14, Section 4, for distortion are not the same as those for computer-generated imagery purposes and are properly ignored in favor of tabular results shown in Table 4, Section 4.

Under normal conditions, that is, with a rotationally symmetric optical system (which means that the object and image are parallel and perpendicular to the optical axis), ideal or Cartesian mapping exists when $r = f \cdot \tan \theta$. The factor r is the radial distance off the optical axis of an image point corresponding to an object point that subtends an angle θ with respect to the optical axis passing through the entrance pupil. The factor f is a constant of proportionality called the focal length. The object is assumed to be far away relative to the focal length, but similar equations apply for nearby objects.

It can be shown that for a rotationally symmetric optical system, deviations from this rule will follow the requirement that terms containing the third power, fifth power, seventh power and so on of the field angle must be the only precise description of the error. Therefore,

while even-powered terms can be used in an effort to do a curve fit, they are not inherent in the distortion function.

In the course of our study it was found that a third-order optical aberration function is insufficient to describe the distortion much beyond 30°. The problem was revealed when a distorted grid was computed that had 16% negative distortion at the sides of a square field. When the plot was extended to include the corners of the field, they actually curved back over the original grid when only the cubic, third-order distortion term was used. Obviously, the image in a rotationally symmetric optical system is single-valued so that such behavior cannot occur. This lead us to consider the logical progression of the higher order terms in a lens.

An example is set by fisheye lenses, which are intended to follow an image formula, $r = f \cdot \theta$, where now θ is measured in radians instead of degrees, and f is the focal length. This is probably the only lens readily available for the inspection of a naturally occurring form of distortion that can be calculated to a very high order.

Distortion is the difference between the Cartesian mapping and the fisheye (often called f -theta or equidistant) mapping, i.e.,

$$\begin{aligned} \text{distortion} &= -\frac{1}{3} \theta^3 - \frac{2}{15} \theta^5 - \frac{17}{315} \theta^7 - \frac{62}{2835} \theta^9, \text{ etc.} \\ &= D_3 \theta^3 + D_5 \theta^5 + D_7 \theta^7 + \dots \end{aligned}$$

A curve fitted to the seventh order term of this series fits the distortion of a $\pm 40^\circ$ display to within a small fraction of 1%.

The Farrand design has a focal length of 13.67 mm and has the distortion characteristic of a fisheye lens, as shown in Table 4. It is necessary for the computer-generated imagery to compensate for this lens

distortion. AFAMRL has proposed an equation of the form,

$$r' = c_2r + c_3r^2 + c_4r^3,$$

where the coefficients are adjustable.

3.7.2. Perspective Distortion

Perspective distortion is not really a distortion at all, but simply the wrong way of looking at things. It is familiar to most of us as "keystone distortion" when we tip our cameras upward, and "wide angle distortion" when we look at the off-axis detail in an enlargement of a wide angle image. The first corresponds to a tilt of the image plane relative to the object plane, and the second is caused by shifting from the original center of perspective, which should coincide proportionately with the location of the lens relative to the film when the image was originally recorded.

Only "keystone" distortion is of concern in the display, although shifted centers of perspective could easily be included. Indeed, the latter would occur unless the displays were set for infinity (zero diopter) focus.

This occurs because the monocular displays have their optical axes tilted outward from between 10° to 30°, while our eyes look nominally straight ahead. Instead of seeing two magnified images of the CRTs straight ahead, what we see can be described as two walls tilted 20° to 60° relative to each other. Therefore, the information presented on these CRT screens must be modified to "look right" when viewed straight ahead. Fortunately, if this is done, the proper perspective occurs when the eyes pivot left and right.

Artistic perspective is generally an aesthetic construction and not accurate for our needs. The deficiency lies in the artist's finding his "vanishing points," that is, where parallels are to converge on the horizon. He chooses these because they "look nice," not because they are proper. In particular, he often applies the rules of two-point perspective when he should be using three-point perspective, presumably because he does not understand how to find a vanishing point that does not lie on the horizon.

Figure 7 shows how the horizons for lines lying on any and all tilted object planes are easily found for any screen orientation.

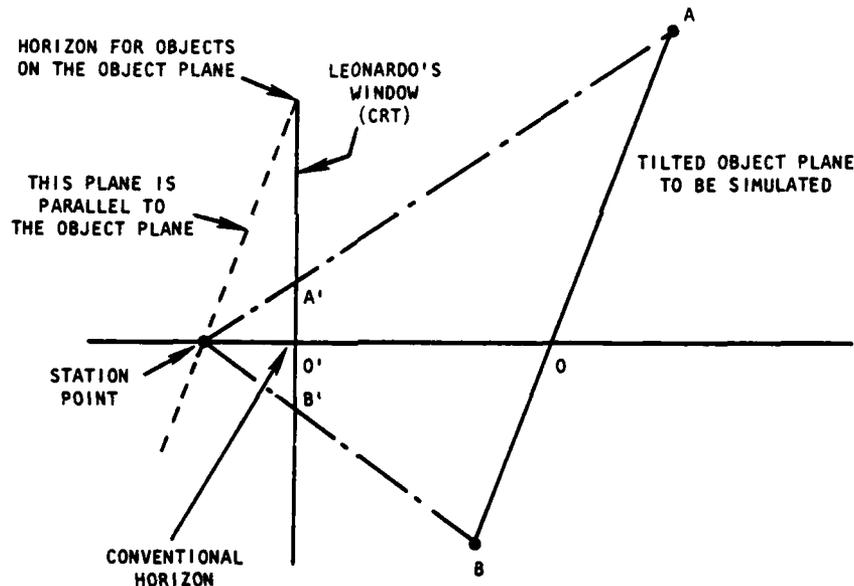


Figure 7. Method for determining correct perspective for a randomly oriented object plane.

Invoking the artist's language, there is a single "station point," which is our eyepoint or exit pupil in the display. The "easel," called "Leonardo's window," is the magnified image of the CRT faceplate. A conventional horizon (of the earth) is obtained by the intersection of a

level plane, drawn through the station point, with the easel. Since objects and separations that are extremely far away appear vanishingly small, it follows that all planes parallel to this original plane must converge in a single line, called the horizon, and that all sets of parallel lines on each plane will appear to converge to different points along the horizon. These are termed "vanishing points." But what about all the other possible planes other than the one level to the earth? Each set of parallel planes has its own horizon and is found in the same way. While a cube will have just three vanishing points for random orientation, a general six-sided solid will have six horizon lines and six vanishing points. Clearly, the problem, while now fairly obvious, is still not easy.

Figure 7 indicates how to compensate for the tilted CRT so that when viewed straight ahead it will look proper. A point-by-point transformation can be done once it is understood that the transformation is linear when the optics are corrected for their own distortion.

Since the Farrand display has optical distortion as well as perspective distortion, the computer-generated and electronics-modified imagery must compensate for both. A computer program called GRIDS was written to illustrate the effect with a uniform square grid. The program first computes the effect of optical distortion (following the equations $r = f \cdot \theta$ to generate negative or barrel distortion, and $r' = f(2 \cdot \tan \theta - \theta)$ for positive or pincushion distortion) on the grid, then performs the linear transformation.

The patterns that should be generated on the CRTs to see a flat, uniform grid image with the Farrand VCASS are similar to those shown in the middle of Figure 8. These patterns were prepared for a collimated,

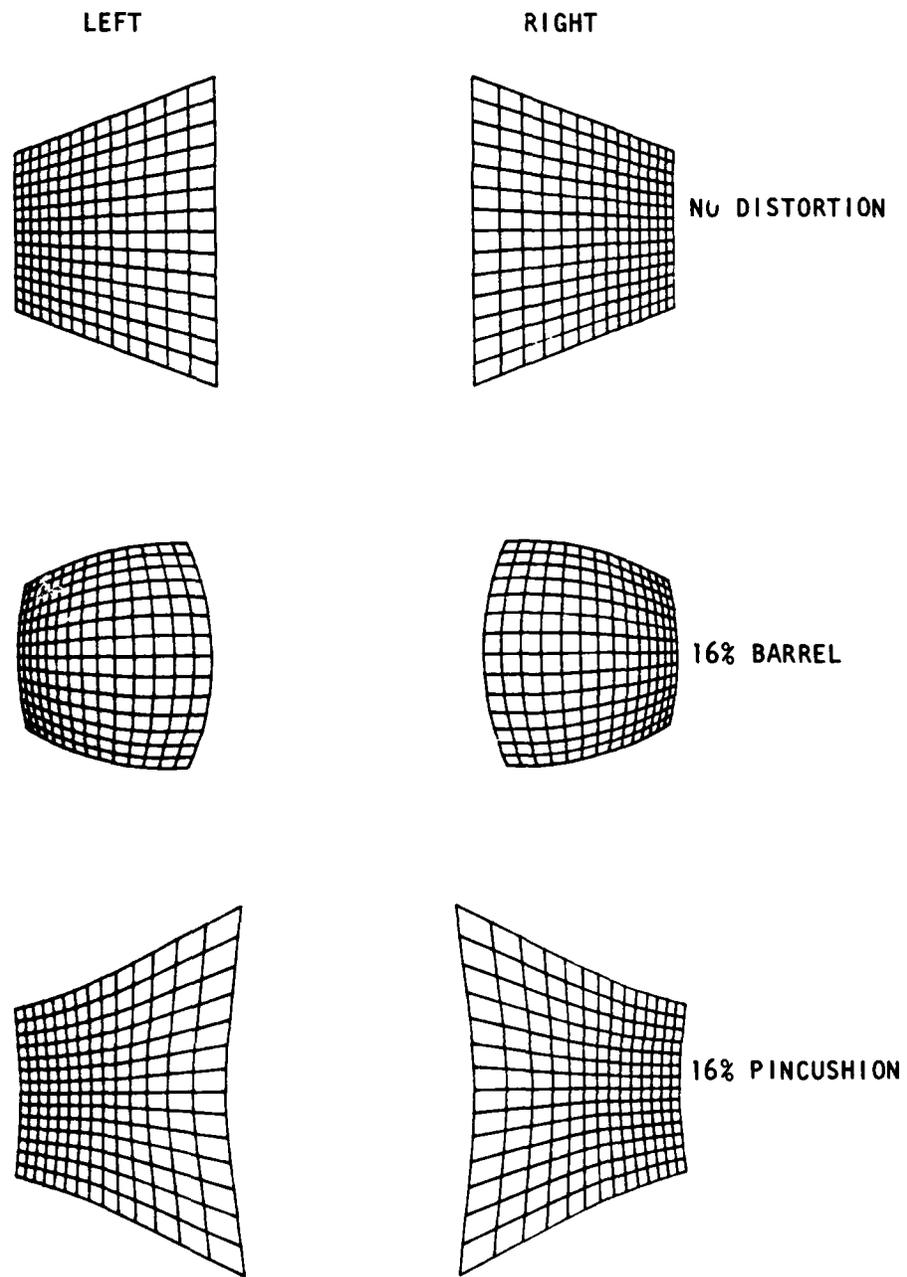


Figure 8. CRT displays with perspective compensation (20° tilt of optical axis).

zero-diopter image, with the display axes tilted 20° , and for a square grid 80° on a side. The patterns were originally designed for our own experimental apparatus, which has a focal length of 38.1 mm, whereas the VCASS has a focal length of 13.67 mm. In principle, transparencies can be made from these plots and back illuminated for use on the actual Farrand display.

If the plots are reversed left for right, it is possible to gain insight into noncompensated CRT images. If a uniform square grid is displayed on the CRT, an image like the top pair reversed occurs. The purpose of predistorting the CRT with the patterns as shown is to cancel out this effect. Now, if in addition the display requires barrel or negative distortion, like the Farrand VCASS, a uniform square grid will look like the image pairs at the bottom of Figure 8, reversed. Therefore, the middle pair is generated to cancel out this effect. A lens that forms a barrel-shaped image will produce an image that looks like a pincushion when used as a magnifier.

3.7.3. False Stereo Cues

If no compensation is made for the two types of distortion in this display, an illusion of a curved image occurs. It appears that, overall, pincushion distortion plus the kind of perspective distortion obtained by tilting the displays outward will generate the illusion of an image sphere centered on the viewer's head. The perspective cues are inappropriate for the case of barrel distortion, which would be required to generate the illusion of a sphere convex toward the observer. The perspective cues are for an object distance of $1/2(IPD)/\sin(\text{tilt})$, where IPD is the interpupillary distance. The curvature cues depend on the degree of optical distortion, so

the strength of the illusion can vary, depending on phenomena termed "the horopter" and "Panum's area."

By reference to Figure 9 it can be shown that optical distortion permits a flat projection, as on our CRT, that gives proper cues to the curvature of a sphere curved toward our head. The intersection of the dashed lines from P must define points on the sphere by their intersection on the tangent plane, our CRT. There must be a positive distortion to get the curvature cues. The distortion we need is equal to SAG times the tangent of angle a . Working this out as a series, one obtains the $SAG = r^2/2R + r^4/8R^3 + \dots$, and tangent of angle a is exactly r/R . Thus, the distortion required is of the form, $D_1r^3 + D_2r^5 + \dots$

As shown in section 3.7.1, this is the same form followed by optical distortion, so the effect of optical distortion is to create the projection of a spherical surface onto the flat CRT screen.

The influence of shifting the eye from P to its proper location in the exit pupil is shown by the longer dashed lines in Figure 9. Because the line to the right side is shorter, we see that section with higher magnification, whereas the section to the left is seen with lower magnification. These are the cues that tell us the original sphere is tilted, or that we have moved our head to the right. The cues produced for the other eye are mirror images of these cues. Except for the overlap of the two image fields, there are no true stereo cues; however, the mind is perhaps willing to extrapolate beyond the overlapping area, so that the illusion is one of having the entire image of a grid lying on a curved sheet concentric with the viewer's head. These effects should not occur when the optical distortion and improper perspective are compensated.

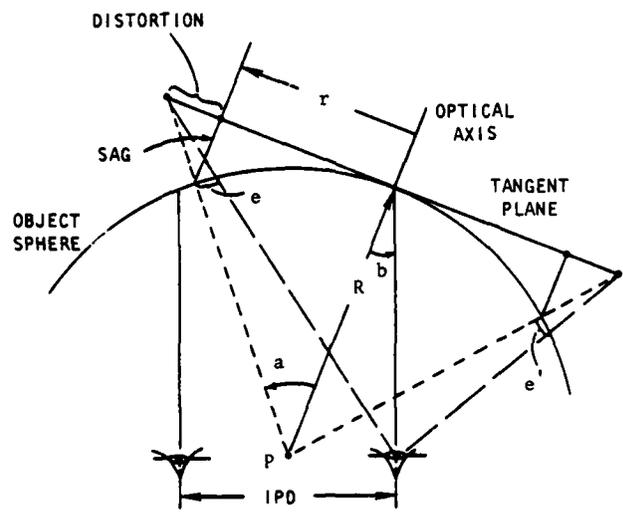


Figure 9. Distortion and perspective error produce stereoscopic cues for a sphere.

4. FINAL DESIGN

4.1. General Layout

Figure 10 shows three views of the final design. Figure 11 is a simplified equivalent optical layout of the optical path for one eye. Figure 12 shows representative ray paths through an equivalent unfolded optical layout. The figure illustrates a system without vignetting, but up to 50% vignetting is permitted for the $\pm 40^\circ$ ray bundles. The same figure shows how rays traverse the optics when a 6-mm diameter pupil, representative of what the viewer's pupil may actually be, is decentered by the maximum amount possible before it begins to exceed the maximum 15-mm pupil design diameter.

4.2. Optical Design

Figure 11 shows that in addition to the beam combiner, there are 11 lens elements plus a prism and polarizing filter in the relay optics. The Pancake WindowTM contains a polarizer, two quarterwave plates (one of which is partially reflectorized), and a partially reflecting concave mirror. The output fiberoptic faceplate of the 19-mm CRT active diameter has been ground to a concave 150-mm radius.

Although there may be technical problems in making a small Pancake WindowTM, it appears the area of greatest technical difficulty lies in making the relay optics. Figure 13 shows that the design uses three aspheric optical surfaces. Table 1, which is an exact mathematical description of the optics, shows these are not simple conic aspherics, but are spheres deformed with up to eighth degree polynomial deformations. However, Farrand has already made several sets of optics to prove feasibility.

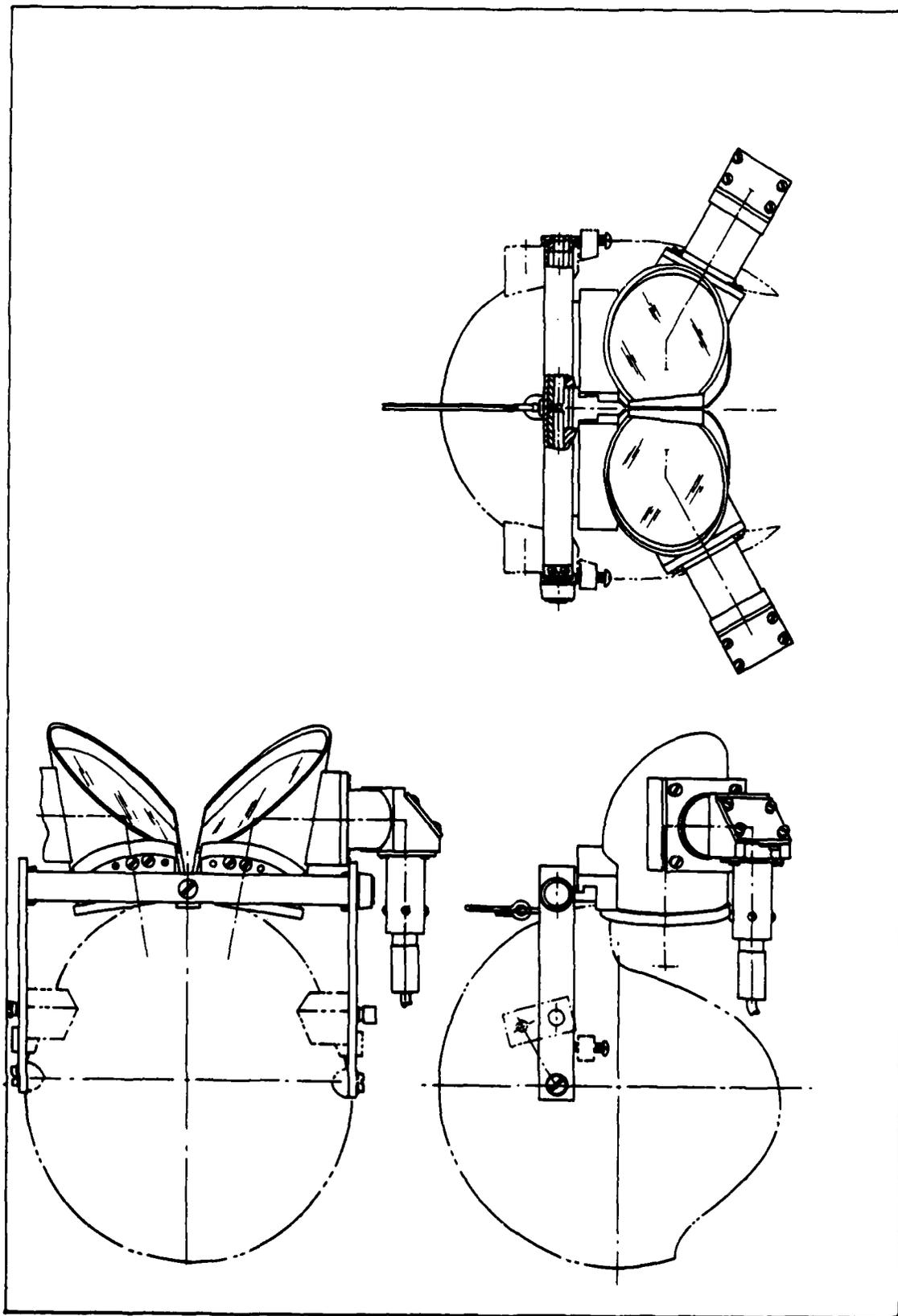


Figure 10. General layout of the Farrand VCASS.

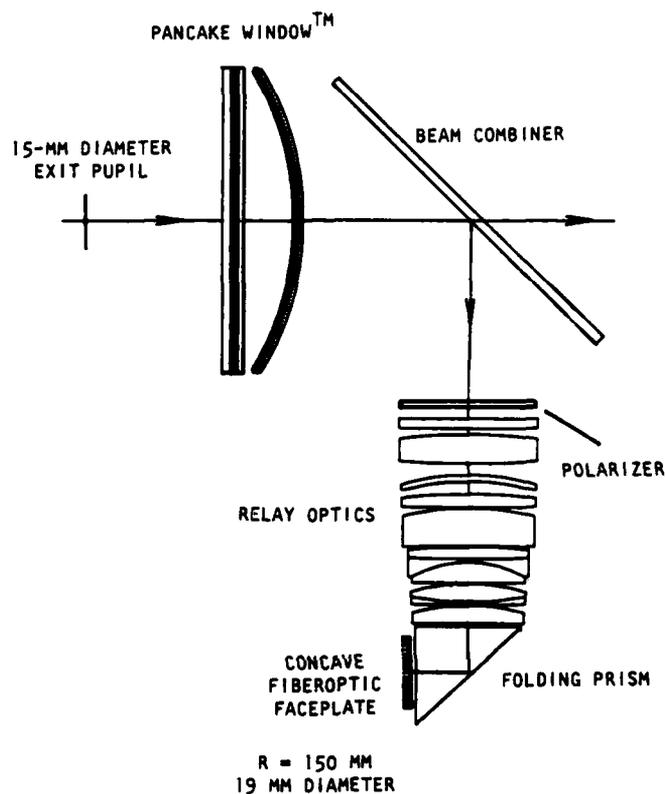


Figure 11. Representative beam combiner folding of the Farrand VCASS optical system.

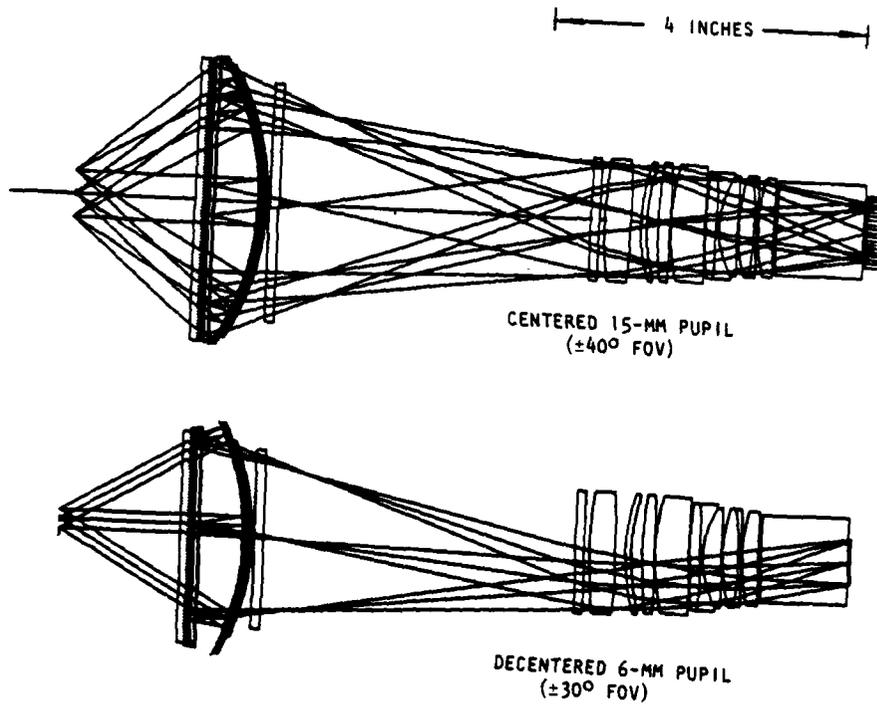


Figure 12. Selected ray paths in the Farrand VCASS design.

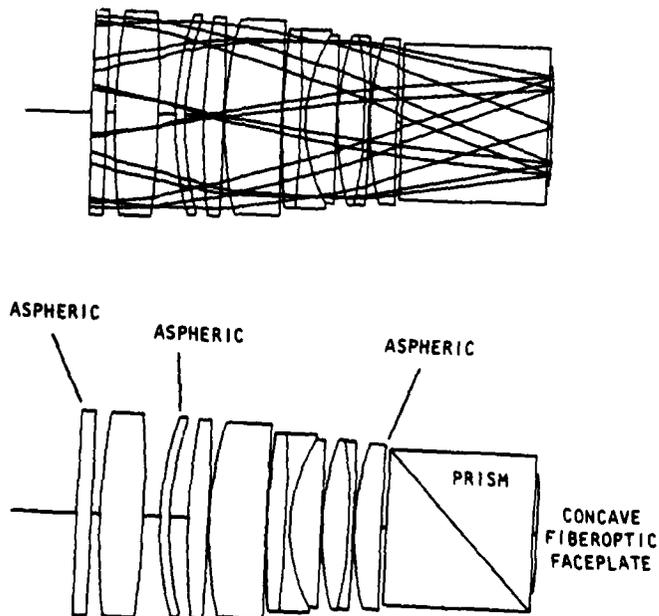


Figure 13. Details of the relay optics.

Table 1. Computerized Prescription for Farrand VCASS Optical System.

