



ANVIS Objective Lens Depth of Field

By

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Aircrew Health and Performance Division

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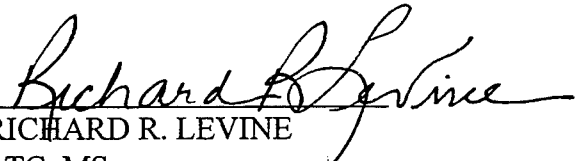
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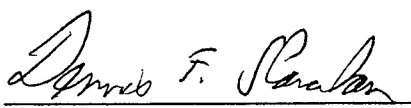
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1. In Appendix D, page 28, the graphs in Figures D-5 and D-6 were switched. The figure captions are correct.
2. In Appendix E, page 34, paragraph 2, last sentence, the viewing distance should be 17 inches, not 34 inches, to equate to 15 degrees horizontally.


William E. McLean

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19. ABSTRACT (Continue on reverse if necessary and identify by block number) Users of the AN/AVS-6 Aviator Night Vision Imaging System (ANVIS) need to know the minimum required distance for focusing the objective lenses to obtain infinity focus. With the increasing use of eye lanes to focus night vision devices, many users have the impression that 20 or 30 feet is "optical infinity" for the eyes as well as the ANVIS. Depth of field of a night imaging device is especially important to infantry soldiers. If a soldier focuses at infinity, near objects will be out of focus and vice versa. This study describes the ANVIS depth of focus using photographic techniques and provides data on changes in resolution with different viewing and focused distances (i.e., resolution vs. different amounts of defocus).					
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Introduction

The definition of "depth of field" of an imaging device is the distance in the object space through which satisfactory definition (resolution) can be obtained when the device is in focus for a particular distance (Laurin, 1990). For example, if a camera lens is focused on an object 25 feet away and the resolution is acceptable to the observer for objects from 20-40 feet, the depth of field extends from 20-40 feet.

The term "depth of focus" is commonly interchanged with "depth of field." Depth of focus is the range of clear focus at the image plane in front and behind the back focal point of the lens. In other words, the depth of field is the range of acceptable distances that produce clear imagery in front of the lens, and depth of focus is the range of clear imagery behind the lens on either side of the image plane. (See Figure 1.)

The actual range criterion for satisfactory or acceptable resolution for the depth of field does not have an actual value, but is usually user-defined by the device and testing conditions. For a given lens with a fixed entrance aperture, the ranges of the distances of the depth of field also change with the focal distance setting of the lens and the viewing distances. For example, the depth of field in linear units such as meters is much greater if a camera is focused at infinity than at 1 meter. In diopter units (the reciprocal of a distance in meters $[1/d]$), the depth of field for a particular optical device is relatively constant for any given focal distance.

Theoretically, the depth of focus of an objective lens, as distinguished from depth of field, can be described by the "tolerable" diameter of an imaged blur circle from a point source of light. This tolerable diameter is not necessarily the just noticeable blur point for objects that are not point sources of light. In photography, a camera lens' acceptable depth of focus also is related subjectively to the grain size of the film and the magnification of the print. For night vision devices, the spacing between the micro-channels equates to the film grain size in photography. The diameter of the blur circle is a function of the aberrations and distortions of the lens, diameter of the entrance pupil, the focal length of the lens, and the difference between the image focal point and the imaging plane, such as sensor elements or film for a camera (Smith, 1990).

The object distance at which a camera (sensor) must be focused so that the far depth of field just extends to infinity is called the "hyperfocal distance." The near limit of the depth of field is then half the hyperfocal distance. For normal photographic work, this distance equals 1000 times the lens aperture diameter (Laurin, 1990).

For the human eye, the minimum viewing distance to simulate infinity for refractive purposes has been assumed to be 20 feet (6.1 meters), but this value is dependent on the pupil size (Adler, 1989). This 6.1-meter distance equates to 0.16 diopter (the reciprocal of the distance in meters or $1/6.1$). The depth of field decreases with increases in the pupil size of the eye.