7/16/82
FARRAND VCASS S2

ELEMENT NUMBER	RADIUS OF CURVATURE FRONT	RADIUS OF CURVATURE BACK	THICKNESS	APERTURE DIAMETER FRONT	APERTURE DIAMETER BACK	GLASS
OBJECT	INF	INFINITY	APERTURE STOP	15.0000		
1	INF	INF	39.0000	01.2009	06.0770	K5
2	INF	-04.0100	6.0000	09.1360		BEFL
3	INF	INF	14.0000	07.9713	07.1604	K5
4	INF	INF	-14.0000	07.1604	07.1604	BEFL
5	-04.0100	-05.0000	-1.0000	07.1604	07.1604	K5
6	INF	INF	14.0000	03.0211	03.3071	BK7
7	A(1)	-1260.4648	101.0000	73.3048	71.6962	K5
8	142.0648	-203.4503	1.0000	36.9903	36.9400	LAKN7
9	A(2)	66.6667	0.4000	36.7722	35.9016	LAKN22
10	130.1391	-008.0000	0.2000	36.0675	35.7010	SFS3
11	72.4630	636.2993	0.2000	39.7713	39.9612	LAK21
12	150.7302	-250.0000	0.2000	39.0055	32.3361	LAK21
13	-250.0000	32.2581	0.2000	31.9577	31.1513	LAK21
14	32.2581	-1407.9590	1.0000	31.1513	29.0660	SFS3
15	36.2309	-03.2323	0.6000	29.0660	30.0411	LAK21
16	-03.2323	-202.0250	0.2000	30.4102	30.2076	LAK21
17	57.0035	A(3)	1.0000	30.2076	30.0494	SFS
18	INF	INF	0.2000	29.4925	28.3509	LAK21
IMAGE	IMAGE DISTANCE =		20.4000	27.0491	19.3091	LAKN16
	-150.0000		0.7617		22.9363	

NOTE - POSITIVE RADIUS INDICATES THE CENTER OF CURVATURE IS TO THE RIGHT
 NEGATIVE RADIUS INDICATES THE CENTER OF CURVATURE IS TO THE LEFT
 - DIMENSIONS ARE GIVEN IN MILLIMETERS
 - THICKNESS IS AXIAL DISTANCE TO NEXT SURFACE

ASPHERIC CONSTANTS

$$Z = \frac{(CURV)^2}{1 + \sqrt{1 - (1+K)(CURV)^2}} + (A)Y^4 + (B)Y^6 + (C)Y^8 + (D)Y^{10}$$

ASPHERIC	CURV	K	A	B	C	D
A(1)	0.0032000	0.000000	-3.54000E-06	-3.19000E-10	0.00000E-01	0.00000E-01
A(2)	0.01499999	0.000000	1.14000E-06	1.40000E-10	-5.00000E-13	0.00000E-01
A(3)	-0.00077563	0.000000	3.40000E-06	0.00000E-01	0.00000E-01	0.00000E-01

REFERENCE WAVELENGTH = 500.0 NM
 SPECTRAL REGION = 400.0 - 656.0 NM

INFINITE CONJUGATES

BEFL	=	-13.4672
BK7	=	-0.4619
BEFL	=	-4.4624
F/NO	=	-0.9111
IMAGE DIST	=	0.7617
OBJ	=	206.0700
PARAXIAL	=	
IMAGE HT	=	11.4601
SEMI-FIELD	=	
ANGLE	=	00.0000
ENTR	=	
DIAMETER	=	15.0000
ENTR	=	0.0000
DIAMETER	=	
ENTR	=	02.9704
DIAMETER	=	-30.3010

Starting with the optical prescription of Table 1, the Farrand design was completely reanalyzed to express the behavior of the nominal form in terms of ray aberration, wave aberration, astigmatism, distortion, and MTF. The mathematically predicted statistical performance was not modelled using Farrand tolerance data, but our own tolerance analysis indicates the optics can be manufactured to the necessary degree of quality.

Farrand apparently designed and analyzed the optics with a computer program called ACCOS. Our initial analysis was performed using a program called GENII, and our final analysis was with CODE V, the latter providing report-presentable output as well as diffraction-based MTF. The results from our two programs agree with each other, and with that from the Farrand analysis.

Table 2 is a paraxial raytrace analysis of the optical system, and enables us to obtain a generalized although approximate understanding of the path any ray can take through the system. It also provides information on local magnification and local focal lengths as well as showing whether the optical system is focussed.

Table 3 is a computed estimate of the weight of all the glass in the optical system. It shows that the pair of optics have a glass weight of about 0.9 kg. The computed center of mass is not valid because the computations are for the unfolded optical layout.

The transmission obtainable for the lens elements with single-layer magnesium fluoride coatings was computed to be 78%. This does not include the polarizing and reflective coatings. Because of the extensive use of high index glass in the Farrand design, the use of multilayer high efficiency coatings will not greatly enhance transmission from this source.

Table 2. Paraxial Raytrace of VCASS
Unfolded Optical System.

SURF	Y	U	YBAR	UBAR
0	0.0000	.000000	-83909963.0000	.839100
1	7.5000	.000000	-.0000	.839100
2	7.5000	.000000	-.0000	.839100
3	7.5000	.000000	33.1444	.551137
4	7.5000	.000000	36.4513	.839100
5	7.5000	.176866	48.1987	.297527
6	5.0239	.116169	44.0333	.195422
7	4.9496	-.116169	43.7401	-.195422
8	4.6754	-.176866	43.4470	-.297527
9	2.1993	-.107770	39.2816	-.038344
10	1.8759	-.174870	39.1666	-.296293
11	1.8759	-.114858	39.1666	-.194611
12	1.5314	-.174870	38.5828	-.296293
13	1.5314	-.174870	38.5828	-.296293
14	-16.3929	-.084860	8.2128	-.189928
15	-16.6399	-.131608	7.6620	-.317621
16	-16.9627	-.033227	7.1220	-.211998
17	-17.1419	-.000000	5.3413	-.367129
18	-17.1419	.108352	4.1297	-.238526
19	-16.9392	.002213	3.6837	-.372002
20	-16.9312	.050266	.23445	-.233536
21	-16.7352	.100842	1.4337	-.384689
22	-16.7150	.151529	1.3567	-.241806
23	-15.0482	.233435	-1.3031	-.397992
24	-15.0015	.179195	-1.3827	-.239204
25	-14.3743	.167170	-2.2199	-.227503
26	-14.2071	.152545	-2.4474	-.243740
27	-13.2919	.256296	-3.9099	-.398076
28	-13.2406	.247955	-3.9895	-.215019
29	-11.9760	.212224	-5.0861	-.200971
30	-11.7638	.414381	-5.2871	-.348730
31	-11.6809	.731493	-5.3568	-.176394
32	-9.9572	.548758	-6.2741	-.286257
33	-9.4084	.716561	-6.5603	-.165133
34	-.4181	.548758	-11.2501	-.286257
35	-.0000	.548758	-11.4682	-.286257
36	-.0000	.548758	-11.4682	-.286257

Table 3. Weight Estimated for Unfolded Optical Components.

ELEMENT NUMBER	VOLUME	SPECIFIC GRAVITY	WEIGHT	CENTER OF MASS
1	38906.59411	2.590	100.76807	3.00000
2	9967.55211	2.590	25.81596	-0.75000
4	18058.23179	2.510	45.32616	-4.15653
5	13997.60492	2.590	36.15019	1.50000
6	3100.48962	3.840	11.90988	1.56501
7	9168.94116	3.730	34.20015	4.29901
8	2264.85864	4.450	10.07862	2.30562
9	3552.07711	3.740	13.28851	2.18903
10	11001.26392	3.740	41.14472	6.15522
11	2541.21007	3.740	9.50412	1.82714
12	2409.01292	4.450	10.70111	1.87869
13	3152.21509	3.740	11.78928	3.74274
14	2598.58191	3.740	9.71879	2.69993
15	1316.46409	5.180	6.81928	-0.87632
16	3213.48893	3.740	12.01845	3.07248
17	20216.70618	4.020	81.27116	14.20000

TOTAL WEIGHT = 464.96938 GRAMS

SYSTEM CENTER OF MASS = 134.26927, MEASURED FROM THE FIRST SURFACE OF SYSTEM

4.3. Image Quality

4.3.1. Ray Aberration

Figure 14 shows the state of astigmatic and distortion correction in the design. These curves are relative to a concave 150-mm image and were obtained by tracing rays from the exit pupil back toward the CRT, as is customary. The astigmatism curves are for millimeters of defocus; this can be converted into diopters by using the lens focal length, 13.67 mm, and finding that one diopter equals about 0.185 mm. This means that the maximum tangential or sagittal defocus is less than 1/3 diopter.

Distortion as computed by this program is not completely valid for a curved fiberoptic faceplate on a CRT. Therefore, Table 4 is recommended for a proper analysis.

Table 4 compares computed image heights for the nominal design with those given by a perfect fisheye lens, following equidistant or $f\theta$ mapping. The agreement is better than 0.3%, and could be improved merely by calibrating the focal length.

Unless the aspheric surfaces, particularly the one nearest the CRT, are poorly made, or some element in the Pancake WindowTM is physically or optically distorted, the actual distortion profile produced by the final display can be adjusted with the computer algorithm to almost the same precision as though the elements were made perfectly. This occurs because the distortion of a lens made with smooth curves follows a progression that is uniform despite the final magnitude of the distortion.

Figure 15 shows the results of raytraces computed in blue, red, and green light. The abscissa is the fraction or distance from the center of the pupil to which the ray aberration pertains. The ordinate has been

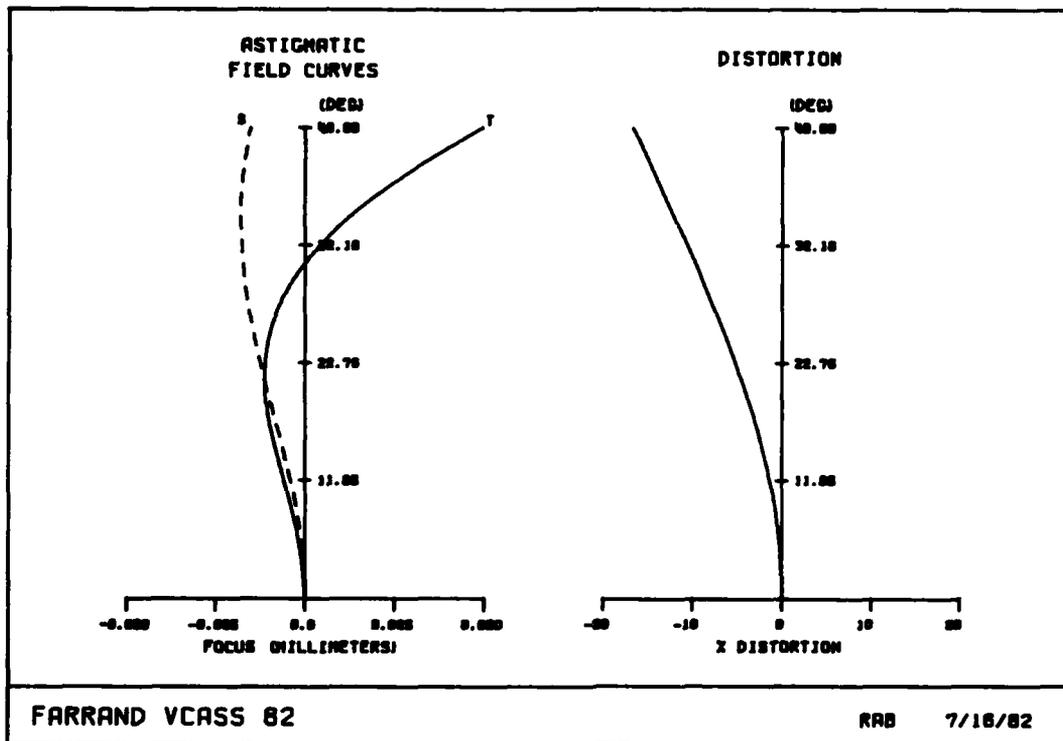


Figure 14. Accommodation and tangent plane distortion for the nominal optical design (aberration relative to 150-mm concave surface).

Table 4. Departure of the Final Design from Exact f - θ Mapping ($f=13.67$ mm, concave input $R=150$ mm).

Field angle (degrees)	Ideal image height (mm)	Actual image height (mm)	Error (%)
5	1.193	1.193	--
10	2.385	2.385	--
15	3.578	3.577	-0.02
20	4.771	4.767	-0.08
25	5.963	5.956	-0.12
30	7.156	7.144	-0.17
35	8.349	8.329	-0.24
40	9.542	9.513	-0.30

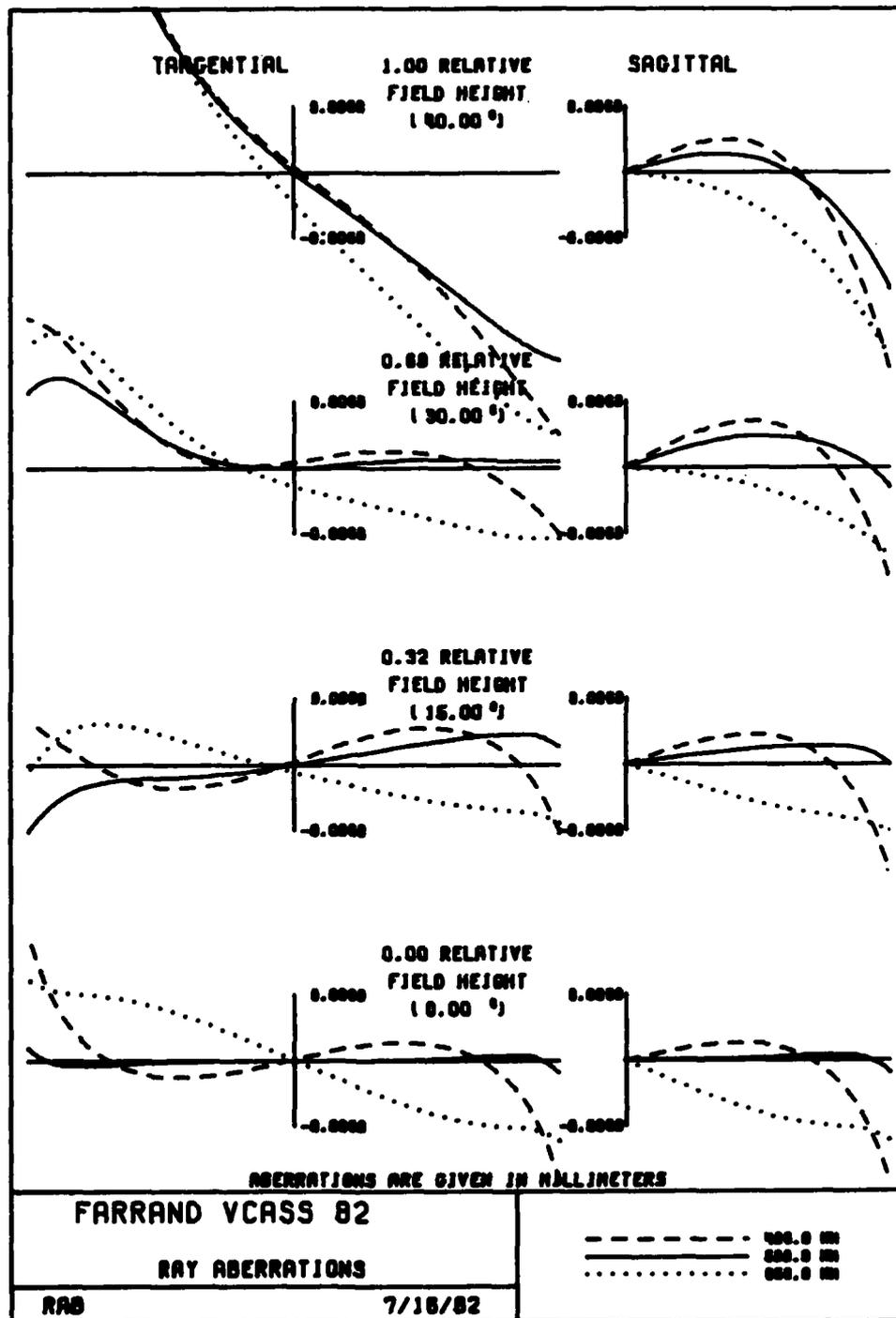


Figure 15. Raytrace analysis for full 15-mm pupil.

marked to show the magnitude of ± 0.5 mrad of equivalent angular aberration. Figure 15 suggests that optical performance is starting to falter seriously at 40° . But since up to 50% vignetting has been allowed, this can be used beneficially to some degree.

These raytraces are for a 15-mm diameter pupil. However, the iris diameter or entrance pupil of the eye is about 6 mm diameter. Therefore, at any given time, the eye sees only $6 \text{ mm}/15 \text{ mm} = 40\%$ of the ray fans.

4.3.2. Wave Aberration

An alternative method of analyzing images is with wave aberration or optical path difference (OPD). This method is particularly meaningful when the computation of MTF is required, since MTF correlates more directly with wave aberration. Because of the tangential flare observed in Figure 15, part of the aperture was deliberately vignetted, and Figure 16 was computed for a full 15-mm pupil. As may be seen, there is a serious amount of defocus in the tangential plane at full field. As our eye moves to one side or the other of center, a 6-mm pupil will interpret this mainly as distortion that moves with the head. The effect is no longer serious at 30° and less.

Next, let us reduce the pupil to just 6-mm diameter and expand the plot, as shown in Figure 17. The eye is perfectly centered in the display, and except at 40° , there is close to a quarterwave monochromatic quality. The image on axis is so well corrected that it does not show up on this plot scale. When the amount of wave aberration is around a quarterwave, the MTF is very high. When the wave aberration reaches a value of only a few waves, the MTF is exceedingly low.

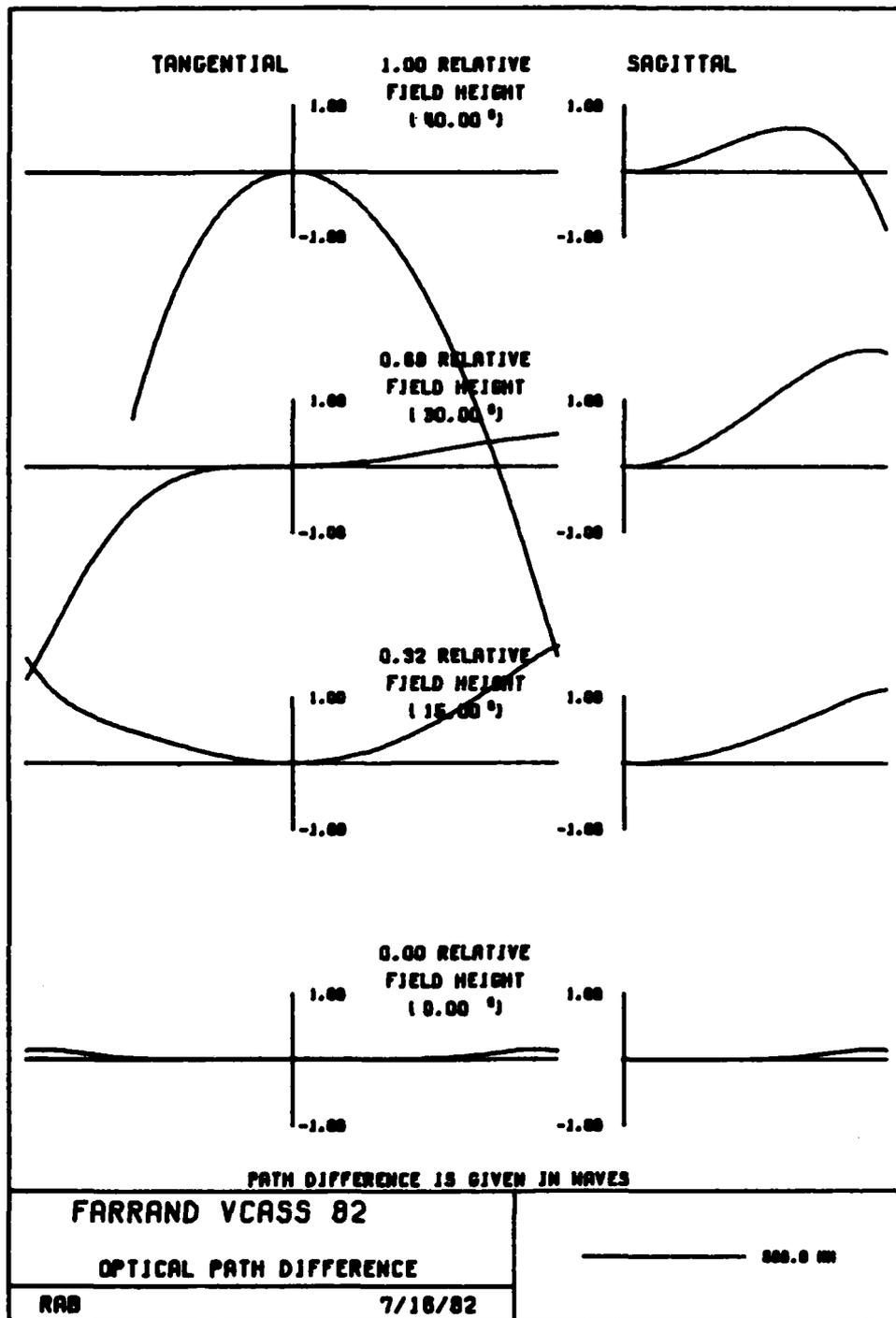


Figure 16. Optical path difference analysis for full 15-mm pupil.

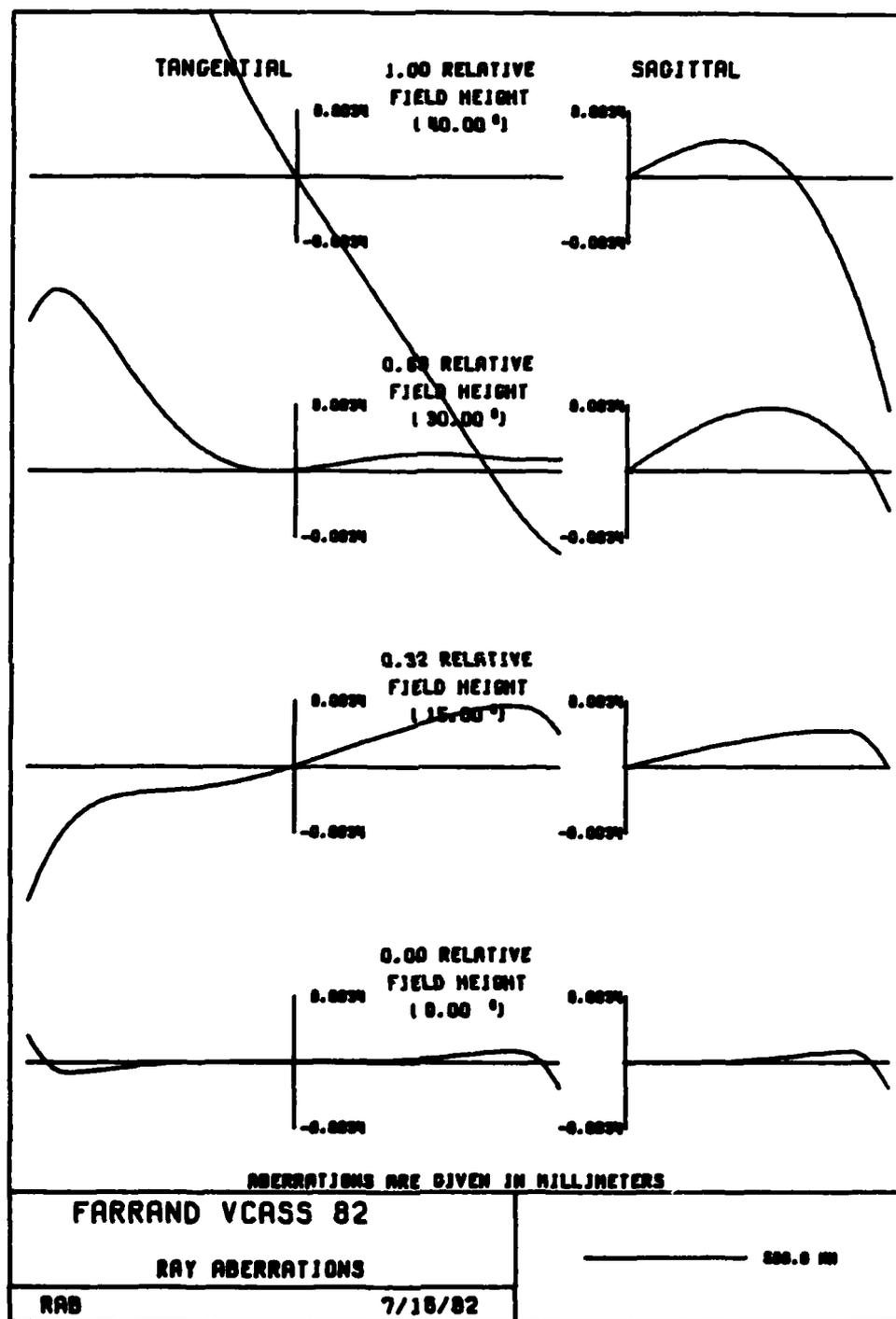


Figure 17. Ray analysis for a 6-mm diameter pupil.

Now, let us decenter the eye by 4.5 mm, which is equivalent to shifting the eye until it just starts to leave the exit pupil of the display. Figure 18 shows the computed OPD for this decentered 6-mm pupil at 30° upper and lower fields, and on the center. As is to be expected, part of the field is better than the other, and in this case the problem is that one side is defocused a little. Nonetheless, the level of aberration is low enough that the MTF can be computed using diffraction-based methods rather than geometrical MTF. When the wave aberration exceeds approximately two waves, techniques for computing diffraction MTF can become invalid, and is one reason for interpreting the design with wave aberration.

4.3.3. MTF

MTF, sine wave response, or contrast versus frequency, are means for comparing and integrating the response of the optics with that of the CRT.

The original MTF performance specification provided a curve of MTF out to 800 cycles per raster width, for a 14.8-mm width. This is the same as 54 line pairs per millimeter, the more common method of defining spatial frequency. The Farrand design now uses a clipped round format so that its raster is closer to 19 mm, and in principle the limiting useful MTF would be at $800/19 = 42$ lp/mm.

The diffraction monochromatic and polychromatic MTF for a centered 6-mm pupil diameter has been calculated with the results shown in Figures 19 and 20. The color is so well corrected that there is very little difference between them.

The monochromatic MTF for the 6-mm pupil decentered by 4.5 mm has also been computed with the results shown in Figure 21, where it has been

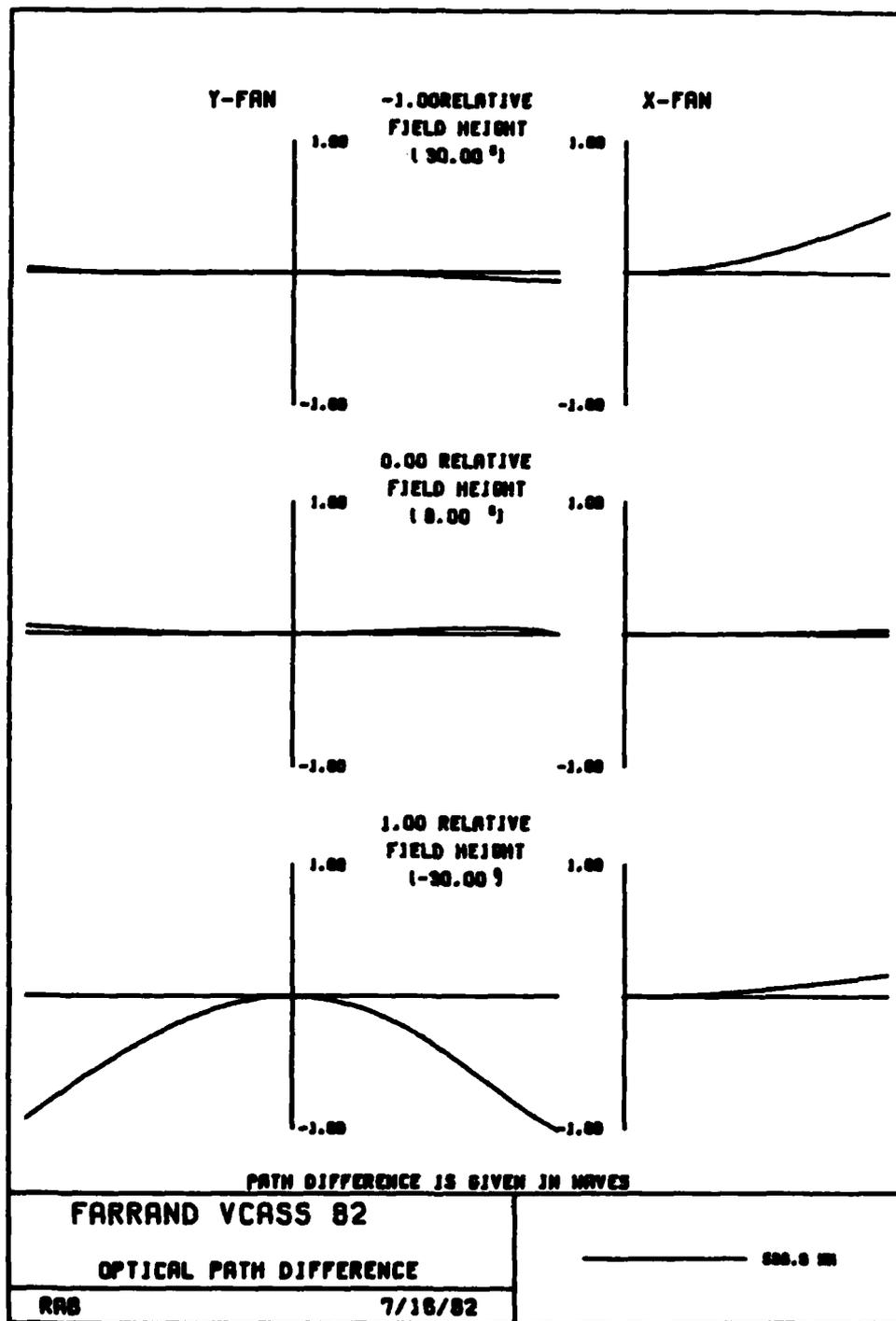


Figure 18. OPD analysis for 6-mm diameter pupil decentered 4.5 mm.

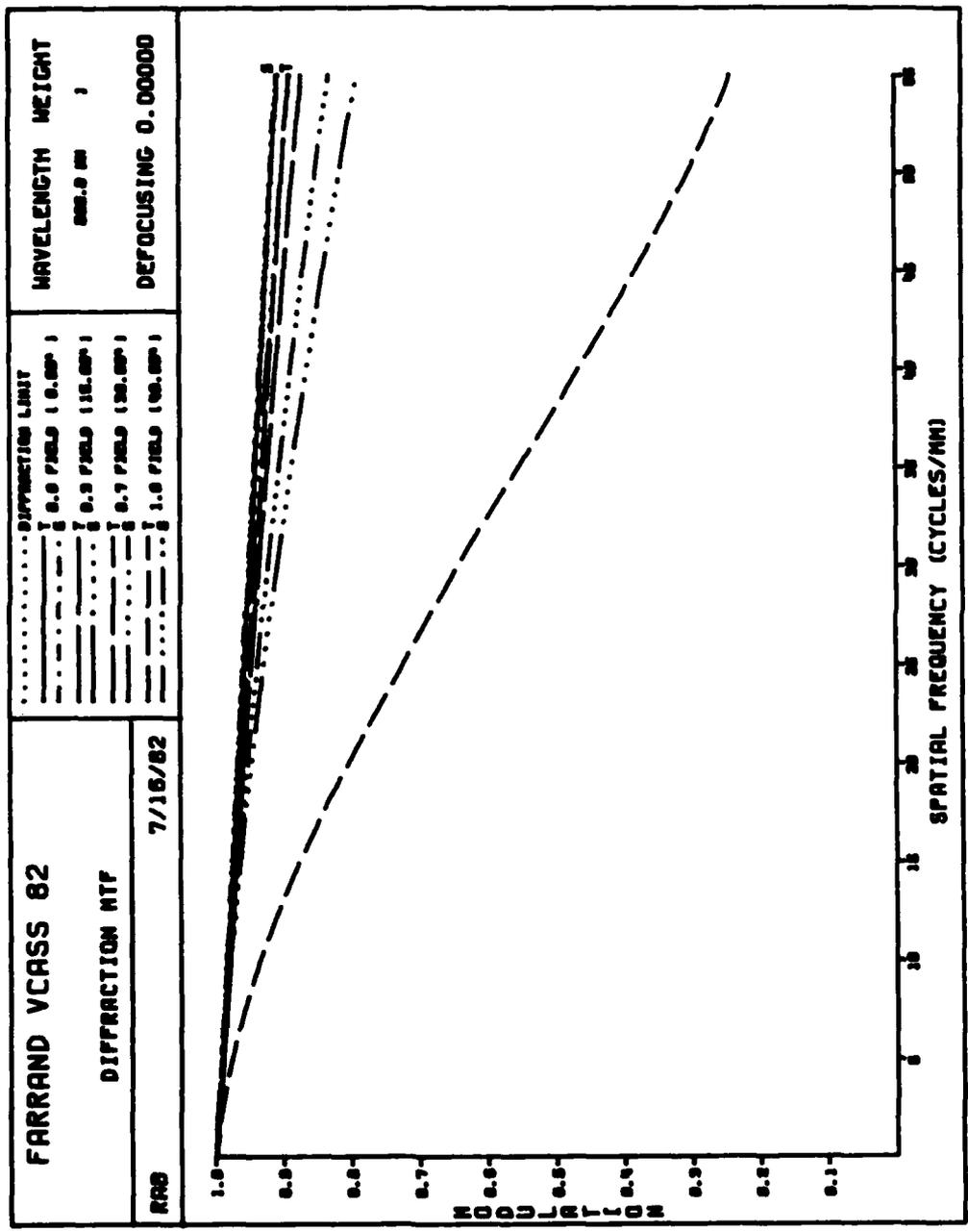


Figure 19. Diffraction MTF for monochromatic light (6-mm diameter centered pupil).

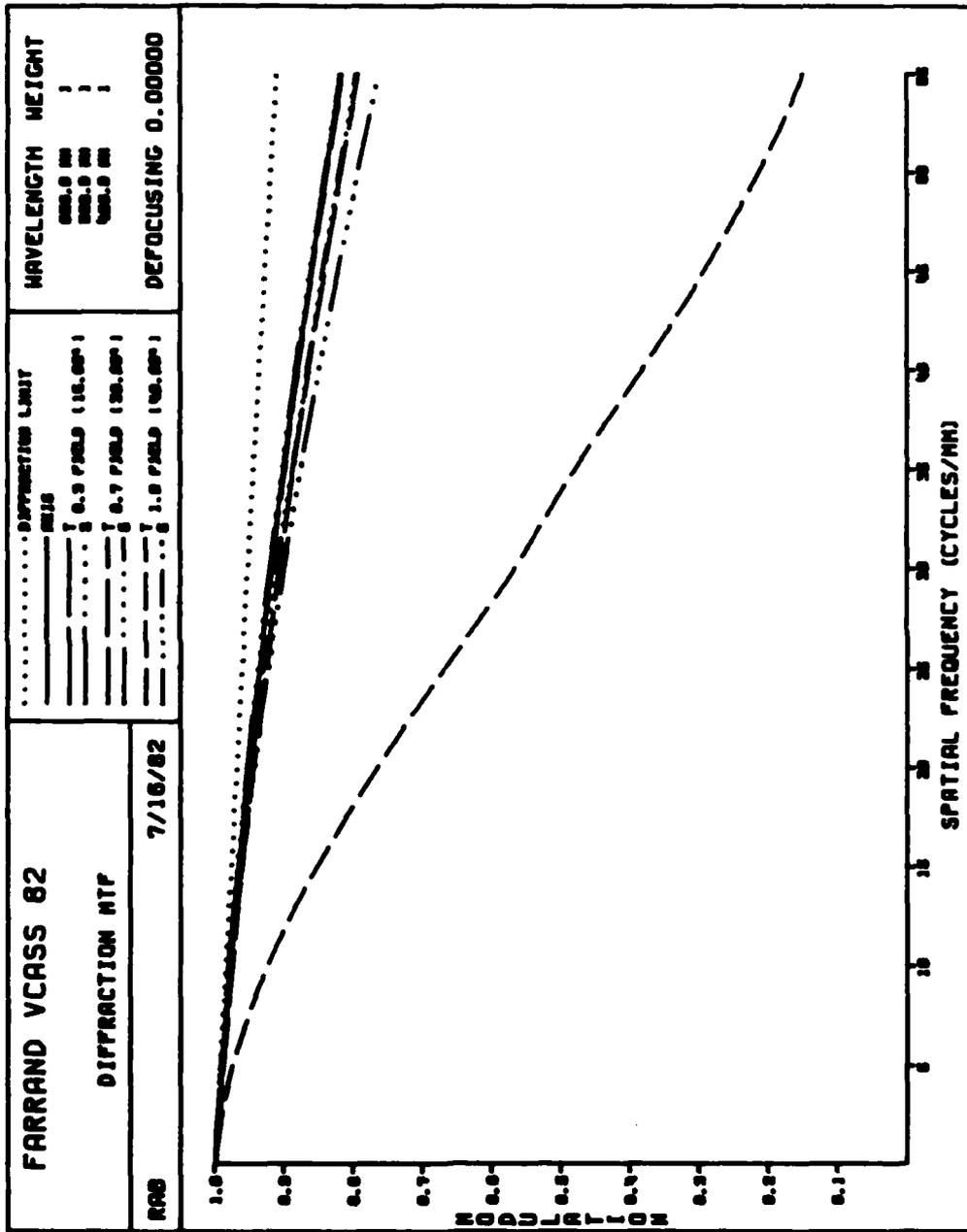


Figure 20. Diffraction MTF for white light (6-mm diameter centered pupil).

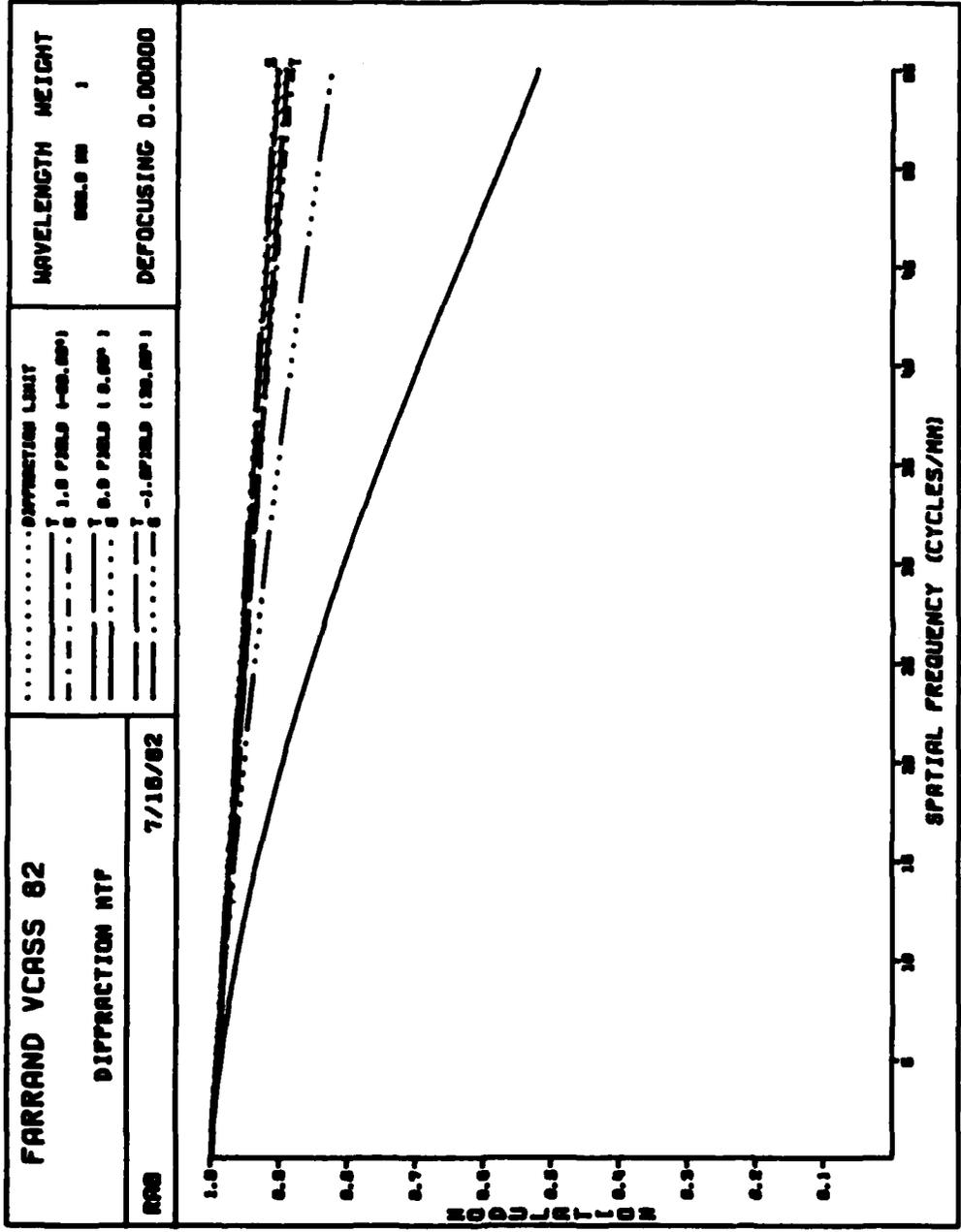


Figure 21. Diffraction MTF for white light for decentered 6-mm pupil.

analyzed, only in the plane of decentration at $\pm 30^\circ$. Generally speaking, most of the critical performance with the display will probably occur in the central field of view, but the loss in performance at 40° is noticeable.

Now, to see whether the design meets the original MTF specification, these computed MTFs must be reconverted into the original form, which is cycles per raster width. This has been done and is represented in Figures 22, 23, and 24. The theoretical performance easily exceeds the specification on-axis and at $\pm 30^\circ$, but just barely at 800 cycles at 40° . However, at lower spatial frequencies, it greatly exceeds the specification even at 40° . Since 800 cycles per raster width (for a width of 14.8 mm) is equivalent to more than 1600 TV lines per raster width, the optics should be significantly superior to the MTF of the CRT.

Some allowance must be made for fabrication errors, but when the difference between computed and specified MTF is as large as occurs with this design, there is generally no difficulty building the optics.

4.4. Transmission

Light transmission, as estimated by Farrand, is shown in Figure 25. Early work presumed a beam combiner with 70% reflectance and 30% transmittance, which led to a CRT path transmission of 0.6% and a see-through transmission of 2.3%. Viewing with the prototype display reveals that the CRT images are bright enough to work in a darkened simulator environment. Improvements with special coatings are unlikely to improve these values by more than a factor of two for the CRT, or more than a factor of three for the see-through condition.

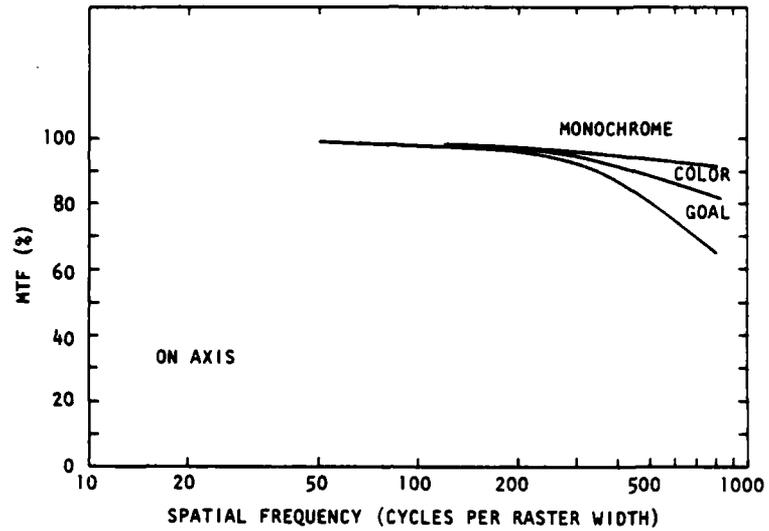


Figure 22. On-axis MTF (optics alone).

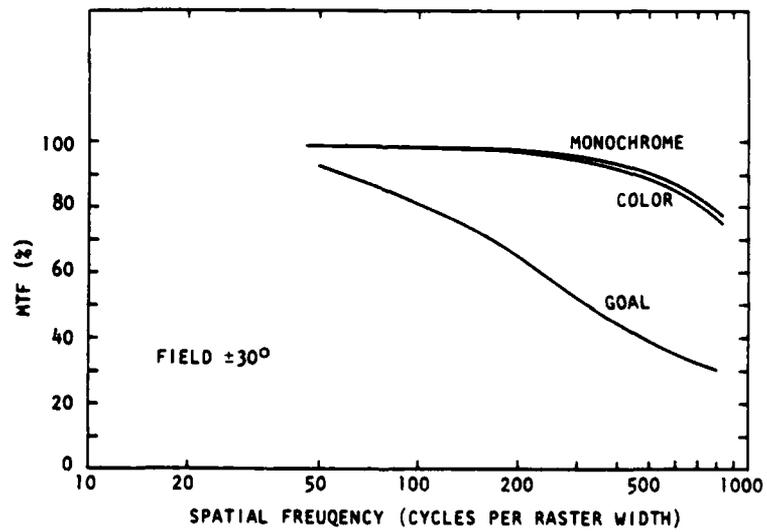


Figure 23. MTF at top and bottom of image.

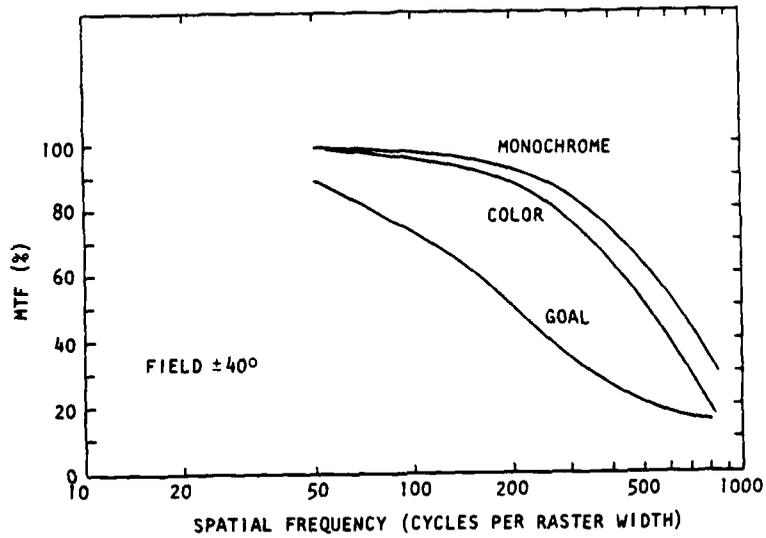


Figure 24. MTF at the sides of image.

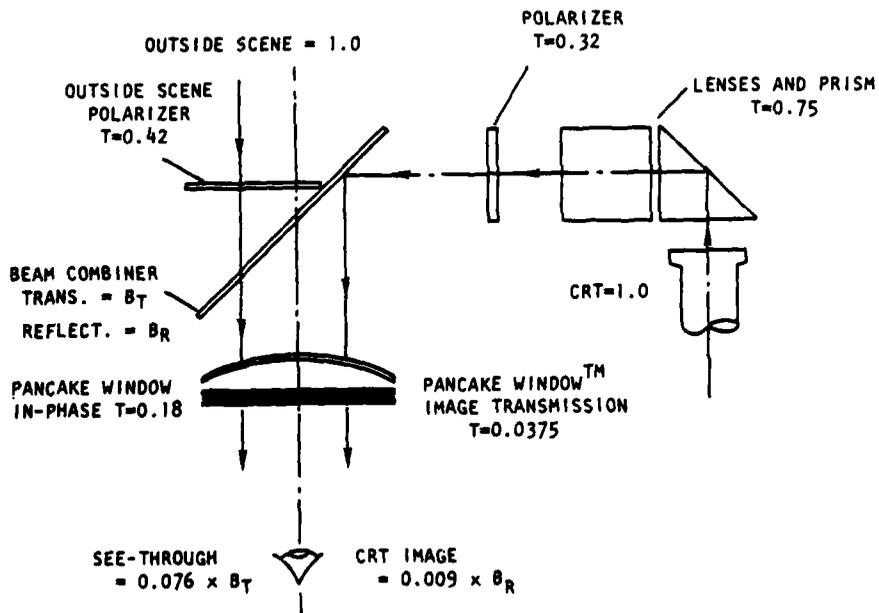


Figure 25. Light loss in the Farrand VCASS.

4.5. Ghost Images

Polarizers and synthetic quarterwave plates are not perfect, and unwanted light does penetrate the Pancake WindowTM. Figure 26 shows what Farrand considers to be the principal light paths, of which only the operating image is desired. Based on their experience with large Pancake WindowsTM used as simple magnifiers of large CRTs, Farrand believes the intensity of these ghosts will be from 1% to 2% as bright as the wanted image. However, since we are "seeing" a small exit pupil rather than a large CRT, as in the normal application of the Pancake WindowTM, the concentration of light into a small area may make that 1% to 2% more apparent. Where the display image is 80° on a side, Farrand calculates that all three of the unwanted sources subtend less than 12.5°, and are similar in angular size.

Additional ghosts of the ordinary kind can occur within any complex lens system. These can be minimized with enhanced antireflection coatings if such ghosts prove to be a problem. Early observations with the prototype optical system have disclosed ghost problems with an opaque combiner.

Observations have not been made with the prototype in other than subdued light, so there are no observations regarding reflections of the eyes or other details on the face or helmet and display apparatus.

4.6. Mechanical Factors

4.6.1. Visual Obstructions

The angular subtense of optical components in the field of view must be no less than the angular field of view measured from each exit pupil, so

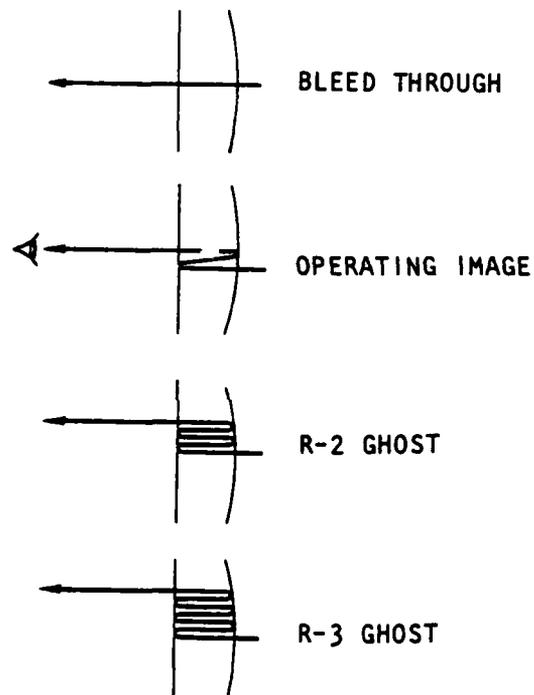


Figure 26. Light transmission in the Pancake WindowTM.

it is difficult to achieve large overlap of the separate images. To obtain 60°, Farrand sacrificed part of the inboard exit pupils of both halves of the display. They report that the inboard horizontal exit pupil is reduced to 5 mm at 40°. Since this vignetting occurs on the outboard side of the pupil, the viewer would have to move his head forward to center his eye on that pupil. Since this is not possible, except as a compromise when originally adjusting the display, it is conceivable in practice that the inboard fields of view will actually be clipped by a few degrees, and at least give an impression of faintness. This occurs regardless of the IPD setting or the overlap of the fields, although by initially restricting the minimum IPD and the maximum overlap, the vignetting could have been reduced as a design compromise.