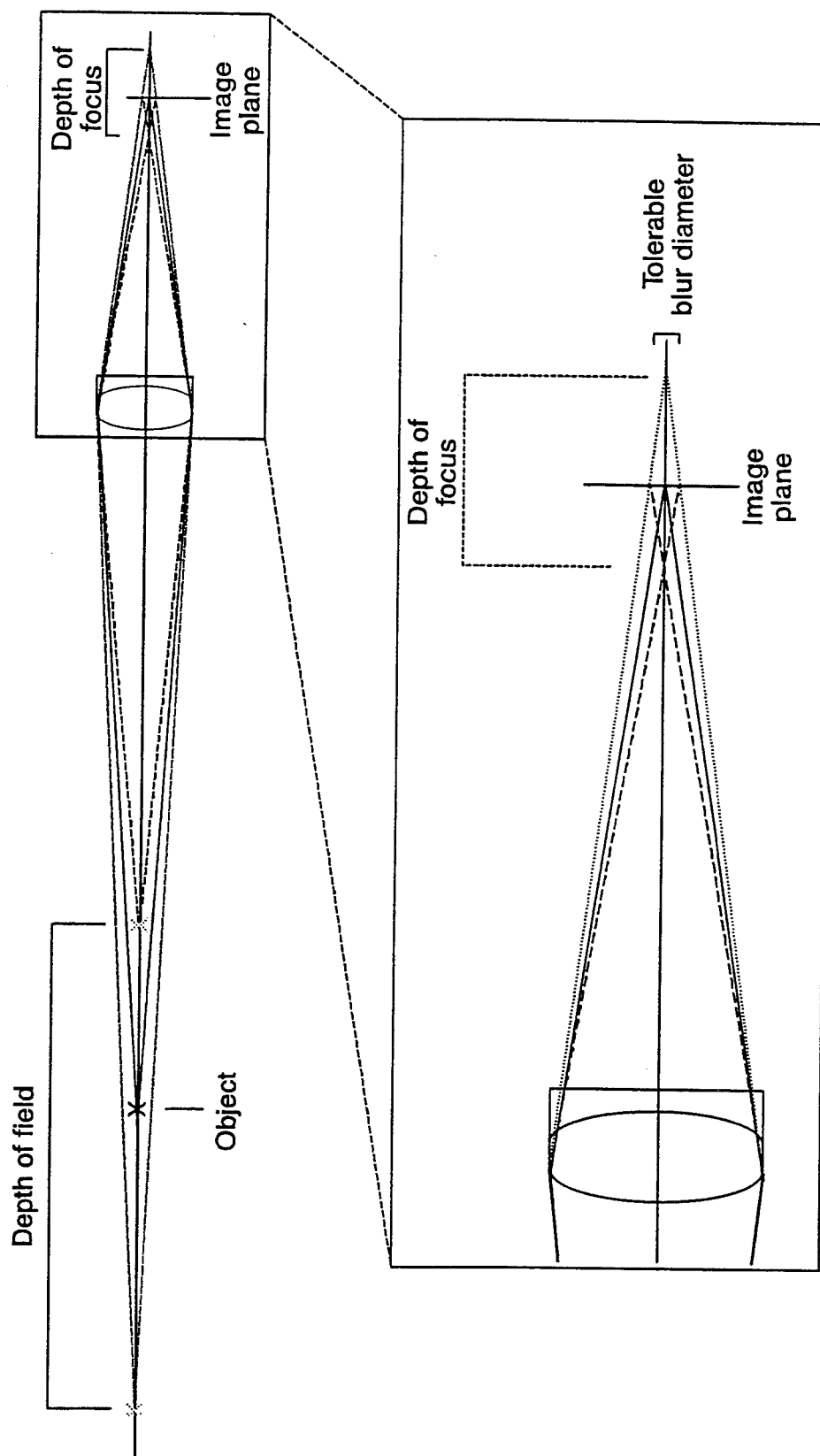


Figure 1. Depth of field and depth of focus illustration.