A more significant obstruction is caused by the mounting fixtures of the optics. The see-through field of view (outside world as seen through the display) is smaller than the CRT field of view. There are no calculations on the difference, nor is it clear whether this problem can be readily alleviated in a modified design.

4.6.2. Materials

The use of metal is restricted because of electromagnetic interference with helmet position sensors. The entire display, except for the CRTs, is made from plastic materials. Machined parts were used for the prototypes.

4.6.3. Adjustments

There are no user adjustments for focus, so if the user wears glasses, he should wear them with the display. As we explained earlier, a dual eye display should ideally be set at zero diopters otherwise parallax exists

and dynamic distortions occur as the eyes pivot in their sockets, and as the head shifts in the helmet.

The IPD can be adjusted from 62 to 72 mm. Since the viewer will usually know his IPD, this can be set before putting on the helmet. Because of the large 15-mm exit pupils, the tolerance on IPD can be several millimeters.

The image overlap can be adjusted from 20° to 60°, and the computer-generated imagery must be changed to compensate for the perspective distortion resulting from different degrees of overlap.

Image alignment would presumably be accomplished before supplying the display to the user; however, the CRTs are reachable by hand and could, if necessary, be rotated slightly to correct for minor errors. There are several ways to collimate the two images; one way is to have centering adjustment on one of the two CRTs. It is unclear as of this writing what procedure will be used to optically align the display. Nominal centering of the display's exit pupil can be accomplished with different liner thicknesses at the top of the helmet.

Brightness disparity between the two displays will be controlled electronically, and image blending will be accomplished by means whose description is beyond the scope of this report.

4.6.4. Weight and Center of Gravity (CG)

The combined weight of the helmet and HMD, as calculated by Farrand, is 2.3 kg. The CG of the helmet and display is at $\bar{X} = 11.63$ cm, $\bar{Y} = -3$ cm, referenced to the helmet centerline. Since the display is symmetrical, \bar{Z} is 0 cm.

Approximately 0.9 kg of the total weight is due to glass components, 0.68 kg to the helmet. Therefore, if weight reduction is to be made, it most likely must be made in the size, quantity, and materials from which the optics are designed.

5. ACCEPTANCE TEST PLAN AND TEST DATA

There is no written information from Farrand or from the Government on how the two separate halves of the display are aligned relative to each other. It is known, however, that the electronic system is capable of generating a variety of image pairs that should match when the optics are properly adjusted. Ordinarily, a binocular is tested against a single lens collimator large enough to encompass both exit pupils at once. This enables the collimation errors to be quantified. Therefore, a test method based on the testing of conventional binoculars should be applicable to the certification of VCASS.

The question of optical testing of each of the separate displays is addressed in the next paragraphs.

5.1. Exit Pupil, Eye Relief, and Vignetting

These parameters are not sensitive to fabrication tolerances, and therefore the tests need be only rudimentary to assure the absence of mistakes as opposed to errors.

The method used by Farrand consists of placing a 15-mm diameter aperture 39.5 mm behind the rear of the Pancake WindowTM, and then putting a 19-mm diameter reticle on a dummy curved fiberoptic faceplate. Lines corresponding to a 60° tall field are marked on the reticle, which is then back illuminated with green light.

Farrand observed that the whole input reticle area is visible over the whole area of the exit pupil except for the inboard area where it is deliberately cut off.

This is not a rigorous test because focal length has not been tested at this point. If the focal length, as will be determined from distortion-

type measurements, is in error, then the results from the present test are questionable. However, as explained, the main usefulness of this test is to look for mistakes rather than to guard against accumulated tolerances.

Assuming the test is critical, tolerances should be set, and when vignetting does occur, it should be quantified. One must be careful too that unnecessary tolerances do not force the engineers to bias the apertures of the lenses, which may lead to unsatisfactory resolution and MTF.

Farrand built three prototypes. This test was performed on all three and the 15-mm pupil at 39.9 mm was filled with no vignetting except at the inboard cut.

5.2. Transmission

A rule of photometry is that the brightness of the exit pupil is the same as the brightness of the source, less the transmission factor. Therefore, if separate measurements are made of the source and the exit pupil, the transmission is obtained as the ratio of these. Additionally, if the field of view of the light measurement device (photometer) is restricted, we can measure transmission as a function of field angle.

First, the transmission from the CRT to the eye must be measured, and then the transmission from the outside world, through the display, to the eye. For the latter, one could simply put a piece of opal glass, back-illuminated, in front of the display and take measurements with and without the display in place. It is more awkward to measure the CRT transmission.

Farrand used two methods. In the first, they removed the CRT and put

an unspecified light source with opal diffuser up to the relay* and took readings with a "Spectra Photometer" focussed on the exit pupil. They then put a light source in front of the display and took the same kind of readings to determine see-through transmission.

In the second method, they placed a 10-mm diameter aperture on the Spectra Photometer objective lens and took similar measurements looking ahead and at $\pm 35^\circ$.

The second method is probably more meaningful than the first and the results from this method are quoted here.

For three prototypes tested without the beam combiner, the CRT transmission on-axis ranged from 0.97 to 1.07, indicating good consistency. At $\pm 35^\circ$, there is a troublesome set of measurements ranging from 0.68 to 0.9, suggesting that possibly mechanical revisions may have been made or that the equipment may have been misaligned when tested. Testing with a full 15-mm pupil will provide more information about the pupil aberration, but it is not clear what should be done with the data. Measurements made with the small 10-mm aperture are more appropriate to vision with the eyes.

The see-through transmission measured without the beam combiner ranged around 11% to 12% and was not measured as a function of angle.

(Note that in principle it does not matter where the light source is positioned as long as it is in front of the element whose transmission is to be measured. In practice stray light can give mistaken readings.)

5.3. Field of View and Optical Distortion

The purpose of this test is to measure the amount of distortion across the field and to verify the field of view. The test is also used to obtain enough data points to find the constants for the electronic correction of fisheye distortion by means of a cubic or higher order equation. Indeed, the linear term of such a formula derives from or leads to the conventional focal length.

Farrand mounts the display on a rotary table that turns about the center of the exit pupil. The display can be turned to permit lateral and vertical measurements of its field of view. They put a reticle on a dummy fiberoptic plate at the focus of the relay, and observe the image with a fixed observing telescope, that also has an error-measuring reticle. Their fiberoptic reticle is calibrated, and they use a calibration table to interpret their measurements; however, these are conveniences and not really necessary. They compare the angles at which lines on the reticle are projected; the table permits them to determine the percent accuracy with which the optics match the design.

Farrand's measurements on the three prototype displays show agreement to within about 0.5. However, this is somewhat misleading in that a given level of precision leads to higher percentages for small field angles than it does for large field angles. The idea of using a calibrated set of lines is a convenience, but it should be remembered that a better fit to the data can be obtained simply by changing the focal length used to calculate the nominal data. That is, a "calibrated focal length" is used for best fit.

Farrand finds the inboard field of view restricted to just 36° instead of 40° , although the inboard clipping was said in the design section to yield a 5-mm pupil at the inboard 40° .

The vertical field exceeds $\pm 40^\circ$, although it need cover only $\pm 30^\circ$.

5.4. Field Curvature and Astigmatism

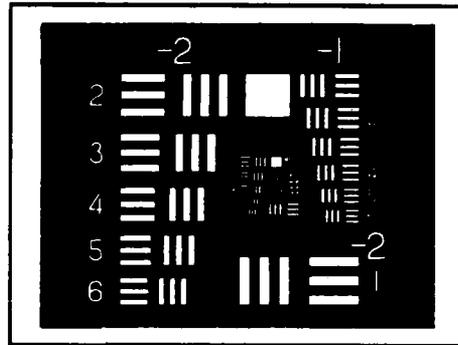
The purpose of this test is to measure the angular field curvature and angular astigmatism of the display. The test is simple, requiring a diopterscope and a resolution chart with horizontal and vertical bars. The same chart used to measure "resolution" can be used.

Farrand suggests two methods. The first is to put a pattern on the flat side of a curved fiberoptic bundle. The other is to shape a curved reticle and to put it at the focal plane. It would be easier to use the fiberoptic method with a high-resolution faceplate with $3 \mu\text{m}$ fibers.

A test pattern is shown in Figure 27 and is explained with text provided by one manufacturer, the Rolyn Company. Table 5 aids in using the pattern.

The faceplate is centered, focussed, and squared-on as well as possible. Any tilt will cause differences in the left, right, up, and down readings. Focus error is observed as a constant bias in all readings and can be subtracted if the tester is aware of its presence. Indeed, a constant diopter value can be deliberately added to each reading to see the effect of compromising focus.

The Farrand measurements are for the axis, and lateral field angles of $\pm 38^\circ$ and vertical field angles of $\pm 30^\circ$. Errors on the order of 0.5 diopter were measured on the three prototypes, which is within acceptable bounds. We suspect from some of the measurements that the test pattern



USAF 1951 TARGET

This is the standard "Air Force" target described in Military Standard 150-A paragraph 5.1.1.7.

An Element consists of two Patterns at right angles to each other. Each Pattern consists of three lines and two spaces of equal width and length five times the width.

The change in pattern size progresses geometrically as the sixth root of two or conversely the lines per millimeter count doubles with every sixth element and these groups of six elements are referred to as a Group and assigned a group number which tells the power of 2 to which the first element in the group was raised to determine the number of lines per millimeter in that element. The zero group then has one cycle per millimeter.

The chart below enables the use of the target without computations.

Figure 27. USAF 1951 target.

Table 5. Interpretation of Pattern Resolution.

		GROUP NUMBER									
Element No.	-2	-1	0	1	2	3	4	5	6	7	
1	0.250	0.500	1.00	2.00	4.00	8.00	16.00	32.0	64.0	128.0	
2	.200	.561	1.12	2.24	4.48	8.96	17.95	36.0	71.8	144.0	
3	.315	.630	1.26	2.52	5.04	10.1	20.16	40.3	80.6	161.0	
4	.353	.707	1.41	2.83	5.66	11.3	22.62	45.3	90.5	181.0	
5	.397	.793	1.59	3.17	6.35	12.7	25.39	50.8	102.0	203.0	
6	.445	.891	1.78	3.56	7.13	14.3	28.51	57.0	114.0	228.0	

was probably not squared-on in every case and the optics are probably better than the measurements indicate. On the other hand, the tangential focus, according to raytrace analysis, should deteriorate rapidly at 40°.

5.5. Resolution

Presumably the same concave-plano dummy high-resolution fiberoptic faceplate will be used for this test as for the astigmatism and field curvature test. Referring to Figure 27 and Table 5, we can examine the image through the diopterscope to see what pattern is just resolvable for both horizontal and vertical bars.

For two of the prototypes, Farrand reports a blanket 7-2 pattern, which from Table 5 is found to mean 144 lines/mm, which is about three times finer than what is needed to resolve with the complete display. The third display resolves groups ranging from 6-5 to 7-4, which means from 102 to 181 lines/mm. Despite the emphasis on modern methods of image analysis, the use of the USAF 1951 resolution target remains extremely useful, and will indicate when an optical problem exists.

5.6. MTF

Modulation transfer function, technically the modulus of the optical transfer function, theoretically holds far more information than "resolution," but requires a high degree of expertise in taking measurements. The MTF is exceedingly sensitive to focus errors and tilts of the image.

Farrand used the Ealing Company's EROS 200 MTF analyzer and slit, an indexing table to turn the display to the desired field angle, and a 6-mm aperture at the exit pupil of the display. They took measurements in 10

lp/mm steps up to 50 lp/mm, which correspond to the design requirement.

The measured MTF data for the three prototypes show considerable variability, suggesting more trouble with focusing the optics than with the quality of the optics themselves. However, it is apparent that with readings almost always above 50 MTF at 50 line pairs/mm, the optics in all three cases are excellent.

These MTFs are for a centered 6-mm pupil; it would be interesting to measure the MTF for the pupil decentered a few millimeters to simulate a slightly misaligned head.

6. FEASIBILITY OF DESIGN ENHANCEMENT

6.1. Exit Pupil

Provided the exit pupil is allowed to vignette at the larger fields of view, it can be enlarged in a design of this kind simply by making the relay optics larger in diameter. However, the present design would need to be recomputed because some of the lenses are so thin that they will run out of edge thickness if the aperture is increased very much.

Practical complications having to do with folding the beam for larger relay optics will occur, and the weight of the relay optics will increase faster than the square of the increase in pupil diameter. However, the present state of on-axis correction is flawless in the Farrand design, which indicates a larger pupil can be obtained.

6.2. Field of View

There are two restrictions upon the field of view. First, there is the inboard interference of the two Pancake WindowsTM. Second, if the display has too wide an angle, the outboard side of the field requires an infinitely long beam combiner. This occurs with a total field around 90°, so the field of view cannot be substantially increased without radical alteration of the boundary constraints. For example, the requirement for see-through transmission inhibits the design of the CRT display. If it was not necessary to see through at all, the beam combiner could be eliminated and projection could be straight in through the conventional Pancake WindowTM simulator. Another design might obscure the upper half of the see-through field and find a new input in place of the present beam combiner.

6.3. Overlap of Visual Fields in Panorama

Presently the display permits a 60° overlap (10° tilt for each half), but it is still necessary to vignette the inboard fields. Overlap can be increased by moving the windows closer to the eye; however, the distance to the eye is already 39.5 mm. If the user wants to continue to wear glasses, changes in the design will be affected by practical limitations. It seems doubtful that the display, in its present form, can have its fields overlapped much more than they already are.

6.4. Color Correction

The Farrand design is well achromatized, but it has 11 lens elements in its relay, adding to weight and absorption. If color correction is abandoned, aspheric lenses may be used to achieve the same level of quality with 1/3 to 1/2 as many elements, and with a great reduction in weight. The use of aspherics and fiber optics should permit the relay to correct for the $f-\theta$ mapping of the present design, resulting in more convenient computer-generated imagery.

Lateral color should be corrected by symmetrical and proportioned lens configurations.

The feasibility of extremely simple monochromatic lenses for a VCASS has been shown on page 11 of our earlier report, AFAMRL-TR-81-133, "Design of a Catadioptric VCASS Helmet-Mounted Display."

6.5. Resolution and MTF

The present Farrand design has an abundance of both resolution and MTF, which can be sacrificed for the sake of simplifying the present design.

On the other hand, when an optical design is unusually good, it implies that the field and exit pupil can be increased by reducing the MTF or resolution.

There seems to be no need to enhance the MTF or resolution of the present design. There is no use to having an optical system with finite MTF beyond the cutoff frequency of the image generator. If we did want to enhance the MTF of the present design, it would be difficult to do so.

6.6. Anaglyphic and Polarizing Displays

While it is probably possible to extend the specifications of the existing design, it might be more beneficial to spend some time exploring new ideas.

Along these lines, consider how stereoscopic motion pictures can be obtained from a single screen by using color or polarization to separate the images when they reach the eyes.

Consider also that the limits on image overlap are set by having to think in terms of a single, rotationally symmetrical optical design for each half of the display. What can we do with deliberately off-axis optics, including holographic elements? There may yet be much to learn in the development of wide angle helmet-worn simulators.

APPENDIX

FARRAND PROTOTYPE CONSTRUCTION DRAWINGS

REVISIONS		DATE	APPROVED
DESCRIPTION		5-27-74	
LTR	ISSUED		

NOTES: UNLESS OTHERWISE INDICATED
 1. ALL DIMENSIONS IN MILLIMETERS
 2. SURF. FIT 1. IRREG. RING . IRREG. RING.
 2. RINGS . IRREG. RING.
 3. SURF. QUAL 1. 80/50 2. 80/50
 4. EDGE THICK. RUNOUT .02 AT 38 MM DIA.
 5. BEVEL EDGES .5 MM. MAX.
 6. ANTI REFLECTION COATING ON SURF. 45...
 7. EFL = 622.76 BFL = 620.45 FFL =
 8. FA-1 = 3B FA-2 = 3B
 9. SAC TABLE SURFACE 1 ON SHEET 2

ASPHERIC CONVEX R = 307.69
 $Z = (CY^2 / (1 + \sqrt{1 - C^2 Y^2})) + \Delta y^2 . c y^6$
 AXIAL RADIUS = +307.69
 C = 1/R
 $\Delta = -3.54 \times 10^{-6}$
 $\epsilon = -3.19 \times 10^{-10}$
 (SEE NOTE 9)

UNLESS OTHERWISE SPECIFIED REMOVE ALL SQUARE CORNER SHARP EDGES DIMENSIONS ARE IN INCHES AND DECIMALS ARE:	CONTRACT NO.	DRAWN	1-2-79
FRACTIONS DECIMALS ANGLES		CHECKED	MS 9/20/79
		FOR THE	MS 7/15/79
		APPROVED	
		RELEASED BY	

ITEM	MERT ASSY	REQD
APPLICATION		

FARRAND OPTICAL CO., INC. 117 WALL ST. VALHALLA, N. Y. 10595	
LENS 1 RELAY SYSTEM	
SIZE	CODE IDENT NO
A	21587
SCALE	DRAWING NO
FULL	151275
SHEET 1	OF 2

REVISIONS		DESCRIPTION	DATE	APPROVED
LTR	ISSUED			
	Y	6.00000	0.9539028	Z
	Y	6.25000	0.9580625	0.1581171
	Y	6.50000	0.9622207	0.1597311
	Y	6.75000	0.9663690	0.1631539
	Y	7.00000	0.9705082	0.1663684
	Y	7.25000	0.9746474	0.1695571
	Y	7.50000	0.9787865	0.1721020
	Y	7.75000	0.9829257	0.1745847
	Y	8.00000	0.9870649	0.1767865
	Y	8.25000	0.9912041	0.1786883
	Y	8.50000	0.9953433	0.1802705
	Y	8.75000	0.9994825	0.1815130
	Y	9.00000	1.0036217	0.1823954
	Y	9.25000	1.0077609	0.1828970
	Y	9.50000	1.0118994	0.1829964
	Y	9.75000	1.0160379	0.1826720
	Y	10.00000	1.0201764	0.1819016
	Y	10.25000	1.0243149	0.1806627
	Y	10.50000	1.0284534	0.1789322
	Y	10.75000	1.0325919	0.1766868
	Y	11.00000	1.0367304	0.1729026
	Y	11.25000	1.0408689	0.1705551
	Y	11.50000	1.0450074	0.1666197
	Y	11.75000	1.0491459	0.1620711
	Y	12.00000	1.0532844	0.1568635
	Y	12.25000	1.0574229	0.1510308
	Y	12.50000	1.0615614	0.1444863
	Y	12.75000	1.0656999	
	Y	13.00000	1.0698384	
	Y	13.25000	1.0739769	
	Y	13.50000	1.0781154	
	Y	13.75000	1.0822539	
	Y	14.00000	1.0863924	
	Y	14.25000	1.0905309	
	Y	14.50000	1.0946694	
	Y	14.75000	1.0988079	
	Y	15.00000	1.1029464	
	Y	15.25000	1.1070849	
	Y	15.50000	1.1112234	
	Y	15.75000	1.1153619	
	Y	16.00000	1.1195004	
	Y	16.25000	1.1236389	
	Y	16.50000	1.1277774	
	Y	16.75000	1.1319159	
	Y	17.00000	1.1360544	
	Y	17.25000	1.1401929	
	Y	17.50000	1.1443314	
	Y	17.75000	1.1484699	
	Y	18.00000	1.1526084	
	Y	18.25000	1.1567469	
	Y	18.50000	1.1608854	
	Y	18.75000	1.1650239	
	Y	19.00000	1.1691624	
	Y	19.25000	1.1733009	
	Y	19.50000	1.1774394	
	Y	19.75000	1.1815779	
	Y	20.00000	1.1857164	
	Y	20.25000	1.1898549	
	Y	20.50000	1.1939934	
	Y	20.75000	1.1981319	
	Y	21.00000	1.2022704	
	Y	21.25000	1.2064089	
	Y	21.50000	1.2105474	
	Y	21.75000	1.2146859	
	Y	22.00000	1.2188244	
	Y	22.25000	1.2229629	
	Y	22.50000	1.2271014	
	Y	22.75000	1.2312399	
	Y	23.00000	1.2353784	
	Y	23.25000	1.2395169	
	Y	23.50000	1.2436554	
	Y	23.75000	1.2477939	
	Y	24.00000	1.2519324	
	Y	24.25000	1.2560709	
	Y	24.50000	1.2602094	
	Y	24.75000	1.2643479	
	Y	25.00000	1.2684864	
	Y	25.25000	1.2726249	
	Y	25.50000	1.2767634	
	Y	25.75000	1.2809019	
	Y	26.00000	1.2850404	
	Y	26.25000	1.2891789	
	Y	26.50000	1.2933174	
	Y	26.75000	1.2974559	
	Y	27.00000	1.3015944	
	Y	27.25000	1.3057329	
	Y	27.50000	1.3098714	
	Y	27.75000	1.3140099	
	Y	28.00000	1.3181484	
	Y	28.25000	1.3222869	
	Y	28.50000	1.3264254	
	Y	28.75000	1.3305639	
	Y	29.00000	1.3347024	
	Y	29.25000	1.3388409	
	Y	29.50000	1.3429794	
	Y	29.75000	1.3471179	
	Y	30.00000	1.3512564	
	Y	30.25000	1.3553949	
	Y	30.50000	1.3595334	
	Y	30.75000	1.3636719	
	Y	31.00000	1.3678104	
	Y	31.25000	1.3719489	
	Y	31.50000	1.3760874	
	Y	31.75000	1.3802259	
	Y	32.00000	1.3843644	
	Y	32.25000	1.3885029	
	Y	32.50000	1.3926414	
	Y	32.75000	1.3967799	
	Y	33.00000	1.4009184	
	Y	33.25000	1.4050569	
	Y	33.50000	1.4091954	
	Y	33.75000	1.4133339	
	Y	34.00000	1.4174724	
	Y	34.25000	1.4216109	
	Y	34.50000	1.4257494	
	Y	34.75000	1.4298879	
	Y	35.00000	1.4340264	
	Y	35.25000	1.4381649	
	Y	35.50000	1.4423034	
	Y	35.75000	1.4464419	
	Y	36.00000	1.4505804	
	Y	36.25000	1.4547189	
	Y	36.50000	1.4588574	
	Y	36.75000	1.4629959	
	Y	37.00000	1.4671344	
	Y	37.25000	1.4712729	
	Y	37.50000	1.4754114	
	Y	37.75000	1.4795499	
	Y	38.00000	1.4836884	
	Y	38.25000	1.4878269	
	Y	38.50000	1.4919654	
	Y	38.75000	1.4961039	
	Y	39.00000	1.5002424	
	Y	39.25000	1.5043809	
	Y	39.50000	1.5085194	
	Y	39.75000	1.5126579	
	Y	40.00000	1.5167964	
	Y	40.25000	1.5209349	
	Y	40.50000	1.5250734	
	Y	40.75000	1.5292119	
	Y	41.00000	1.5333504	
	Y	41.25000	1.5374889	
	Y	41.50000	1.5416274	
	Y	41.75000	1.5457659	
	Y	42.00000	1.5499044	
	Y	42.25000	1.5540429	
	Y	42.50000	1.5581814	
	Y	42.75000	1.5623199	
	Y	43.00000	1.5664584	
	Y	43.25000	1.5705969	
	Y	43.50000	1.5747354	
	Y	43.75000	1.5788739	
	Y	44.00000	1.5830124	
	Y	44.25000	1.5871509	
	Y	44.50000	1.5912894	
	Y	44.75000	1.5954279	
	Y	45.00000	1.5995664	
	Y	45.25000	1.6037049	
	Y	45.50000	1.6078434	
	Y	45.75000	1.6119819	
	Y	46.00000	1.6161204	
	Y	46.25000	1.6202589	
	Y	46.50000	1.6243974	
	Y	46.75000	1.6285359	
	Y	47.00000	1.6326744	
	Y	47.25000	1.6368129	
	Y	47.50000	1.6409514	
	Y	47.75000	1.6450899	
	Y	48.00000	1.6492284	
	Y	48.25000	1.6533669	
	Y	48.50000	1.6575054	
	Y	48.75000	1.6616439	
	Y	49.00000	1.6657824	
	Y	49.25000	1.6699209	
	Y	49.50000	1.6740594	
	Y	49.75000	1.6781979	
	Y	50.00000	1.6823364	
	Y	50.25000	1.6864749	
	Y	50.50000	1.6906134	
	Y	50.75000	1.6947519	
	Y	51.00000	1.6988904	
	Y	51.25000	1.7030289	
	Y	51.50000	1.7071674	
	Y	51.75000	1.7113059	
	Y	52.00000	1.7154444	
	Y	52.25000	1.7195829	
	Y	52.50000	1.7237214	
	Y	52.75000	1.7278599	
	Y	53.00000	1.7319984	
	Y	53.25000	1.7361369	
	Y	53.50000	1.7402754	
	Y	53.75000	1.7444139	
	Y	54.00000	1.7485524	
	Y	54.25000	1.7526909	
	Y	54.50000	1.7568294	
	Y	54.75000	1.7609679	
	Y	55.00000	1.7651064	
	Y	55.25000	1.7692449	
	Y	55.50000	1.7733834	
	Y	55.75000	1.7775219	
	Y	56.00000	1.7816604	
	Y	56.25000	1.7857989	
	Y	56.50000	1.7899374	
	Y	56.75000	1.7940759	
	Y	57.00000	1.7982144	
	Y	57.25000	1.8023529	
	Y	57.50000	1.8064914	
	Y	57.75000	1.8106299	
	Y	58.00000	1.8147684	
	Y	58.25000	1.8189069	
	Y	58.50000	1.8230454	
	Y	58.75000	1.8271839	
	Y	59.00000	1.8313224	
	Y	59.25000	1.8354609	
	Y	59.50000	1.8395994	
	Y	59.75000	1.8437379	
	Y	60.00000	1.8478764	
	Y	60.25000	1.8520149	
	Y	60.50000	1.8561534	
	Y	60.75000	1.8602919	
	Y	61.00000	1.8644304	
	Y	61.25000	1.8685689	
	Y	61.50000	1.8727074	
	Y	61.75000	1.8768459	
	Y	62.00000	1.8809844	
	Y	62.25000	1.8851229	
	Y	62.50000	1.88	

REVISIONS		DATE	APPROVED
DESCRIPTION		5-2-79	
LTR	ISSUED		
A			

NOTES: UNLESS OTHERWISE INDICATED

- ALL DIMENSIONS IN MILLIMETERS
- SURF. FIT 1. $\frac{3}{4}$ RINGS, IRREG. $\frac{1}{4}$ RING.
- SURF. QUAL 1. 80/50
2. 80/50
- EDGE THICK. RUNOUT .004 AT $\frac{3}{8}$ MM DIA.
- BEVEL EDGES $\frac{1}{4}$ MM. MAX.
- ANTI REFLECTION COATING ON SURF. $\frac{1}{4}$
- EFL = 130.25 BFL = 127.23 FFL =
- FA-1-38 FA-2-38

UNLESS OTHERWISE SPECIFIED		CONTRACT NO.	
DESIGN ALL DIMENSIONS			
SHOWN UNLESS OTHERWISE SPECIFIED			
UNLESS OTHERWISE SPECIFIED			
FRACTIONS DECIMALS ANGLES			
MATERIAL: LAK 22		DRAWN: JLR	4-2-79
W4-1651129		CHECKED: M.S.	4/26/79
VJ-55. B9		PROJ ENG: M.S.	4/27/79
FINISH:		APPROVED:	
		RELEASED BY:	

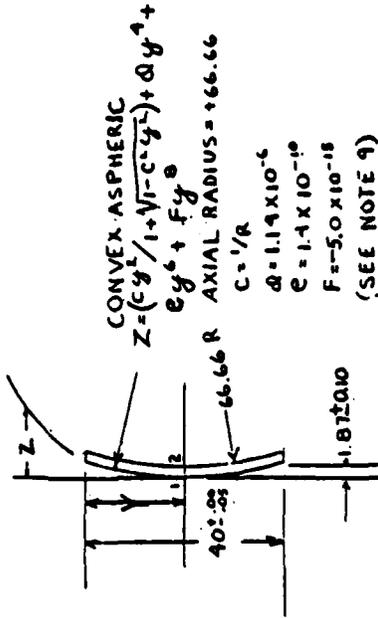
ITEM	NEET ASSY	REQD	
APPLICATION			

SIZE	CODE IDENT NO	DRAWING NO	SHEET 1 OF 1
A	21587	151276	
SCALE FULL			USED ON 507

REVISIONS		
LTN	DESCRIPTION	DATE APPROVED
A	ISSUED	3-2-79

NOTES: UNLESS OTHERWISE INDICATED

1. ALL DIMENSIONS IN MILLIMETERS
2. SURF. FIT 1. --- RING, IRREG. --- RING.
3. SURF. QUAL 1. 80/50
4. EDGE THICK. RUNOUT: ± 0.1 AT 1 ϕ . MM DIA.
5. BEVEL EDGES ± 0.5 MM. MAX.
6. ANTI REFLECTION COATING ON SURF. 1 & 2
7. EFL = 77.47 BFL = 76.56 FFL =
8. FA-1 = 38 FA-2 = 38
9. SAG TABLE SURFACE 1 ON SHEET 2



FARRAND OPTICAL CO., INC. 117 WALL ST. VALHALLA, N. Y. 10595	
LENS 3 RELAY SYSTEM	
SIZE CODE IDENT NO A 21587	DRAWING NO 151277
SCALE FULL	SHEET 1 OF 2 USED ON 507
CONTRACT NO.	DRAWN 7/2 CHECKED M.S. DATE 4/20/79 APPROVED 4/25/79 RELEASED BY SP
UNLESS OTHERWISE SPECIFIED REMOVE ALL SHARP EDGES AND CHAMFER ALL SHARP EDGES AND DIMENSIONS ARE IN MILLIMETERS	MATERIAL: SF 53 N# 1728701 V# 28.69 FINISH
ITEM	NEXT ASSY
APPLICATION	RECD

X	Y	Z	REVISED	ISSUED		REVISIONS		DATE	APPROVED
				DESCRIPTION	DESCRIPTION	DESCRIPTION	DESCRIPTION		
0.250000	0.000668	0.0018751	0.000000	0.2270321	12.750000	1.2609547		5-2-75	
0.500000	0.002132	0.0075016	0.250000	0.2953620	13.000000	1.3126113			
1.000000	0.0075016	0.0075016	0.500000	0.3186756	13.000000	1.3654051			
1.250000	0.0117226	0.0117226	0.750000	0.3449767	13.750000	1.4194335			
1.500000	0.0168829	0.0168829	0.000000	0.3805574	13.750000	1.4744342			
1.750000	0.0229834	0.0229834	0.000000	0.4268453	14.000000	1.5308648			
2.000000	0.0300250	0.0300250	0.000000	0.4561374	14.000000	1.5881029			
2.500000	0.0380088	0.0380088	0.000000	0.4864303	14.500000	1.6466965			
2.500000	0.0469361	0.0469361	0.000000	0.5172527					
2.750000	0.0568882	0.0568882	0.000000	0.5500823					
3.000000	0.0676266	0.0676266	0.000000	0.5834434	14.750000	1.7064734			
3.250000	0.0793932	0.0793932	0.000000	0.6178259	15.000000	1.7674415			
3.500000	0.0921097	0.0921097	0.000000	0.6532441	15.250000	1.8294088			
3.750000	0.1057781	0.1057781	0.000000	0.6897016	15.500000	1.8929834			
4.000000	0.1204006	0.1204006	0.000000	0.7272040	15.750000	1.9575733			
4.250000	0.1359794	0.1359794	0.000000	0.7657569	16.000000	2.0232865			
4.500000	0.1525169	0.1525169	0.000000	0.8053662	16.250000	2.0904312			
4.750000	0.1700159	0.1700159	0.000000	0.8460360	16.500000	2.1587155			
5.000000	0.1884789	0.1884789	0.000000	0.8877785	16.750000	2.2282475			
5.250000	0.2079069	0.2079069	0.000000	0.9305928	17.000000	2.2990351			
5.500000	0.2283020	0.2283020	0.000000	0.9744905	17.250000	2.3710865			
5.750000	0.2496823	0.2496823	0.000000	1.0194750	17.500000	2.4444097			
			0.000000	1.0655542	17.750000	2.5190125			
			0.000000	1.1127347	18.000000	2.5949029			
			0.000000	1.1610236					
			0.000000	1.2106278					

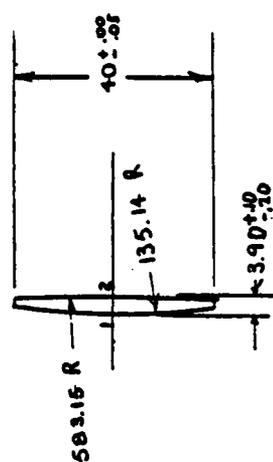
FARRAND OPTICAL CO., INC.
 117 WALL ST
 VALHALLA, N. Y. 10995
SAG TABLE LENS 3
SURF 1, RELAY SYSTEM
 SIZE CODE IDENT NO
A 21587 DRAWING NO
151277
 SCALE
 SHEET 2 OF 2
 USED ON 507

DRAWN P.W. CHECKED J.E.S. APPROVED W.L.S. RELEASED BY	DATE 5-2-75 DATE 4/10/75 DATE 4/12/75
CONTRACT NO PARTS ORDERED SPECIFIC CHECK ALL PARTS DIMENSIONS AND IN DIMENSIONS AND IN TOLERANCES OF FINISHES, WEIGHTS, QUANTITIES	MATERIALS FINISHES
ITEM NEXT ASSY APPLICATION	RECD

REVISIONS		DATE	APPROVED
LTR	ISSUED	5-2-79	
A			

NOTES: UNLESS OTHERWISE INDICATED

- ALL DIMENSIONS IN MILLIMETERS
- SURF. FIT
 - 2-RINGS - IRREG. RING.
 - 6-RINGS - IRREG. RING.
- SURF. QUAL.
 - 80/50
 - 80/50
- EDGE THICK. RUNOUT QSAT 3B. MM DIA.
- BEVEL EDGES .35. MM. MAX.
- ANTI REFLECTION COATING ON SURF. 1/2
- EFL = 171.66 BFL = 169.72 PFL =
- FA-1 - 38 FA-2 - 38



FARRAND OPTICAL CO., INC. 117 WALL ST. VALHALLA, N. Y. 10995	
LENS 4 RELAY SYSTEM	
SIZE CODE IDENT NO A 21587	DRAWING NO 151278
SCALE FULL	SHEET 1 OF 1
CONTRACT NO.	DRAWN: <i>PL</i> CHECKED: <i>MS</i> PROJ ENG: <i>MS</i> APPROVER: <i>PL</i> RELEASED BY:
UNLESS OTHERWISE SPECIFIED ALL DIMENSIONS ARE IN MILLIMETERS DIMENSIONS ARE IN PARENTHESES ARE IN INCHES FRACTIONS DECIMALS ANGLES	MATERIAL: LAK 7-1 NJ-1640496 V1-6010 FINISH:
ITEM	MERT ASSY
APPLICATION	REOD

USE ON 507

REVISIONS		DATE	APPROVED
LTR	A ISSUED	8-2-79	

Technical drawing of a lens showing dimensions: 72.46 R (top radius), 10.2-0.05 (height), 636.30 R (bottom radius), and 11.0-0.1 (thickness).

NOTES: UNLESS OTHERWISE INDICATED

1. ALL DIMENSIONS IN MILLIMETERS
2. SURF. FIT 1. S. RINGS . IRREG. 1/2-RING.
2. S. RINGS . IRREG. 1-RING.
3. SURF. QUAL 1. 80/50
2. 80/50
4. EDGE THICK. RUNOUT .005 AT 30. MM DIA.
5. BEVEL EDGES 35 MM. MAX
6. ANTI REFLECTION COATING ON SURF. 1 & 2
7. EFL = 126.71 BFL = 119.95 FFL = -
8. FA-1 = 38 FA-2 = 38

FARRAND OPTICAL CO., INC.		117 WALL ST. VALHALLA, N. Y. 10585	
LENS 5 RELAY SYSTEM		DRAWING NO. A 21587 151279	
CONTRACT NO.		SCALE FULL	
DRAWN: J. J. 1-2-77		SHEET 1 OF 1	
CHECKED: W. S. 4/18/77		UNTD. ON 507	
PROF. ENG. W. S. 7/12/79		SIZE CODE IDENT NO. DRAWING NO.	
APPROVED: <i>OR</i>		A 21587 151279	
RELEASED BY:		DRAWING NO.	
UNLESS OTHERWISE SPECIFIED		MATERIAL: LAK 21	
REWORK ALL DIMENSIONS AND TOLERANCES ARE IN MILLIMETERS AND DECIMALS UNLESS OTHERWISE SPECIFIED		NF 1.6409L	
FUNCTIONS: RECTANGULAR ANGLES		VD=60.10	
FINISH:		RECD	
ITEM		NEXT ASSY	
APPLICATION		RECD	

REVISIONS		DATE	APPROVED
LTR	ISSUED	5-2-71	
A			

NOTES: UNLESS OTHERWISE INDICATED
 1. ALL DIMENSIONS IN MILLIMETERS
 2. SURF. FIT 1-2-RINGS, IRREG. 1/2-RING.
 2-2-RINGS, IRREG. 1-RING.
 3. SURF. QUAL 1.80/50
 2.80/50
 4. EDGE THICK. RUNOUT .005 AT 2.1 MM DIA.
 5. BEVEL EDGES .25 MM. MAX.
 6. ANTI REFLECTION COATING ON SURF. 1.
 7. EFL = 152.09 BFL = 150.78 PFL =
 8. FA-1 = 34 FA-2 = 34

CONTRACT NO.		FARRAND OPTICAL CO., INC. 117 WALL ST. VALHALLA, N. Y. 10595	
UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN MILLIMETERS AND TOLERANCES ARE:		LENS 6 RELAY SYSTEM	
DRAWN	1-2-71	SIZE	CODE IDENT NO
CHECKED	4/5	A	21587
APPROVED	4/5	DRAWING NO	151280
RELEASED BY	9PC	SCALE	FULL
		SHEET	1 OF 1

ITEM	15-257	REC'D
APPLICATION		

REVISIONS		DATE	APPROVED BY
1	ISSUED	5-2-74	

NOTES: UNLESS OTHERWISE INDICATED
 1. ALL DIMENSIONS IN MILLIMETERS
 2. SURF. FIT 1-2-RINGS: IRREG. 1-RING.
 2-2-RINGS: IRREG. 1-RING.
 3. SURF. QUAL 1. 80/50
 2. 80/50
 4. EDGE THICK. RUNOUT: .995 AT 3.1 MM DIA.
 5. BEVEL EDGES .25 MM. MAX.
 6. ANTI REFLECTION COATING ON SURF. ---
 7. EFL = -39.17 BFL = -39.24 PFL = ---
 8. FA-1 = 34 FA-2 = 34

CONTRACT NO.		FARRAND OPTICAL CO., INC. 117 WALL ST. VALHALLA, N. Y. 10985	
DRAWING NO.		LENS 7 RELAY SYSTEM	
DRAWN	70	DATE	5-2-74
CHECKED	MS	DATE	5/10/74
PROJ. ENG.	YS	DATE	5/10/74
APPROVED	92	SIZE CODE IDENT NO.	DRAWING NO.
RELEASED BY		A 21587	151281
MATERIAL: SF 53		SCALE	FULL
Nd: 1720304		SHEET OF	
VJ: 20.69		507	
FINISH:			
ITEM	151287	REC'D	
APPLICATION			

REVISIONS		DATE	APPROVED
LTR	DESCRIPTION	3-2-74	
A	ISSUED		

NOTES: UNLESS OTHERWISE INDICATED

- ALL DIMENSIONS IN MILLIMETERS
- SURF. FIT 1. $\frac{1}{2}$ -RING $\frac{1}{2}$. IRREG. $\frac{1}{2}$ -RING.
2. $\frac{1}{2}$ -RING. IRREG. $\frac{1}{2}$ -RING.
- SURF. QUAL 1. 80/50
2. 80/50
- EDGE THICK. RUNOUT: ± 0.01 AT $\frac{1}{2}$ MM DIA.
- BEVEL EDGES $\frac{1}{32}$ MM. MAX.
- ANTI REFLECTION COATING ON SURF. $\frac{1}{2}$.
- EFL = 51.46 BFL = 41.72 FFL =
- FA-1 = 34 FA-2 = 34

CONTRACT NO.		FARRAND OPTICAL CO., INC. 117 WALL ST. VALHALLA, N. Y. 10595	
DRAWN		LENS 8 RELAY SYSTEM	
CHECKED	DATE	SIZE	CODE IDENT NO
PROJ. ENG.	4-2-74	A	21587
APPROVED	4/10/74	DRAWING NO	
RELEASED BY	AC	151282	
UNLESS OTHERWISE SPECIFIED INCLUDE ALL DIMENSIONS SHOWN SHARP CORNERS DIMENSIONS AND TOLERANCES AND TOLERANCES ARE FRACTIONS DECIMALS ANGLES		SCALE FULL	
MATERIAL: LAK 21		SHEET	
Nd = 1.640496		OF	
N _d = 60.10		507	
FINISH			
ITEM	QTY	APPLICATION	
2	151288	NEXT ASSY	
		RECD	

REVISIONS		DATE	APPROVED
DESCRIPTION		5-2-79	BT
LTR	ISSUED		
A			

NOTES: UNLESS OTHERWISE INDICATED

- ALL DIMENSIONS IN MILLIMETERS
- SURF. FIT 1. 2-RING . IRREG. 1/2-RING
2. 2-RING . IRREG. 1-RING
- SURF. QUAL 1. 60/40
2. 60/40
- EDGE THICK. RUNOUT .002 AT 3.1 MM DIA.
- BEVEL EDGES .15 MM. MAX.
- ANTI REFLECTION COATING ON SURF. 1---
- EFL = 53.25 BFL = 51.37 FPL =
- FA-1 = 34 FA-2 = 34

8133 R
56.36 R
36.00
5.10 +.05 / -.10
410139

CONTRACT NO.		FARRAND OPTICAL CO., INC.	
		117 WALL ST VALHALLA, N. Y. 10595	
DRAWN		LENS 9 RELAY SYSTEM	
CHECKED	4-1-79	SIZE	CODE IDENT NO
FOR THE	M.S.	A	21587
APPROVED	M.S.	DRAWING NO	151283
RELEASED BY	JK	SCALE	FULL
		SHEET	1 OF 1
		USED ON	307

UNLESS OTHERWISE SPECIFIED REMOVE ALL DIMENSIONS AND TOLERANCES FROM THIS DRAWING	FUNCTIONS	REQUIREMENTS
MATERIAL: LAK31		
ND=1.60496		
VD=60.10		
FINISH:		
ITEM	1	151283
NEXT ASSY		
REQD		
APPLICATION		

REVISED		REVISIONS		DATE	APPROVED
LTR	ISSUED	DESCRIPTION		5-2-71	

NOTES: UNLESS OTHERWISE INDICATED
 1. ALL DIMENSIONS IN MILLIMETERS
 2. SURF. FIT 1. .1 RING . IRREG. 1/4 RING.
 2. .1 RING . IRREG. 1/4 RING.
 3. SURF. QUAL 1. 60/40
 2. 60/40
 4. EDGE THICK. RUNOUT .01 AT 15. MM DIA.
 5. BEVEL EDGES ... MM. MAX
 6. ANTI REFLECTION COATING ON SURF. 2.
 7. EFL = -143.07 BFL = -143.84 FFL =
 8. FA-1 = 32 FA-2 = 32

UNLESS OTHERWISE SPECIFIED INCLUDE ALL DIMS UNLESS SHOWN OTHERWISE AND UNLESS OTHERWISE SPECIFIED		CONTRACT NO.	
FRACMENTS	DECIMALS	ANGLES	
MATERIAL: SF 6			
NJ 91.00518L			
VD 25.43			
FINISH:			

DRAWN	5-2-71
CHECKED	4/10/71
PROL. ENG.	4/10/71
APPROVED	<i>MC</i>
RELEASED BY	

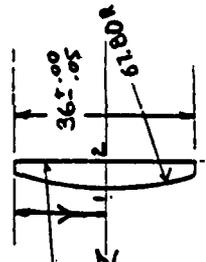
FARRAND OPTICAL CO., INC.		117 WALL ST. VALHALLA, N. Y. 10595	
LENS 10 RELAY SYSTEM			
SIZE	CODE IDENT NO	DRAWING NO	
A	21587	151284	
SCALE	FULL	SHEET 1	OF 1

APPLICATION RECORD
 ITEM 2 NEXT ASSY 1 RECD
 3-6 (REVISED 5/10/61)

REVISIONS		DATE	APPROVED
LTR	A	5-2-71	
ISSUED			

NOTES: UNLESS OTHERWISE INDICATED

1. ALL DIMENSIONS IN MILLIMETERS
2. SURF. FIT 1.-L-RING . IRREG.-RINGS
- 2.-L-RING . IRREG.-RINGS
3. SURF. QUAL 1. 30/10 2. 30/10
4. EDGE THICK. RUNOUT .005 AT 39. MM DIA
5. BEVEL EDGES .5 MM. MAX.
6. ANTI REFLECTION COATING ON SURF. 1.5
7. EFL = 86.5 BFL = 83.96 PFL =
8. FA-1 = 31 FA-2 = 30
9. SAC TABLE SURFACE 2 ON SHEET 2



$Z = (C \frac{y^2}{2} / (1 + \sqrt{1 - C^2 y^2})) + d y^4$
 ASPHERIC CONVEX
 AXIAL RADIUS = -1289.27
 $C = 1/R$
 $R = 3.4 \times 10^{-6}$
 (SEE NOTE 9)

CONTRACT NO.		FARRAND OPTICAL CO., INC. 117 WALL ST. VALHALLA, N. Y. 10595	
UNLESS OTHERWISE SPECIFIED USE THE FOLLOWING DIMENSIONS AND TOLERANCES UNLESS OTHERWISE SPECIFIED		LENS II RELAY SYSTEM	
DRAWN	Y.S.	4-27-71	
CHECKED	Y.S.	4/20/71	
PROJ. ENG.	Y.S.	7/1	4/20/71
APPROVED			
RELEASED BY			
MATERIAL: LAK-2-1 NJ-1670496 WJ-60.10		SIZE	CODE IDENT NO. DRAWING NO.
ITEM		A	21587 151285
NEXT ASSY		SCALE	FULL
APPLICATION		SHEET	1 OF 2

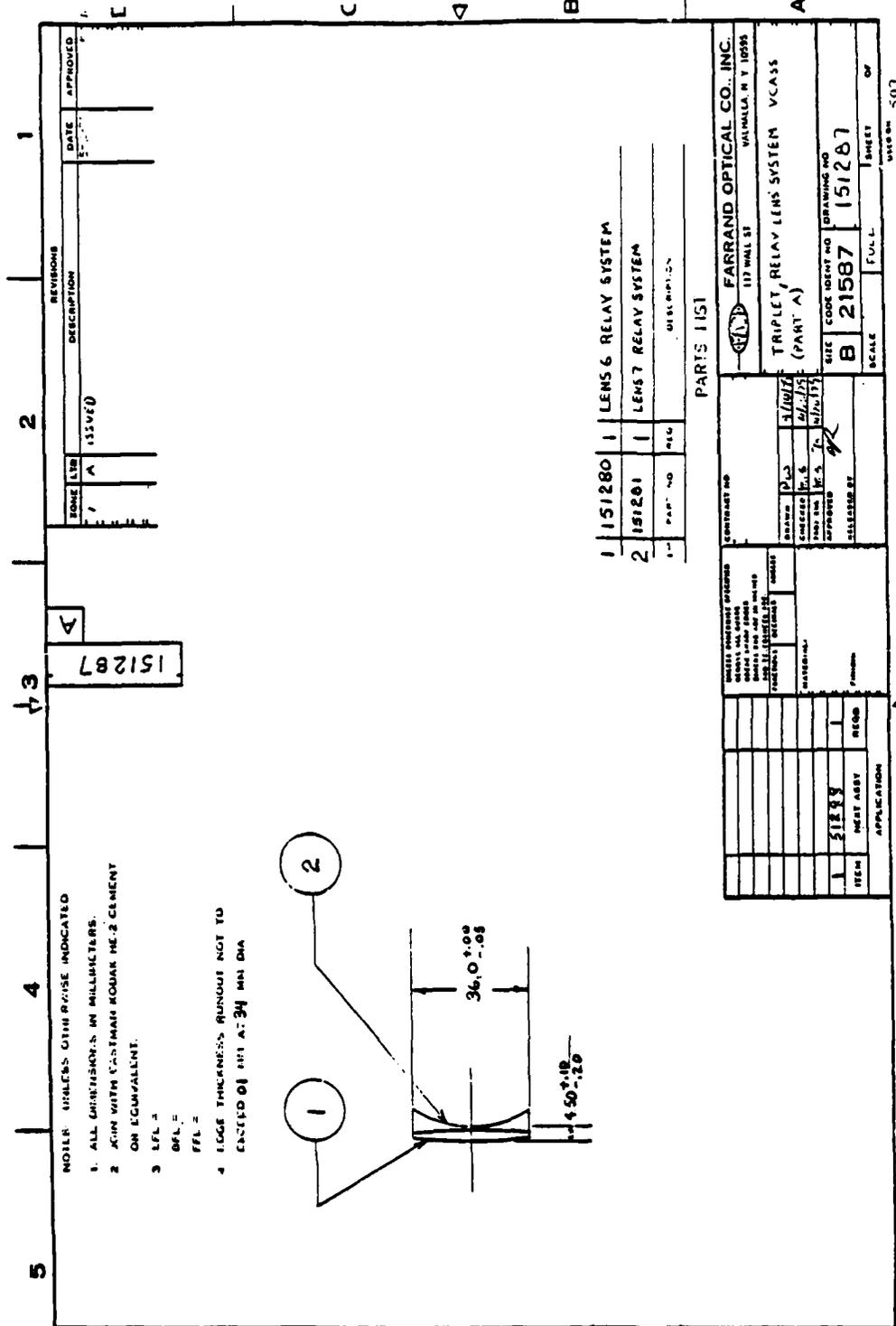
USED ON 507

REVISIONS		DATE	APPROVED
DESCRIPTION		3-2-11	
LTR	ISSUED		

NOTES: UNLESS OTHERWISE INDICATED

1. ALL DIMENSIONS IN MILLIMETERS
2. SURF. FIT 3-1-1-RING . IRREG. 1/4-RING.
2-1/2-RING . IRREG. 1/4-RING.
3. SURF. QUAL 1.50/10
2.50/10
4. EDGE THICK. RUNOUT --- AT --- MM DIA.
5. BEVEL EDGES .25. MM. MAX.
6. ANTI REFLECTION COATING ON SURF. 1 & 3
7. EFL = BFL = FTL =
8. FA-1 = 28 FA-2 = 35X20, FA3 = 22
9. PYRAMID ERROR NOT TO EXCEED 2 MIN
10. SURFACE 2 TO BE SILVERED AND PROTECTED WITH INCONEL LACQUER
11. SURFACE QUALITY, SURF 3 = SURF 1. HOWEVER BEST SURF. SHOULD FACE TUBE.