If we assume an eye pupil size range from 2 to 6 mm and an eye focal length of approximately 24 mm, then the calculated f -number ($f/\#$) (focal length divided by the entrance pupil diameter) for the eye would range from 12.0 to 4.0. For the ANVIS, the entrance aperture is approximately 23 mm and the focal length is approximately 27 mm. Therefore, the calculated $f/\#$ for the objective lens of the ANVIS is approximately 1.17.

The Air Force standard operating procedures for night vision goggle (NVG) flights include the use of NVG eye lanes. A resolution chart of high contrast vertical and horizontal bars with varying spatial frequencies is used to check the image intensifier tubes of the goggles, preadjust mechanical alignment, and focus the eyepieces and objective lenses for optimum vision prior to flight (Antonio et al, 1994). These NVG eye lanes typically are 20 to 30 feet long and illuminated with a 7-watt incandescent lamp having a small light exit hole of approximately 5 mm. There has been some misunderstanding about whether the 20-foot distance (6.1 meters) is optical infinity for the ANVIS as well as for the eye. In the above report, it was stressed that the ANVIS objective lenses needed to be refocused in the aircraft using objects at least 75 feet (23 meters) away. The specific objects suggested for focusing prior to flight were ones with well-developed vertical or horizontal features, or the symbology in the head-up display (HUD), if the aircraft has a HUD. As last resort, a bright star or distant light was suggested for focusing the objective lens.

Objective

This study was designed to quantify the ANVIS objective lens depth of field using infinity and near infinity objects, such as stars and trees, and a 5-meter focusing distance. The 5-meter ANVIS focus distance was selected to obtain changes in resolution with equal diopters of blur both in front of the focused distance and behind the focused distance with the 1.3 by 1 meter width-to-height dimension of a standard 1951 Air Force 3-bar field resolution chart. Additionally, there had been a request by the night vision section of the Aviation Training Brigade at Fort Rucker, Alabama, to evaluate the use of an infrared (IR) light emitting diode (LED) commonly called the "Bud lite" as a covert focusing target.

Approach

To avoid the numerous potential confounds associated with using subjects to determine depth of field for ANVIS, a photographic assessment was made with the focus of the ANVIS objective lens optimized by an experienced NVG user and investigator. High ambient light levels and a high contrast resolution chart which maximized the limiting measurable ANVIS resolution was used. Lower contrast targets and lower ambient light levels would increase the depth of field because of the lower best obtainable resolution to the observer. However, our primary interest was in the smallest measurable depth of field under the most favorable conditions and for an infinity focus position.

To ensure that the photographed images obtained through the ANVIS were limited in resolution by the intensifier tube and not the combination of film, camera, or viewer resolution limits, the 3-bar chart was photographed during the day without the ANVIS, using the intended camera, a 135-mm focal length camera lens, a 3.0 neutral density filter (0.1 percent transmission), and 400 ASA black and white film. The camera and film system resolution were calculated and compared to the measured ANVIS limiting resolution. Note that a 135-mm camera lens has approximately a 15-degree field of view (FOV) with a 35-mm film camera. (Film width is actually 36 mm.)

Methods

Apparatus

The following were used:

-- ITT* single tube ANVIS image intensifier with the objective lens housing modified to use fine mounting threads for focusing. With this modification, one rotation of the objective lens equaled approximately 1.33 diopters of focus change as compared to a standard ANVIS objective lens focusing knob where a ½-turn equals approximately 4 diopters of focus change. This fine focus modification is equivalent to the objective lens focusing threads on the recently fielded model F4949 "Super ANVIS."

-- Canon T50* 35-mm single-lens reflex still photographic camera with a 135-mm focal length, *f*/# 2.8 telephoto lens, and ANVIS to camera adapter; Ilford black and white XP1 or XP2* 400 film (ISO 400 or 400 ASA).

-- U.S. Air Force 1951 high contrast 3-bar resolution charts produced by the Rochester Institute of Technology with a resolution range from -6,1 to -1,6 (group, element). See Appendix B for a description of the chart and a method to calculate Snellen resolution for a given viewing distance in meters.

-- Tripods and resolution chart mounts.

-- Near infrared (IR) light emitting diode (LED) marker light ("Bud lite") with peak intensity at 865 nanometers.

* See manufacturer's list in Appendix A

Procedure

Photographs of the resolution chart and objects focused were taken through ANVIS on the following dates under the listed conditions:

- 13 Mar 1995 at 90 percent moon, clear skies
- 7 Apr 1995 at 48 percent moon, clear skies
- 15 Apr 1995 at 100 percent moon, clear skies
- 27 Apr 1995 inside USAARL with a filter over the ANVIS objective lens, 5 meter focusing distance

Ten viewing distances previously were marked off from 2.5 meters (0.40 diopter) to 20 meters (0.05 diopter) in 0.05 diopter steps, and at 40 (0.025 diopter) and 50 meters (0.02 diopter). The ANVIS objective lens initially was focused at each of the 10 viewing distances (from 2.5 meters to 50 meters) and photographs of the 3-bar chart were taken for documentation to determine limiting ANVIS/camera resolution at the focused distances. The ANVIS objective lens was focused either at >100 meters to infinity (<0.01 diopter) or at 5 meters, and photographs taken of the 3-bar chart at the 10 different viewing distances without refocusing the ANVIS objective lens during a trial (see data recording forms in Appendix B). A minimum of five trials were conducted at each focus distance for each focusing object, alternating between ascending and descending viewing distances. The ANVIS objective lens and the camera lens were refocused between ascending and descending trials. For the noninfinity focus distances, the 3-bar U.S. Air Force resolution chart was used for focusing. For infinity focus in the field test site, three different objects located beyond 100 meters (<0.01 diopter) were used, including a near IR 9-volt marking LED ("Bud light"), trees, and stars.

The ANVIS eyepiece was focused between 5 meters (0.20 diopter) and infinity using the focusing scale on the 135-mm telephoto lens. The Canon T50 SLR camera has three different methods of determining optimum focus: (1) the laser matte screen appears blurred when out of focus; (2) the microprism rangefinder shimmers when the object is out of focus; and (3) the split screen rangefinder shows target aligned vertically when in focus. Method (3) was used as the primary technique and verified with method (1) in focusing the camera to the ANVIS eyepiece focus.

To determine the focus for the ANVIS objective lens, the investigator minimized the spot size when using the stars and the IR LED, and maximized the contrast to detect the highest spatial frequencies (smallest visible elements) when viewing the resolution chart and tree structures through the viewfinder of the camera. The optimum focus point was obtained after rotating the ANVIS objective lens focusing knob back-and-forth and centering between just noticeable blur positions.

The camera iris/diaphragm and shutter speed settings were in the "automatic" position. Previous photographs in the laboratory with the Canon T50 and 135-mm focal length camera lens through ANVIS have shown that the resolution on the U.S. Air Force 3-bar high contrast chart to be the same from below starlight to full moon illumination when the "automatic" exposure setting of the camera is selected. The camera automatically increases the exposure time with decreasing light levels. For high contrast targets, the noise in the intensifier tube is averaged without any apparent loss in limiting resolution within the ambient illumination tested for a high contrast target.

The location for the field portion of this study was behind the USAARL building in an area approximately 250 meters from the main road and surrounded by trees except for a narrow asphalt path. The resolution chart was placed west of the ANVIS/camera combination such that the moon was always behind the camera during the trials, which maximized the illumination on the chart. On the nights selected for data collection, the sky conditions were clear or partially cloudy such that stars were visible in all four quadrants of the sky. Photographs did not begin until at least 1 hour after sunset.

The photographic film was black and white, 400 ASA. One investigator determined the minimum size 3-bar pattern discernable on the film negatives using up to three different magnifiers between 2.6X and 10X for each condition and viewing distance. We originally looked at 7 x 9 inch prints of the negatives and concluded that the printing process also could reduce the resolution and increase the variability. Since the patterns on the 3-bar chart are coded in group and element numbers or cycles per millimeter, the angular resolution such as Snellen acuity would not be known by the investigator until it was calculated using an equation (Appendix B) for a given viewing distance.