CONTRACT NO.		FARRAND OPTICAL CO., INC.	
		117 WALL ST. VALHALLA, N. Y. 10595	
UNLESS OTHERWISE SPECIFIED REMOVE ALL DIMENSIONS UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN MILLIMETERS UNLESS OTHERWISE SPECIFIED		DRAWING NO. 4-2-79	
DIMENSIONS IN MILLIMETERS		CHECKED BY J.S. 4/10/79	
MATERIAL: LAM 16		APPROVED BY J.S. 7/10/79	
MATERIAL: Wd. 7385		RELEASED BY J.R.	
MATERIAL: Wd. 51.65			
FINISH:			
ITEM	NEXT ASSY	RECD	
APPLICATION			
SCALE FULL			
SIZE CODE IDENT NO. DRAWING NO.		SHEET OF	
A 21587 151286		507	



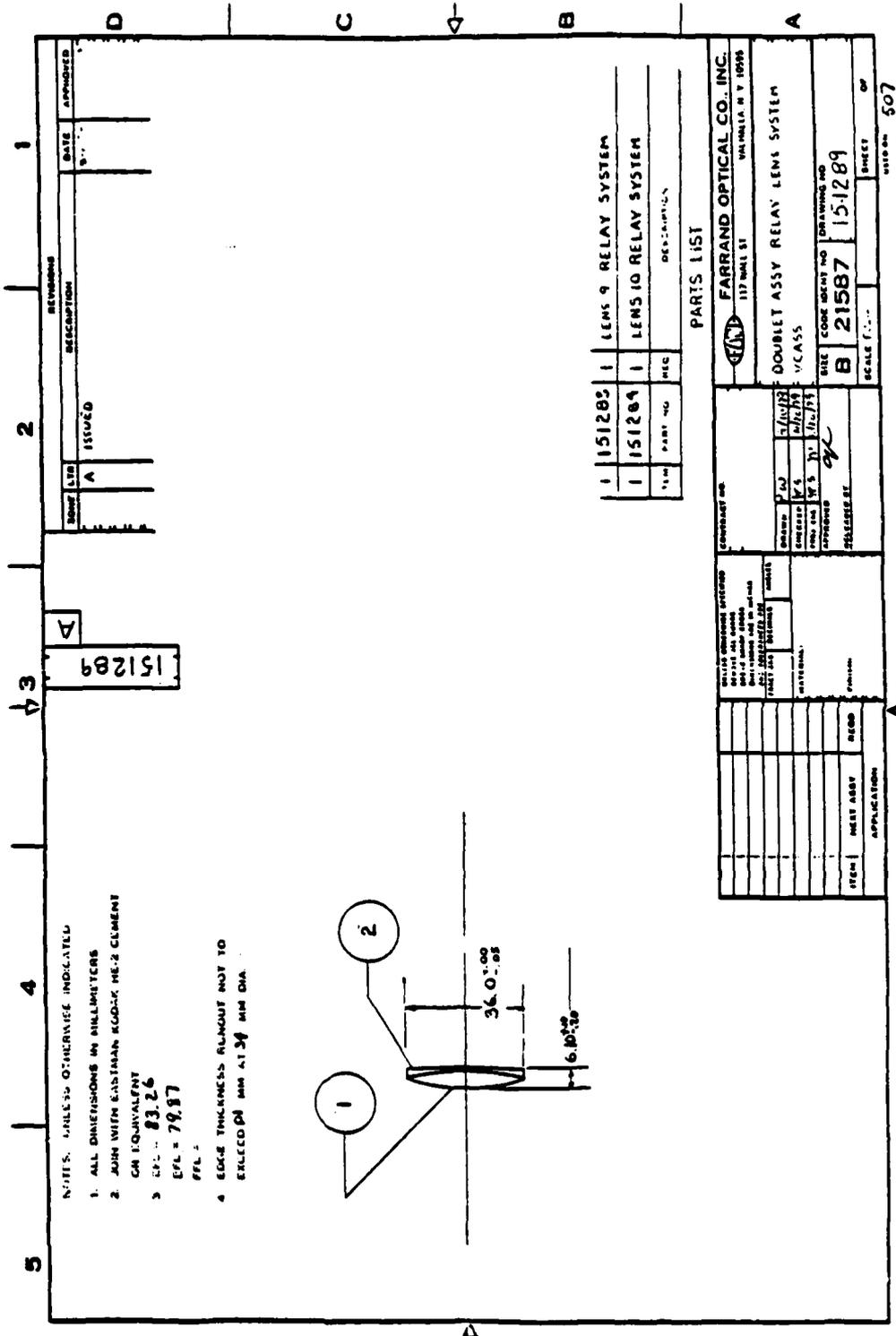
- NOTE: UNLESS OTHERWISE INDICATED
1. ALL DIMENSIONS IN MILLIMETERS.
 2. FIN WITH CASTOR OIL HE-2 CEMENT ON EQUIVALENT.
 3. LFL =
OFL =
FFL =
 4. EDGE THICKNESS RUNOUT NOT TO EXCEED 0.101 AT 34 MIN DIA

REV	DATE	DESCRIPTION	APPROVED
1	11/24/60		

REV	DATE	DESCRIPTION
1	11/24/60	LENS 6 RELAY SYSTEM
2	11/24/60	LENS 7 RELAY SYSTEM

PARTS 1151

FARRAND OPTICAL CO., INC. 117 WALL ST VALHALLA, N Y 10988	
TRIPLET RELAY LENS SYSTEM VCASS (PART A)	
DRAWN BY: P.J.S. CHECKED BY: W.S. APPR'D BY: W.S. DATE: 11/24/60	SIZE: B CODE IDENT NO: 21587 DRAWING NO: 151287
SHEET OVERAGE ORDERED SHEET TOTAL ORDERED SHEET TOTAL ORDERED SHEET TOTAL ORDERED SHEET TOTAL ORDERED	SCALE: FULL SHEET OF: 507

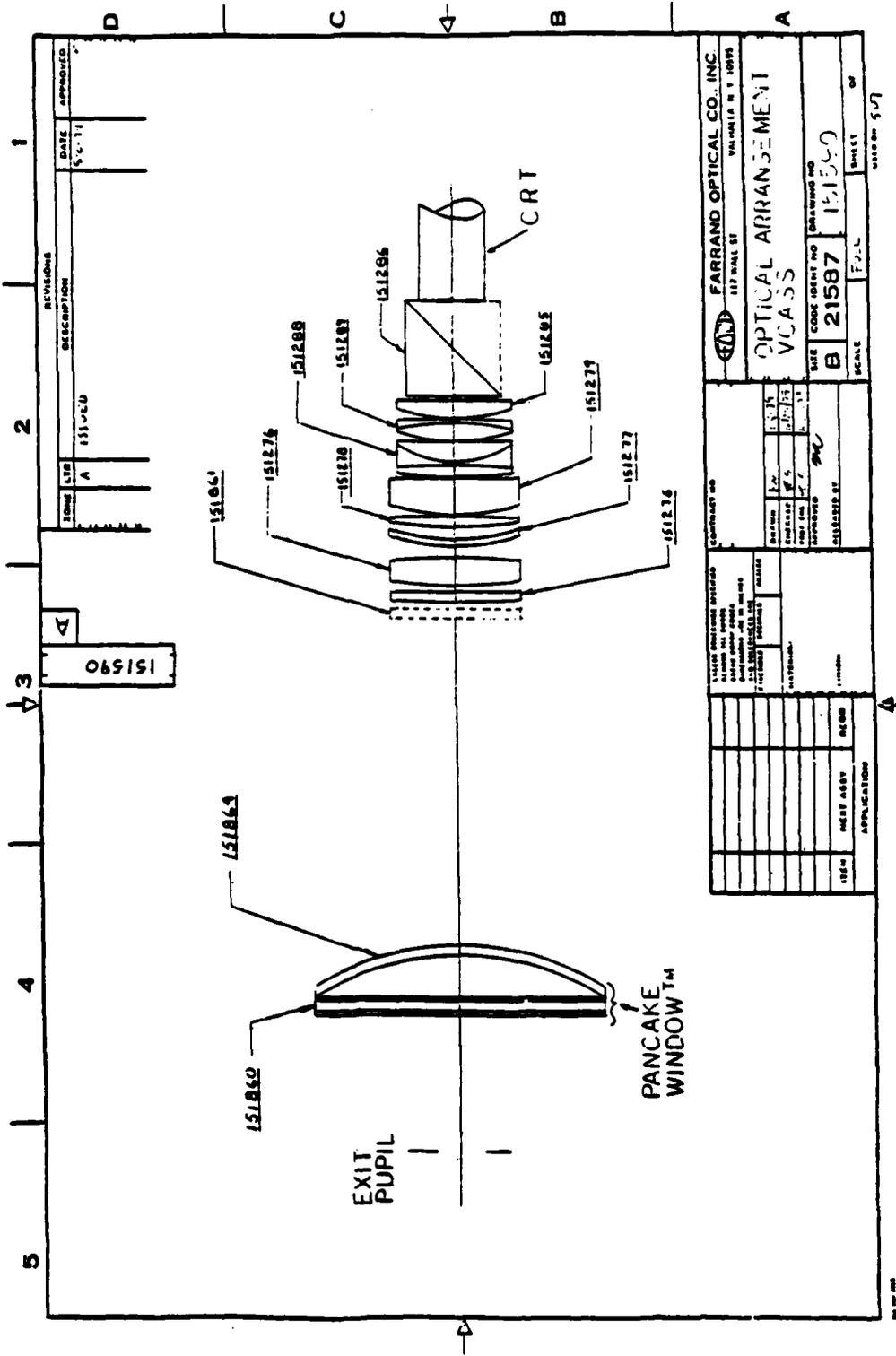


- NOTES: UNLESS OTHERWISE INDICATED
1. ALL DIMENSIONS IN MILLIMETERS
 2. JOIN WITH EASTMAN KODAK NE-2 CEMENT OR EQUIVALENT
 3. EFL = 83.26
EFL = 79.87
PFL =
 4. EDGE THICKNESS ALMOST NOT TO EXCEED 0.1 MM AT 34 MM DIA

PARTS LIST

QTY	PART NO	DESC
1	151285	LENS 9 RELAY SYSTEM
1	151289	LENS 10 RELAY SYSTEM

FARRAND OPTICAL CO. INC. 117 WALL ST PHILADELPHIA, PA 19106	
DRAWN BY: J. J. [Signature] CHECKED BY: [Signature] DATE: 1/10/73 APPROVED BY: [Signature]	CONTRACT NO. DRAWING NO. SCALE: 1:1
DOUBLE ASSY RELAY LENS SYSTEM VCASS	
PART NO: B 21587 DRAWING NO: 15-1289	SHEET NO. OF SHEETS: 507



REV	DESCRIPTION	DATE	APPROVED
1	151860	5-1-71	

REV	DESCRIPTION	DATE	APPROVED
1	151860	5-1-71	

REV	DESCRIPTION	DATE	APPROVED
1	151860	5-1-71	

REV	DESCRIPTION	DATE	APPROVED
1	151860	5-1-71	

REV	DESCRIPTION	DATE	APPROVED
1	151860	5-1-71	

REV	DESCRIPTION	DATE	APPROVED
1	151860	5-1-71	

REV	DESCRIPTION	DATE	APPROVED
1	151860	5-1-71	

REV	DESCRIPTION	DATE	APPROVED
1	151860	5-1-71	

FARRAND OPTICAL CO., INC.
117 WALL ST
VALHOLA N.Y. 10985

OPTICAL ARRANGEMENT
VCASS

DATE CODE IDENT NO. DRAWING NO.
B 21587 151560

SCALE: 7.2:1 SHEET 5 OF 5

DATE	BY	CHECKED	APPROVED
5-1-71			

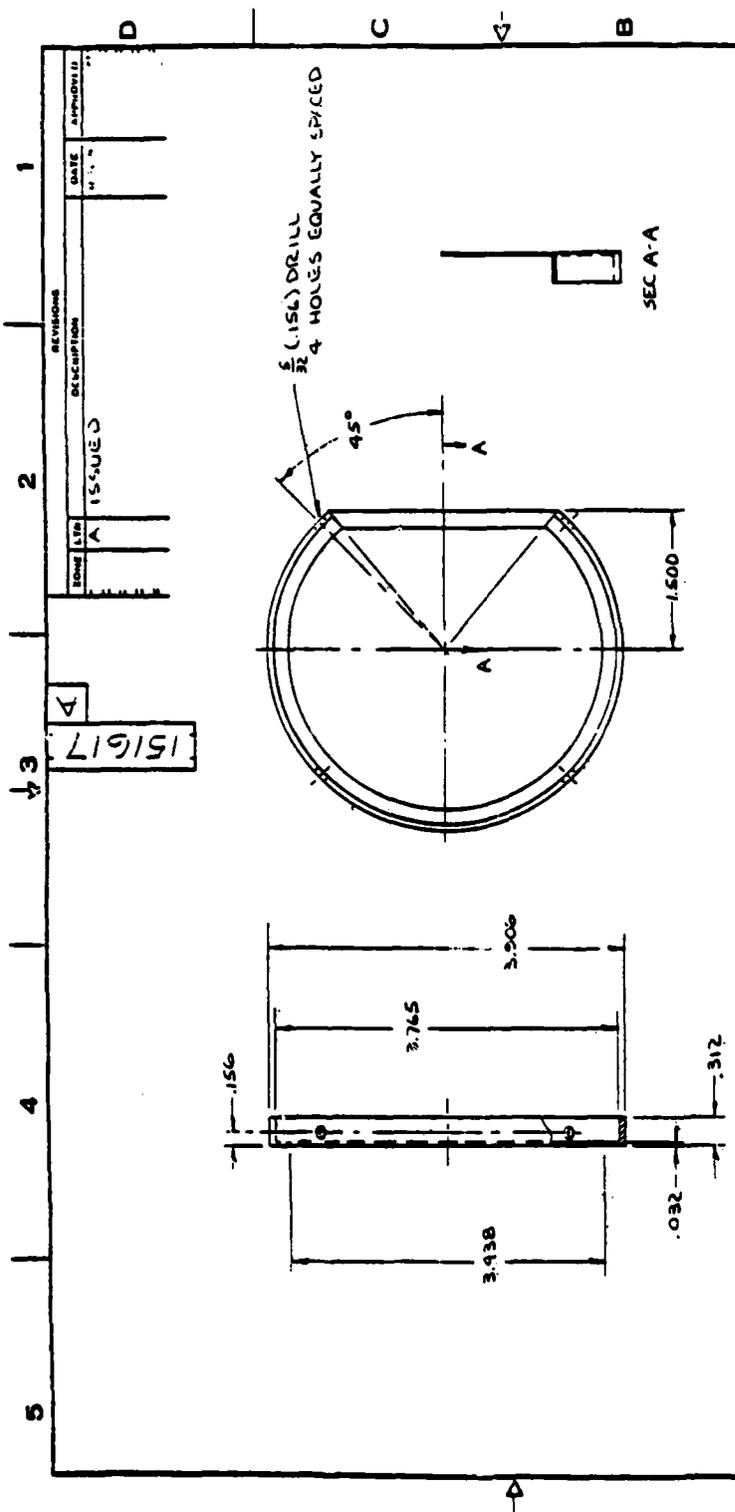
DATE	BY	CHECKED	APPROVED
5-1-71			

DATE	BY	CHECKED	APPROVED
5-1-71			

DATE	BY	CHECKED	APPROVED
5-1-71			

DATE	BY	CHECKED	APPROVED
5-1-71			

DATE	BY	CHECKED	APPROVED
5-1-71			



NOTE: CEMENT 3/16 x .032 THK STRIP TO FLANGE WITH WELD-ON N# 40.

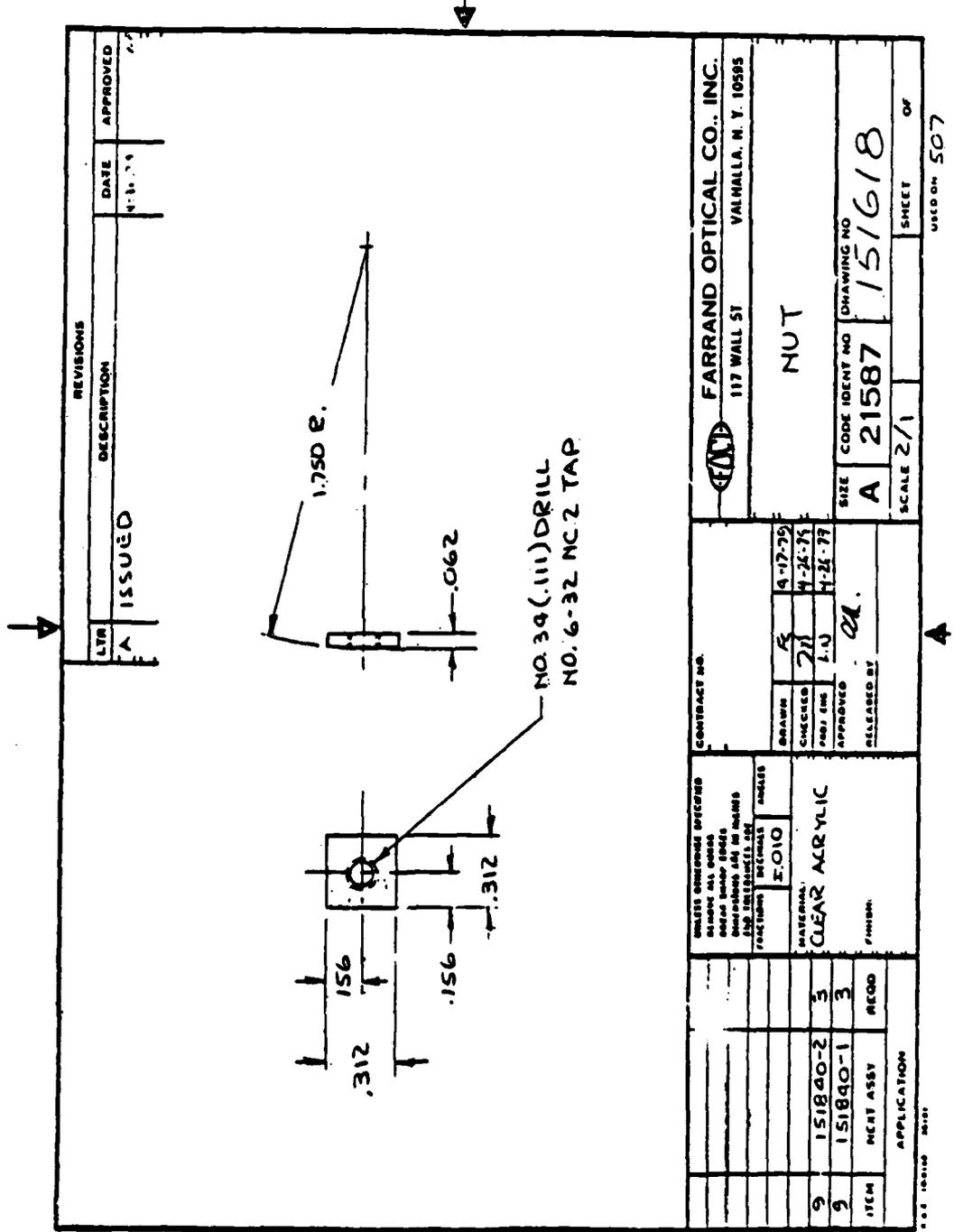
REV	DATE	DESCRIPTION
1	11/1/55	ISSUED

151617

FARRAND OPTICAL CO. INC. 117 WALL ST. BALTIMORE, MD. 21201	
RETAINER	
FILE CODE IDENT NO B 21587	DRAWING NO 151617
SCALE 1/1	SHEET OF 507

CONTRACT NO	DATE	BY	CHECKED	APPROVED	RELEASED BY
	11/1/55				

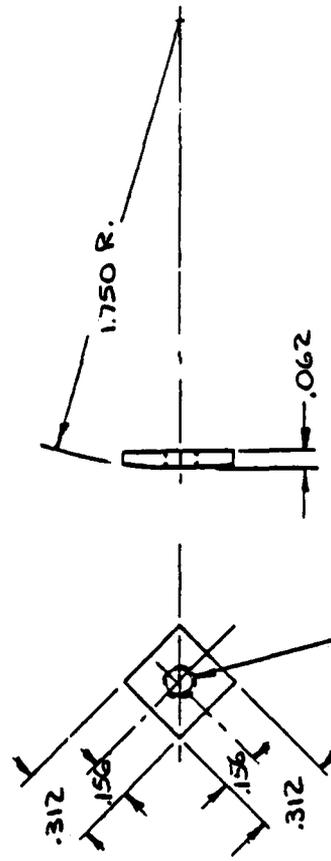
UNITED STATES PATENT AND TRADEMARK OFFICE OFFICE OF THE COMMISSIONER OF PATENTS AND TRADEMARKS WASHINGTON, D. C. 20530 APPLICATION NO. 151617 CLASSIFICATION: 359.10	APPLICATION NO. 151617 CLASSIFICATION: 359.10
F 2-140-2 B 3-B 40-1 ITEM NEXT ASSY WEGO	APPLICATION



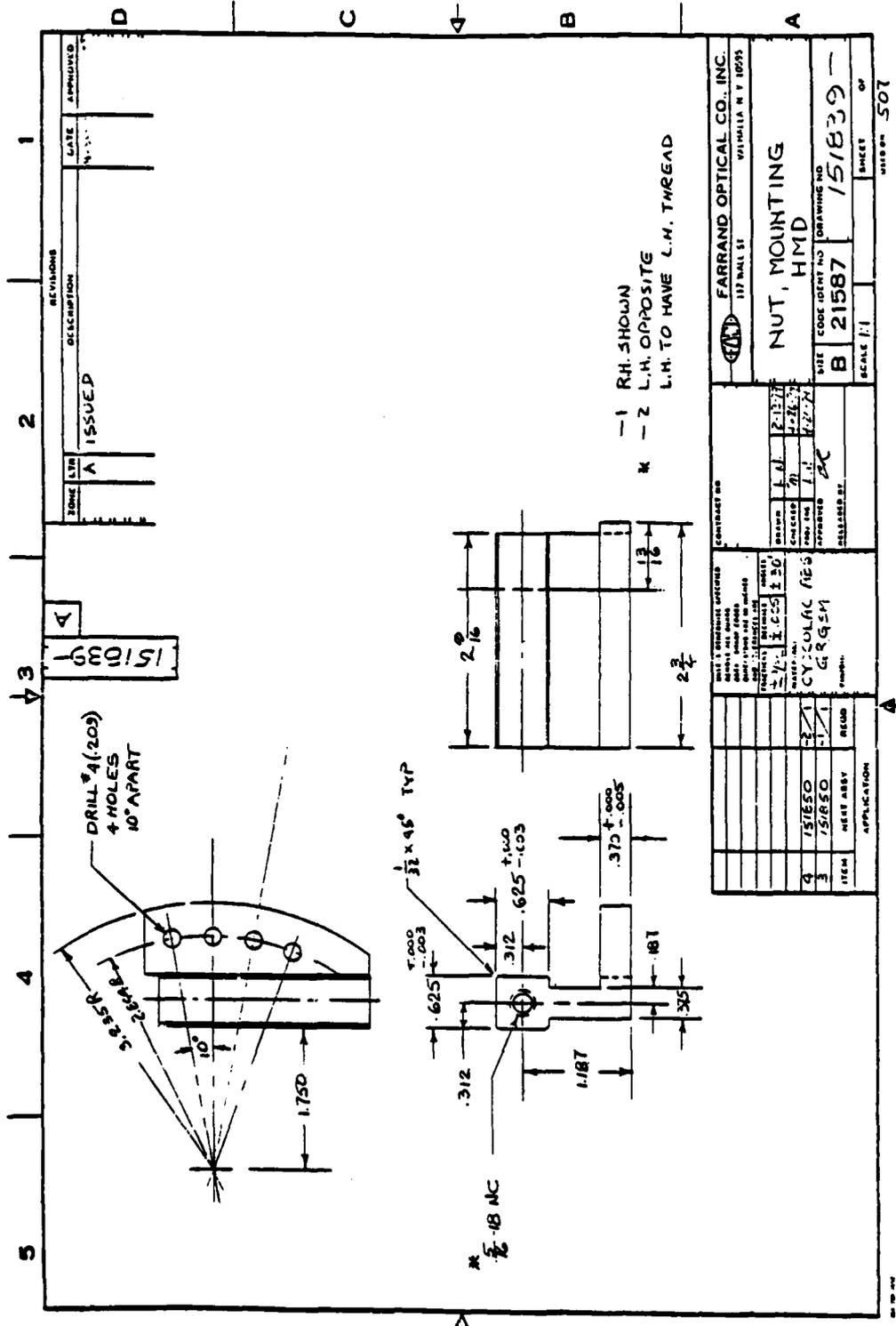
REVISIONS		
LTN	DESCRIPTION	DATE
A	ISSUED	4-17-75