The different combinations of ANVIS focus distances, focusing object, and viewing distances for each trial are shown in the data form (Appendix C). For all infinity objective lens focus conditions, photographs were taken from 50 meters to a minimum distance of 4 meters instead of the 2.5 meter distance for some of the trials to reduce the data collection time.

For the depth of field trials at 5.0 meters, the investigator also used the hallways in USAARL in the evening to photograph through the ANVIS. At the outdoor field site, accurate placement of the ANVIS/camera combination with respect to the stationary resolution chart required a plum line from the ANVIS objective lens with respect to the distance markers on the path to reduce placement errors. By using the hallways inside the USAARL building, the tripod legs were marked to correspond to the same position as the plum line, thus reducing the amount of time needed to readjust positions and improving accurate placement of the ANVIS objective lens. An attenuating filter was added to the ANVIS objective lens to allow sufficient light to minimally activate the automatic gain control in the ANVIS power supply and allow the experiment to be conducted using only the hallway fluorescent lighting. The attenuating filter both protected the ANVIS and permitted the maximum light output from the ANVIS eyepiece.

Results

Calibration

The mean limiting focused resolution determined at each viewing distance from 2.5 to 50 meters for the camera, lens, 3.0 neutral density filter, and film combination without the ANVIS was 20/9.3 Snellen resolution. The standard deviation (SD) of the denominator was 0.85 (i.e. 20/8.45 to 20/10.15 for ± 1 SD). The number of viewing distances was 10. This mean limiting resolution equates to 0.47 arc minutes, 3.7 cycles per milliradian, or 26.9 line pairs per millimeter on the film negatives.

With ANVIS and the camera system, the average limiting Snellen resolution from 2.5 to 50 meters averaged 20/48.1, with a SD of 3.32 for the denominator ($N = 20$) on the full moon night, and 20/47.9, with a SD of 2.50 ($N = 10$) on the $\frac{1}{2}$ moon illumination night.

Focused at infinity

Stars -- Figure 2 shows the plots of the mean resolutions with 1 standard error (SD/square root of N) from 2.5 to 50 meters when the ANVIS objective lens was focused using stars. The dotted line is from the model derived from the data. The model is described in Appendix D. The data were averaged over the three nights with 48-, 90-, and 100 percent moon illumination. Figure 3 shows the same resolution data for each trial plotted versus diopters of blur. Note that on the plot of the six individual trials, the spread between the curves is approximately 0.05 diopter.

Trees -- Figure 4 shows the plots of the mean resolutions with 1 standard error from 2.5 meters to 50 meters when the ANVIS objective lens was focused using trees beyond 100 meters. The dotted line is from the model and deviates from the data beyond approximately 10 meters. Figure 5 shows the six individual plots and the model prediction using the diopter scale. Note the increase in variance between trials when using the trees to focus rather than the stars. The diopter spread is a little more than 0.05 diopter.

IR LED -- Figure 6 shows the plots of the mean resolutions with 1 standard error when focusing the ANVIS on the IR LED, which was located at greater than 100 meters. The dotted line is from the model and shows a significant deviation from the data at distances 10 meters (0.10 diopter) or closer. Figure 7 shows the plots for each of the five trials with the model using the diopter scale. Note that the ranges for the five trials appear to be slightly less than 0.05 diopter for a given resolution.

After plotting the data for the infinity focused objects, it was noted that the IR LED appeared to focus closer in diopters than its actual location. Figure 8 shows the IR LED data shifted by 0.02 diopter, which provides a better fit to the model.