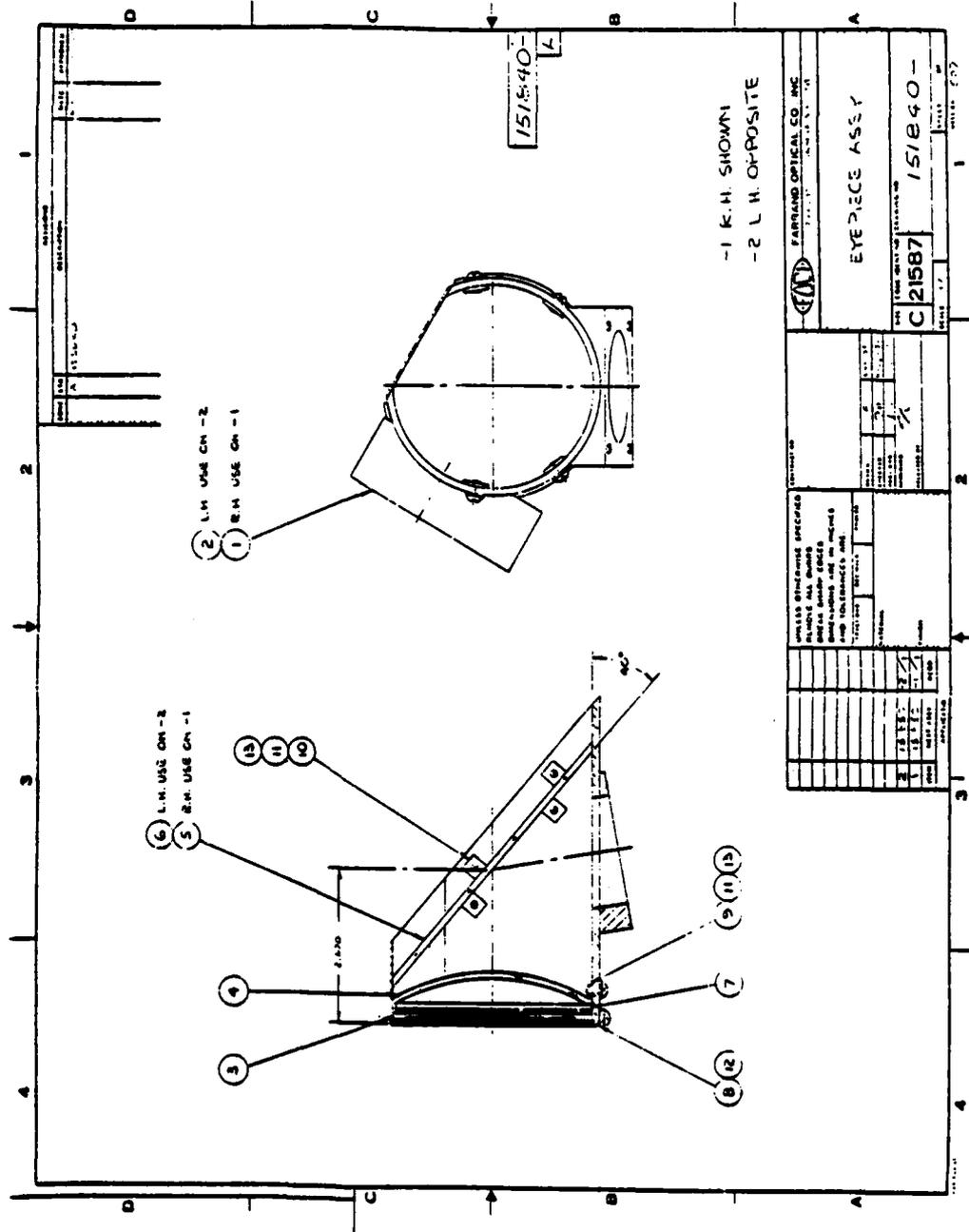
FARRAND OPTICAL CO., INC. 117 WALL ST VALHALLA, N. Y. 10585		NUT	
CONTRACT NO. DRAWN: 5 CHECKED: 77 PROJ. ENG: J-U APPROVED: <i>AL</i> RELEASED BY:	DATE: 4-17-75 4-26-75 4-26-77	SIZE CODE IDENT NO A 21587	DRAWING NO 151618
QUOTE SPECIFICATIONS SPECIFY: DRAWING ALL DIMENSIONS UNLESS OTHERWISE SPECIFIED. DIMENSIONS ARE IN INCHES AND DECIMALS UNLESS OTHERWISE SPECIFIED.		SCALE 2/1	SHEET OF
MATERIAL: CLEAR ACRYLIC FINISH:	APPLICATION: NUT ASSY RECD	USED ON 507	

REVISIONS		DATE	APPROVED
LTR	DESCRIPTION		
A	ISSUED	9-23-79	



UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES AND DECIMALS ARE IN THOUSITHS		CONTRACT NO.		FARRAND OPTICAL CO., INC. 117 WALL ST. VALHALLA, N. Y. 10595	
FRACTIONS	DECIMALS	ANGLES	DRAWN	DATE	DESCRIPTION
	±0.10		RS	9-27-79	NUT
MATERIAL: CLEAR ACRYLIC			CHECKED	DATE	
			TM	4-26-79	
			APPROVED	DATE	
			L.N.J.	7-28-79	
			RELEASED BY		
			SK		
10	1518 40-2	B	SIZE	CODE IDENT NO	DRAWING NO
10	1518 40-1	B	A	21587	151619
ITEM	PERT ASSY	REQD	SCALE	2/1	SHEET
APPLICATION					OF
					507





PARTS LIST

FARRAND OPTICAL CO., INC.
 117 EAST 33 STREET, NEW YORK 10002

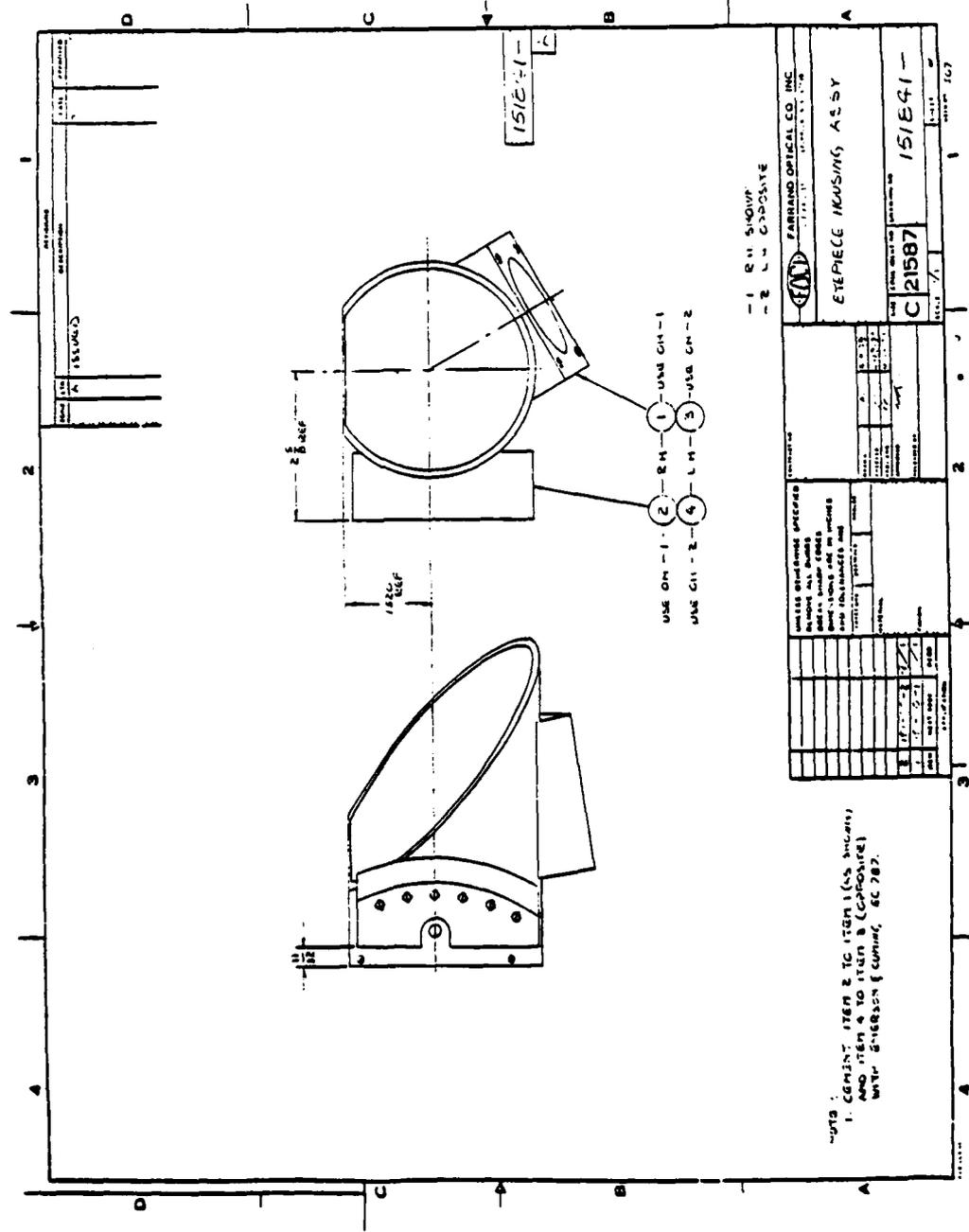
PL 151840 - A
 KEY OF
 PROJ NO 21587
 DATE

1 R.H.
 2 L.H.

LIST TITLE EYEPiece ASSY

QTY	UNIT	DESCRIPTION	QTY
1	C	151841-1 EYEPiece HOUSING ASSY R.H.	1
2	C	151841-2 EYEPiece HOUSING ASSY L.H.	1
2	C	151840 BIREFRINGENT ASSY	1
3	C	151844 SPHERICAL BEAMSPLITTER	1
5	A	151615-1 COMBINER R.H.	1
6	B	151615-2 COMBINER L.H.	1
7	B	151616 SPACER - C	1
8	E	151617 RETAINER	1
9	A	151618 NUT	3
10	A	151619 NUT	3
11	C	NYLON FLAT WASHER NO. 6 1/2 X 3/16 X 1/8	11
12	C	NYLON SLOTTED RD HD SCREW 6-32 X 3/16 LG	4
13	C	NYLON SLOTTED RD HD SCREW 6-32 X 1/4 LG	11

APPROVED BY: [Signature]
 DATE: 7/28/53
 SHEET 507

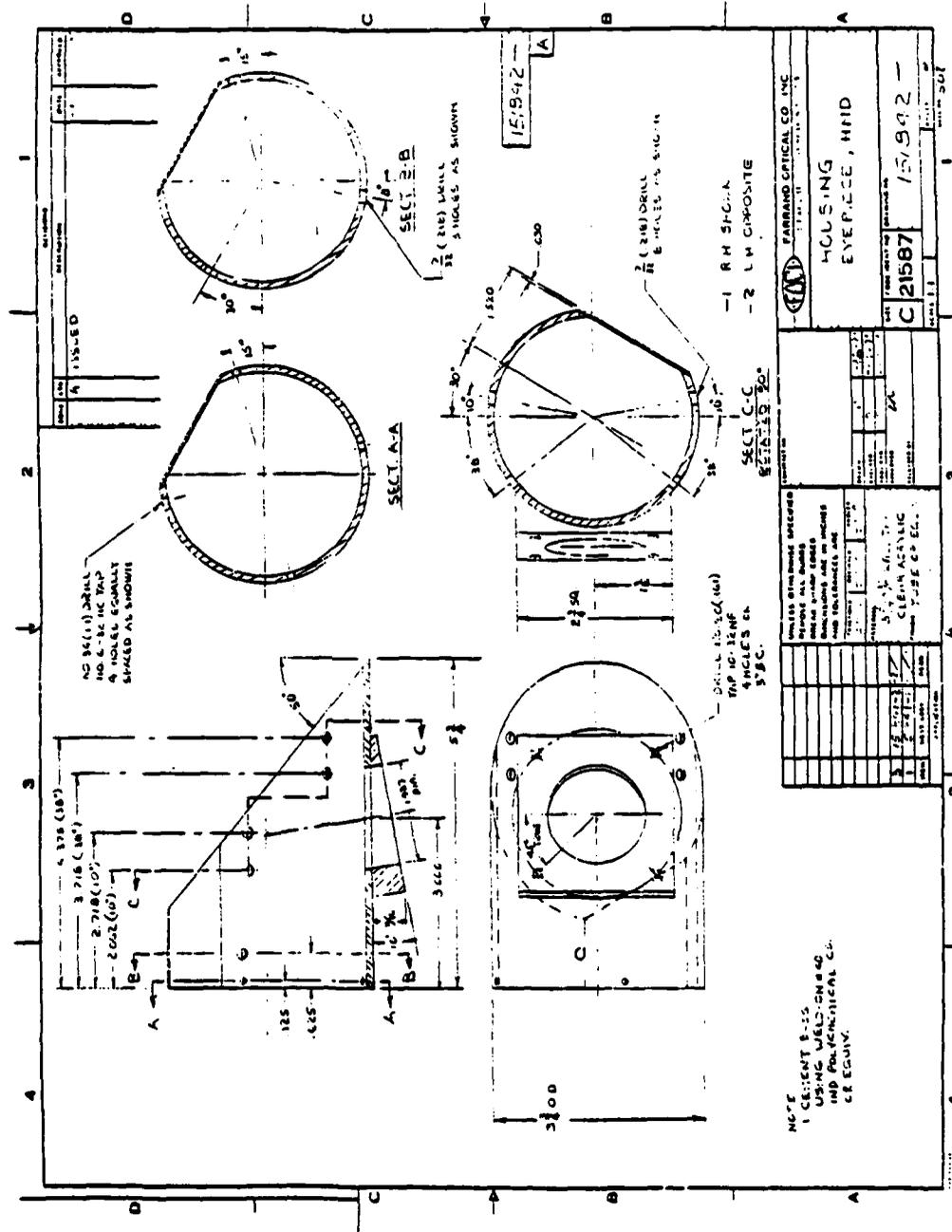


NOTES:
 1. COMB. ITEM 2 TO ITEM 1 (AS SHOWN)
 AND ITEM 4 TO ITEM 3 (AS SHOWN)
 WITH SHERSON GUMM, SC 782.

USE CM - 1 - 1 - USE CM - 1
 USE CM - 2 - 2 - RN - 3 - USE CM - 2
 USE CM - 2 - 4 - LH - 5 - USE CM - 2

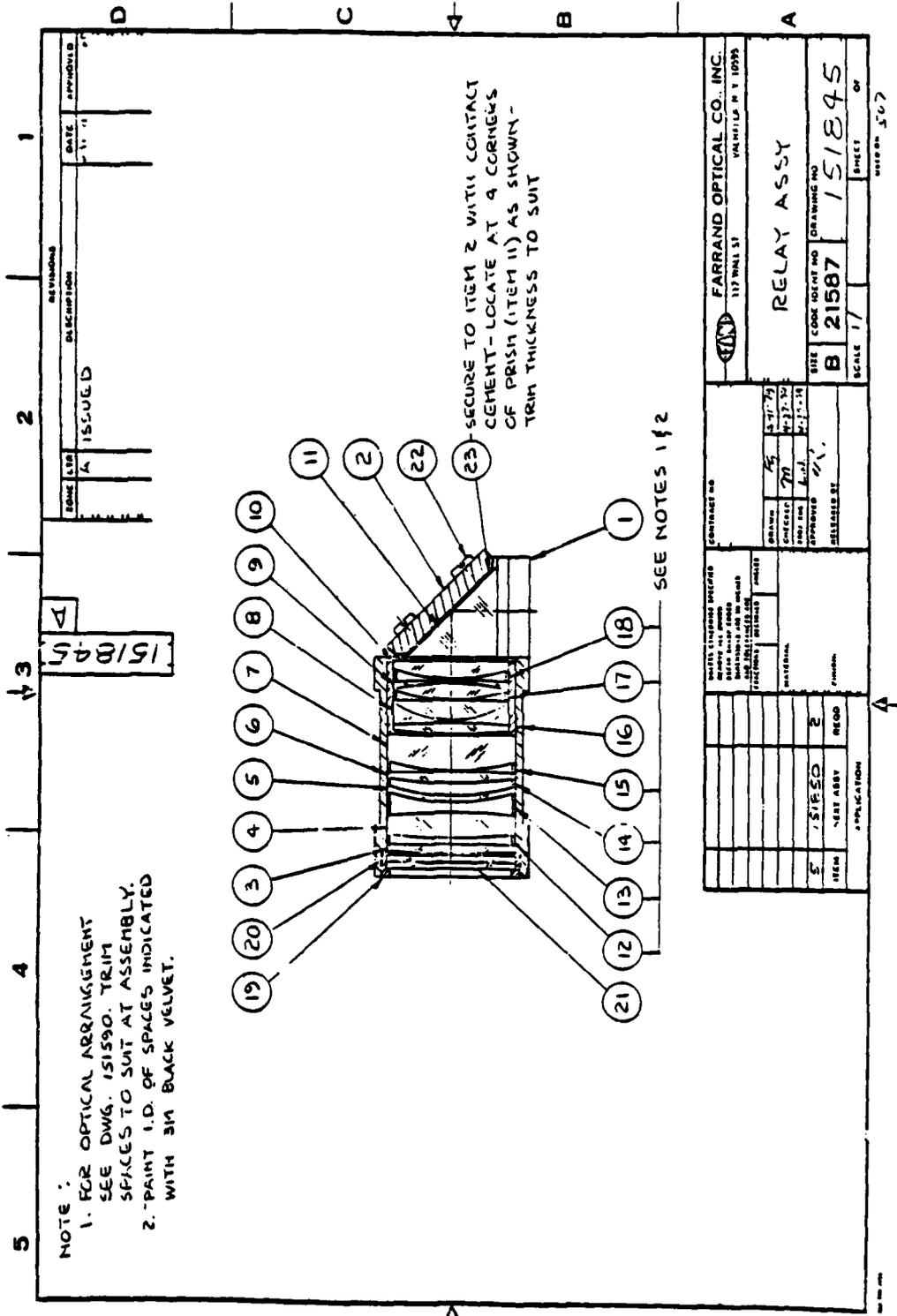
- 1 RN SHOWP
 - 2 L 2 COOSATE

		FARRAND OPTICAL CO. INC. EYEPIECE HOUSING AS.SY	
PART NO. C21587		DRAWING NO. 151E-1	
DATE: 11/13/53		SCALE: 1/1	
DESIGNED BY:		CHECKED BY:	
DRAWN BY:		APPROVED BY:	
MATERIALS:		FINISHES:	
WEIGHT:		VOLUME:	
PARTS LIST:		QUANTITY:	



HOUSING EYEPIECE, HND	
PART NO. C21587	REV. NO. 151992
DATE 11/15/50	DRAWN BY JAC
CHECKED BY JAC	APPROVED BY JAC
WORKSHEET NO. 1	TOTAL SHEETS 1
PART NAME HOUSING EYEPIECE, HND	PART NO. C21587
REV. NO. 151992	DATE 11/15/50

NOTE
 1. ELEMENT 8-25
 USING WELD-ON #40
 AND POLYMERICAL C.
 CE EQUIV.



NOTE :

- FOR OPTICAL ARRANGEMENT SEE DWG. 151590. TRIM SPACES TO SUIT AT ASSEMBLY.
- PAIN'T I.D. OF SPACES INDICATED WITH 3M BLACK VELVET.

SECURE TO ITEM 2 WITH CONTACT CEMENT - LOCATE AT 4 CORNERS OF PRISM (ITEM 11) AS SHOWN - TRIM THICKNESS TO SUIT

SEE NOTES 1 & 2

REV	DATE	DESCRIPTION	APPROVED
A	11-11	ISSUED	

151845

FARRAND OPTICAL CO., INC. 117 WALTON ST VAN HOUTEN, N.Y. 10995	
RELAY ASSY	
SIZE B 21587	DRAWING NO. 151845
SCALE 1/1	SHEET 17 OF 507

CONTRACT NO.	
DRAWN	5-21-79
CHECKED	10-17-79
APPROVED	11-15-79
RELEASED BY	

MATERIALS LISTED IN THIS DRAWING ARE TO BE USED UNLESS OTHERWISE SPECIFIED.	MATERIAL QUANTITY UNIT
5	1 SIZED 2 REED
	APPLICATION

PARTS LIST
FARRAND OPTICAL CO., INC.
 117 WALL ST
 YONKERS, N.Y. 10596

PL 151845
 SHEET 1 OF 1
 PROJ 5013R
 COUN IDENT 21807

LIST TITLE RELAY ASSY

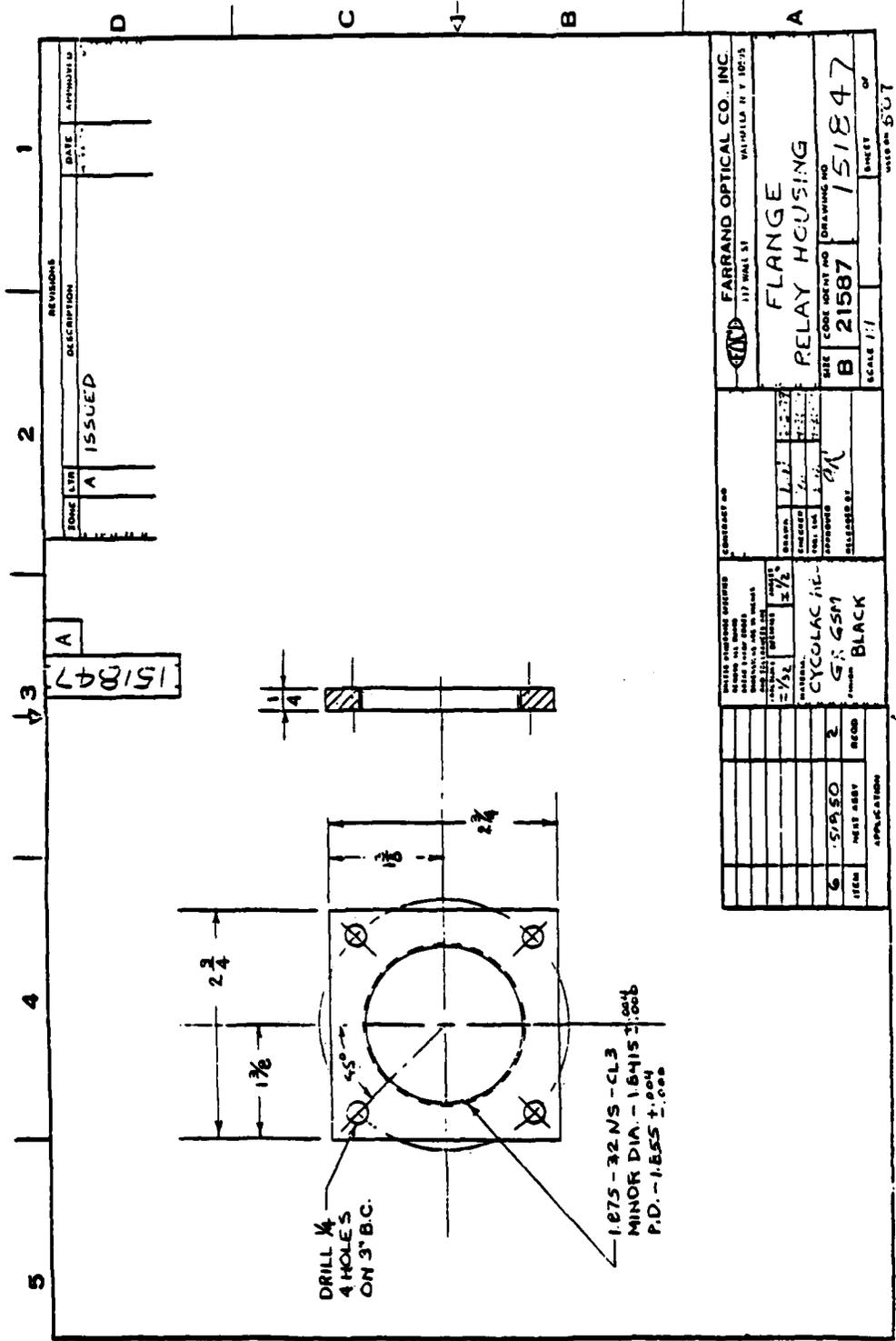
QTY	UNIT	DESCRIPTION	QTY	UNIT
1	C	HOUSING	1	
2	A	RETAINER	1	
3	A	LENS NO. 1	1	
4	A	LENS NO. 2	1	
5	A	LENS NO. 3	1	
6	A	LENS NO. 4	1	
7	A	LENS NO. 5	1	
8	B	TRIPLET	1	
9	B	DOUBLET	1	
10	A	LENS NO. 11	1	
11	A	PRISM	1	
12	B	SPACER A	1	
13	B	SPACER B	1	
14	B	SPACER C	1	
15	B	SPACER D	1	
16	A	CELL LENS	1	
17	B	SPACER E	1	
18	B	SPACER F	1	
19	B	RETAINER	1	
20	A	RETAINER LENS	1	
21	A	LINEAR POLARIZER	1	
22	COMPL	NYLON SLAGTED PANNO SLOPE B-32 X 7/16	4	
23	COHL	CORRECTION 1/8 SQ X 1/2 THK	4	
24	B	OPTICAL ARRANGEMENT	-	

DATE OF APPROVAL 11/27/57
 DATE OF RELEASE
 ALL DRAWING OR 151845
 SHEET 1 OF 1
 PL 151845
 SHEET 507

REVISIONS		DATE	APPROVED
LTR	A	ISSUED	9 20 74

FARRAND OPTICAL CO., INC.		VALHALLA, N. Y. 10585	
117 WALL ST.		RETAINER PRISM HMD	
CONTRACT NO.	211	SIZE	A
DRAWN	L. J.	CODE IDENT NO.	21587
CHECKED	J. J.	DRAWING NO.	151846
PROG. ENG.	J. J.	SCALE	1:1
APPROVED	J. J.	SHEET	OF 507
RELEASED BY	J. J.	USED ON	507

UNLESS OTHERWISE SPECIFIED		CYCLOCAC ABS	
INCLUDE ALL DIMENSIONS		GR GSM	
DIMENSIONS ARE IN INCHES		FINISH: BLACK	
FRACTIONS DECIMALS ANGLES	± .005		
1/2 1.005			
2	151845	1	RECD
ITEM	NEXT ASSY		
APPLICATION			



REV. NO.	DESCRIPTION	DATE	APPROVED BY
1	ISSUED		

151847

FARRAND OPTICAL CO., INC. 117 WALL ST WASHINGTON, D.C.	
FLANGE RELAY HOUSING	
SITE CODE B 21587	DRAWING NO. 151847
SCALE 1:1	SHEET 507
CONTRACT NO.	DATE
DRAWN BY	CHECKED BY
DESIGNED BY	APPROVED BY
RELEASED BY	DATE
THIS DRAWING IS THE PROPERTY OF FARRAND OPTICAL CO., INC. IT IS TO BE KEPT IN CONFIDENCE AND NOT TO BE REPRODUCED OR COPIED IN ANY MANNER WITHOUT THE WRITTEN PERMISSION OF FARRAND OPTICAL CO., INC.	MATERIAL CYCOLAC HE- G; GSM COLOR BLACK
ITEM 6	QTY 2
PART NAME	REQ'D
APPLICATION	

REVISIONS		DATE	APPROVED
LTR	DESCRIPTION	4-30-79	
A	ISSUED		

THD. 5/16-18 NC - RH. THD. 5/16-18 NC L.H.

10 1/2

7/16

5/16

.244 ± .002 DIA. TYP.

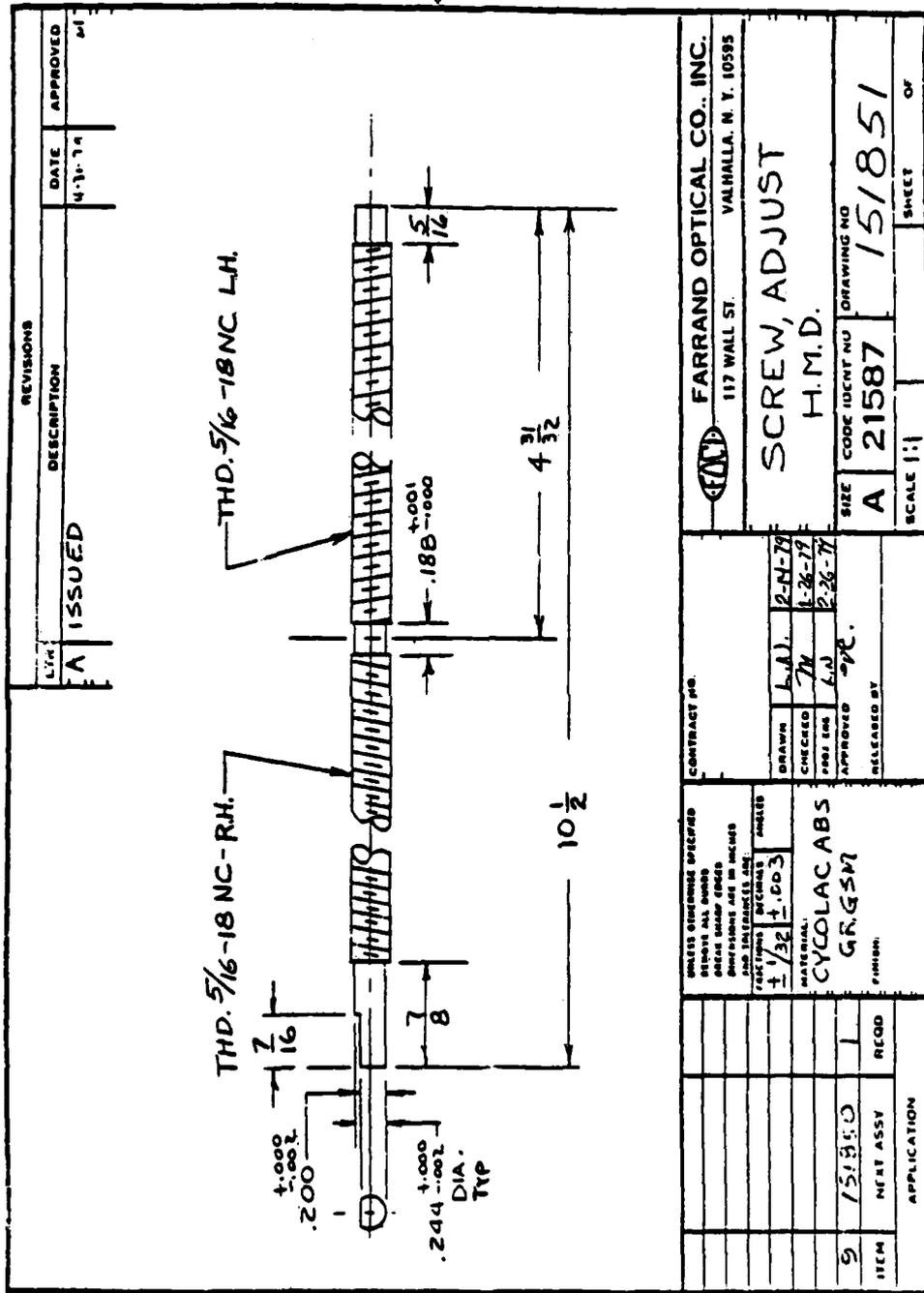
.200

1/16

180-1000

31 4 3/2

FARRAND OPTICAL CO., INC. 117 WALL ST VALHALLA, N. Y. 10595	
SCREW, ADJUST H.M.D.	
SIZE CODE I.D.N.F. NO A 21587	DRAWING NO 151851
SCALE 1:1	SHEET OF 507
CONTRACT NO.	DRAWN L.A.L. CHECKED W.M. FARRAND OPTICAL CO. INC. APPROVER E.J.J. RELEASED BY W.P.C.
UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES DECIMALS AND FRACTIONS ARE TO BE USED	MATERIAL: CYCOLAC ABS GR. 5M FINISH:
ITEM 9	QTY 1
PART NO. 151850	REQD.
APPLICATION	



FARRAND OPTICAL CO., INC. 117 WALL ST. VALHALLA, N. Y. 10595	
SCREW, ADJUST H.M.D.	
SIZE CODE IDENT NO A 21587	DRAWING NO 151851
SCALE 1:1 SHEET OF	
4 USED ON 507	
CONTRACT NO.	
DRAWN L.A. 2-24-73	CHECKED J.N. 1-28-74
PROJ ENG L.A. 2-26-74	APPROVED [Signature]
RELEASED BY	
UNLESS OTHERWISE SPECIFIED DIMENSIONS ALL DIMENSIONS ARE IN INCHES DECIMAL DIMENSIONS ARE IN THOUSITHS OF AN INCH FRACTIONS DIMENSIONS ARE IN THOUSITHS OF AN INCH	
MATERIAL CYCOLAC ABS GR.GSM	FINISH
ITEM 9	RECD 1
APPLICATION NEXT ASSY	

REVISIONS		DATE	APPROVED
LTR	DESCRIPTION	4-30-71	
A	ISSUED		

UNLESS OTHERWISE SPECIFIED REMOVE ALL DIMENSIONS AND FINISHES DIMENSIONS ARE IN INCHES AND TOLERANCES ARE		CONTRACT NO.
FRACTIONAL DECIMALS	SINGLES	
1/64 ±0.005		
MATERIAL:	CYCOLAC ABS	
	GR. GSM	
	FINISH	

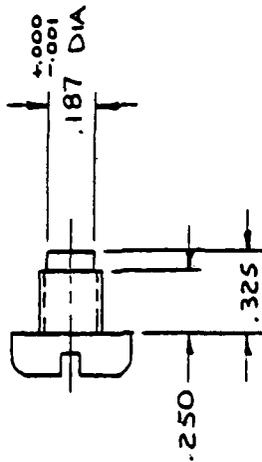
ITEM	10	151850	2	RECD
		NEXT ASSY		
		APPLICATION		

DRAWN	L.M.	2-14-71
CHECKED		
POST ENG	20	11-16-71
APPROVED	20	
RELEASED BY		

FARRAND OPTICAL CO., INC.	
117 WALL ST VALHALLA, N. Y. 10585	
BUSHING	
HMD	
SIZE	CODE IDENT NO
A	21587
DRAWING NO	151852
SCALE	1:1
SHEET	OF
	507

NOTE :

- 1. MAKE FROM 1/4-28 x 3/8 LONG NYLON SLOTTED PAN HEAD MACHINE SCREW

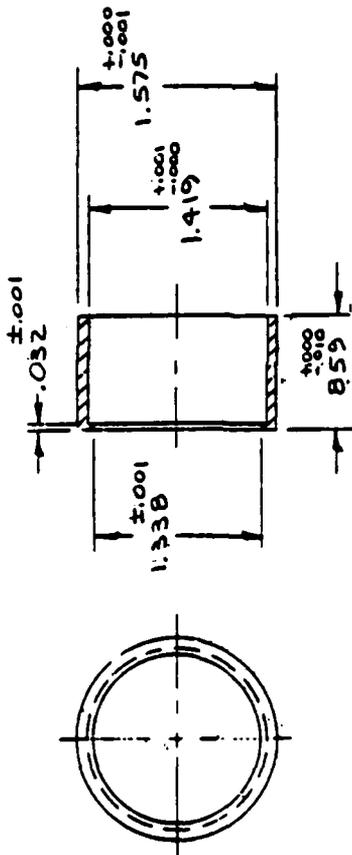


REVISIONS		DATE	APPROVED
LTN	A ISSUED	4-30-74	

<p>UNLESS OTHERWISE SPECIFIED REMOVE ALL BURRS CHAMFER SHARP EDGES DIMENSIONS ARE IN INCHES AND DECIMALS ARE</p>		<p>CONTRACT NO.</p>
<p>FRACTIONS DECIMALS ANGLES</p>	<p>1 010</p>	<p>FARRAND OPTICAL CO., INC. 117 WALL ST. VALHALLA, N. Y. 10595</p>
<p>MATERIAL SEE NOTE 1</p>	<p>DRAWN 9-6-73</p>	<p>SCREW - DOG</p>
<p>FINISH</p>	<p>CHECKED 7/1 4-24-74</p>	<p>SIZE CODE IDENT NO DRAWING NO A 21587 151853</p>
<p>ITEM 151850 RECD</p>	<p>APPROVED L.J. 4-24-74</p>	<p>SCALE 2/1 SHEET OF</p>
<p>APPLICATION</p>	<p>RELEASED BY K</p>	<p>USED ON 507</p>

NOTE :
 1. DIAMETERS TO BE
 CONCENTRIC WITHIN .001

REVISIONS		DATE	APPROVED
LTR	DESCRIPTION		
A	ISSUED		



FARRAND OPTICAL CO., INC.
 117 WALL ST. VALHALLA, N. Y. 10595

CELL-LENS

SIZE CODE IDENT NO DRAWING NO
A 21587 151856

SCALE 1/1 SHEET OF

CONTRACT NO.		DRAWN <i>FS</i> 8-11-77	
		CHECKED <i>L.W.</i> 4-26-77	
		PROF. ENG. <i>P.T.</i> 4-26-77	
		APPROVED <i>M</i>	
		RELEASED BY	

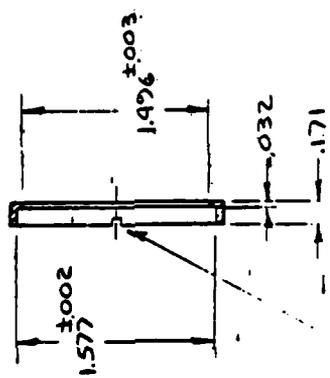
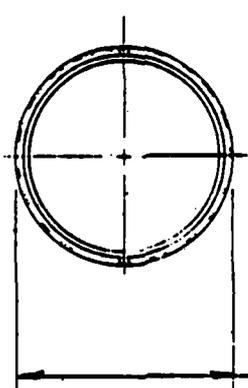
UNLESS OTHERWISE SPECIFIED
 DIMENSIONS ARE IN INCHES
 FRACTIONS DECIMALS ANGLES

MATERIAL:
**RULOM,
 BLACK**

ITEM	DESCRIPTION	REQD	APPLICATION
16	151E 45	1	NEXT ASSY

USED ON 507

REVISIONS		
LTR	DESCRIPTION	DATE
1A	ISSUED	4.15.74



.062 ±.010 W. X. 062 ±.010 D
 2 SAW SLOTS 180° APART

FARRAND OPTICAL CO., INC. 117 WALL ST. VALHALLA, N. Y. 10595		RETAINER - LENS	
CONTRACT NO.		SIZE CODE	IDENT NO
DRAWN: <i>EL</i> 4-11-74 CHECKED: <i>EL</i> 4-26-74 APPROVED: <i>EL</i> 4-26-74 RELEASED BY: <i>EL</i>		A	21587
UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES TOLERANCES ARE AS SHOWN FINISHES ARE AS SHOWN TOLERANCES ARE AS SHOWN		DRAWING NO	SHEET
MATERIAL: RULON, BLACK		151858	1/1
ITEM: 20	QTY: 1	SCALE: 1/1 OF	
APPLICATION: NEPT ASSY		USE ON: 507	

REVISIONS		DATE	APPROVED
LTR	DESCRIPTION		
A	ISSUED	4-22-59	

.062 $\pm .010$ W X .030 $\pm .008$ D
 2 SAW SLOTS 180° APART

MAJOR DIA. 1.687 $\pm .005$
 PITCH DIA. 1.667 $\pm .004$
 32 NS THD

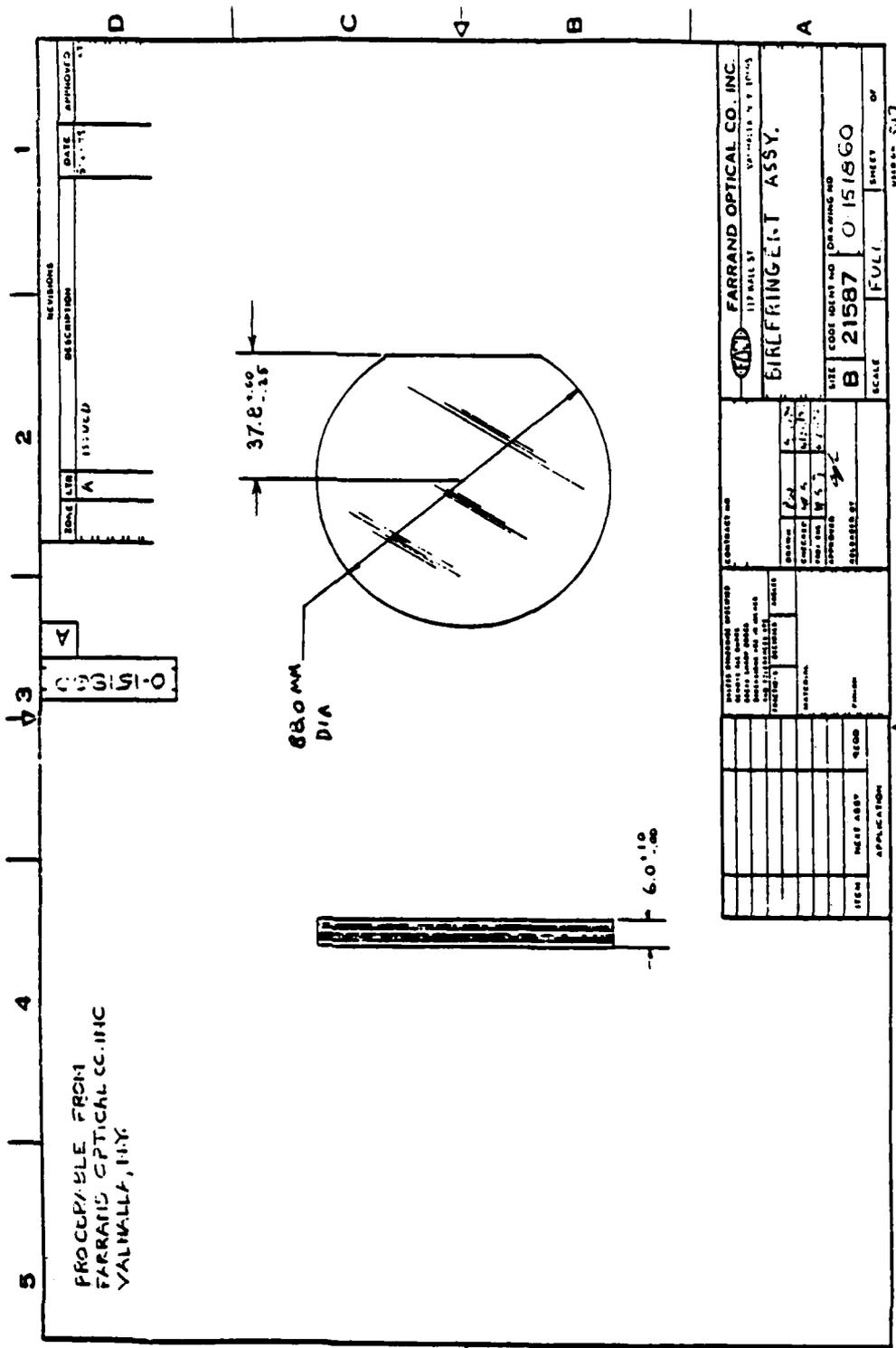
UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES DECIMALS AND FRACTIONS TOLERANCES ARE:		FINISH
DRAWING	15	RULON BLACK
CHECKED	L.H.	
APPROVED	J.H.	
RELEASED BY		

CONTRACT NO. **FARRAND OPTICAL CO., INC.**
 117 WALL ST. VALHALLA, N. Y. 10595

RETAINER

SIZE	CODE IDENT NO	DRAWING NO	SHEET	OF
A	21587	151859	1/1	507

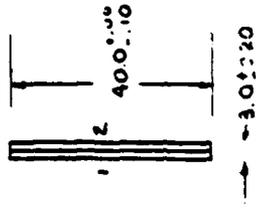
ITEM 151845 1 RECD
 APPLICATION NERT ASSY



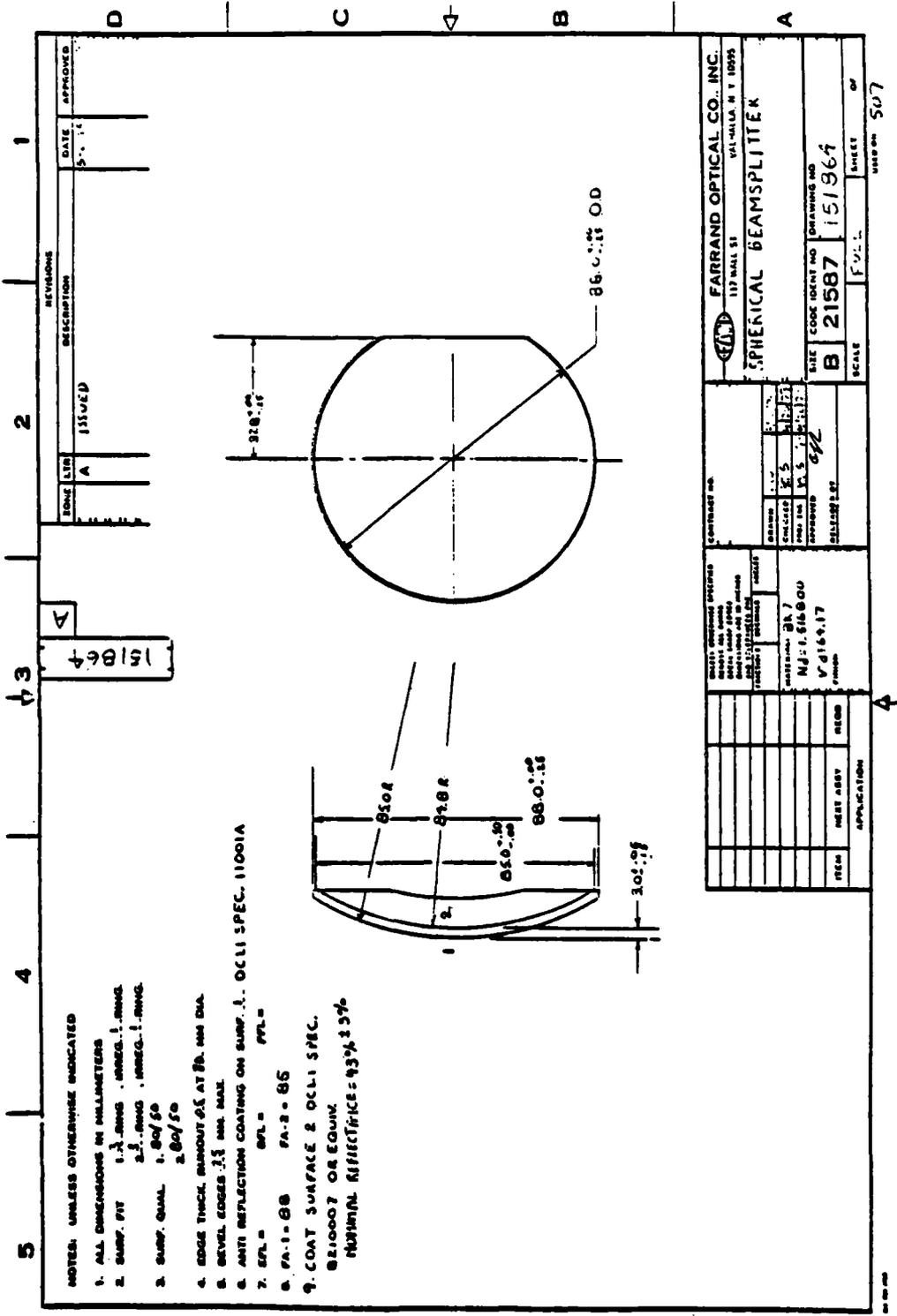
PROCURABLE FROM
FARRAND OPTICAL CO., INC.
VALHALLA, N.Y.

REVISONS		DATE	APPROVED
1	DESCRIPTION	3-2-51	
2			

- NOTES: UNLESS OTHERWISE INDICATED
1. ALL DIMENSIONS IN MILLIMETERS
 2. SURF. FIN. 1. REG. RING . IRREG. RING.
 3. SURF. QUAL. 1. 2.
 4. EDGE THICK. RUNOUT . . . AT . . . MM DIA.
 5. BEVEL EDGES . . . MM. MAX.
 6. ANTI REFLECTION COATING ON SURF. 1. 2.
 7. EFL = - BFL = - FFL =
 8. FA-1 = FA-2 =



FARRAND OPTICAL CO., INC. 117 WALL ST VALHALLA, N.Y. 10595		CONTRACT NO.	
LINEAR POLARIZER ASSY.		DRAWING NO.	
SIZE	CODE IDENT NO	DRAWING NO	
A	21587	0-151861	
SCALE		SHEET	OF
UNLESS OTHERWISE SPECIFIED REQUIRE ALL DIMENSIONS BEHIND DIMENSION LINES DIMENSIONS ARE IN MILLIMETERS AND TOLERANCES ARE		MATERIAL	
FRACTIONS IN DECIMALS ANGLES		FINISH	
DRAWN	CHECKED	APPROVED	RELEASED BY
W.P.S.	M	PC	
PROJ. ENG.			
ITEM	MAT ASSY	REQD	APPLICATION



- NOTES: UNLESS OTHERWISE INDICATED
1. ALL DIMENSIONS IN MILLIMETERS
 2. SURF. FTY 1. J. ANNO . ANNO. 1. ANNO.
2. J. ANNO . ANNO. 1. ANNO.
 3. SURF. QUAL 1. 80/50
2. 80/50
 4. EDGE THICK. WITHOUT .05 AT 90. MM DIA.
 5. BEVEL EDGES .33 MM MAX.
 6. ANTI REFLECTION COATING ON SURF. 1. OCLI SPEC. 11001A
 7. SFL = PFL =
 8. FA-1-88 FA-2-88
 9. COAT SURFACE & OCLI SPEC. 8210007 OR EQUIV.
MINIMUM REFLECTANCE = 93% ± 3%

FARRAND OPTICAL CO., INC. 117 HALL ST YONKERS, N. Y. 10553	
SPHERICAL BEAMSPLITTER	
CONTRACT NO. DRAWN BY CHECKED BY DATE APPROVED BY DESIGNED BY	SIZE CODE IDENT NO B 21587
DRAWING NO 151864	SCALE 1:1
SHEET NO 507	OF 507