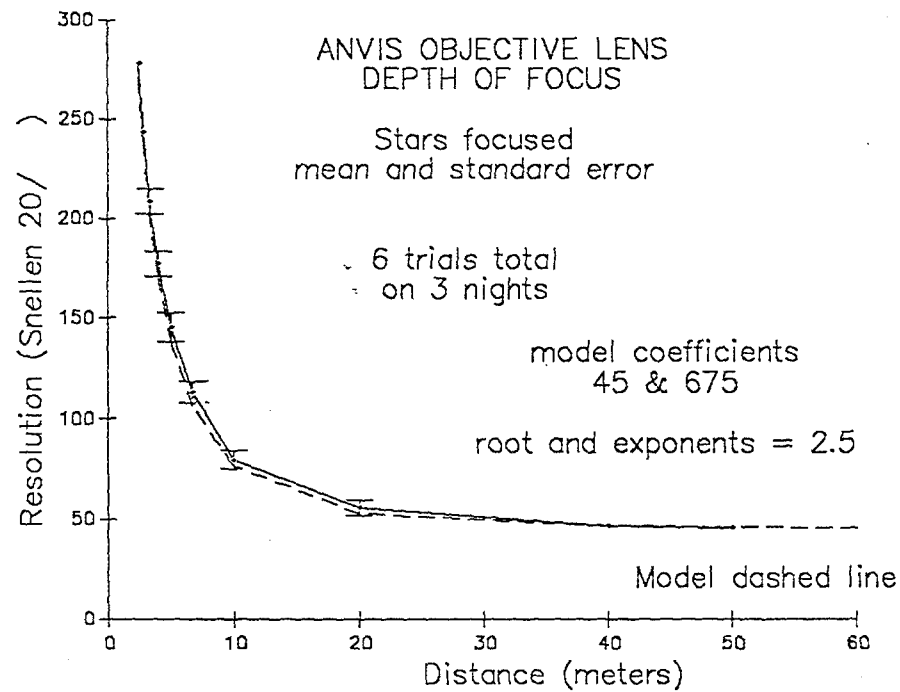


Figure 2. Stars focused; mean resolutions and model versus viewing distances.

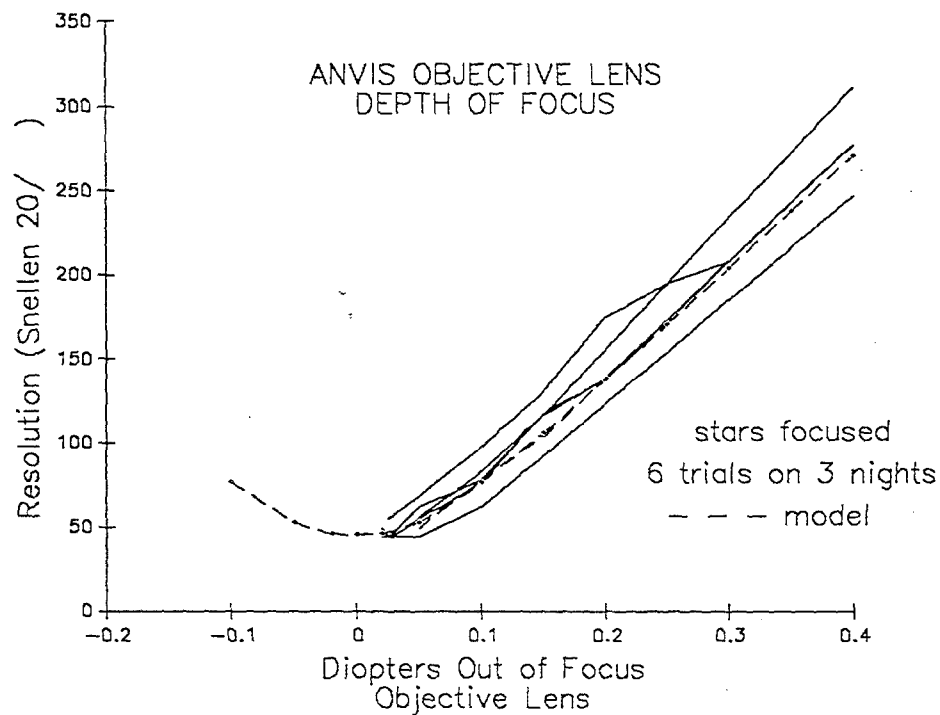


Figure 3. Stars focused; individual trials -- resolution versus diopters of blur.

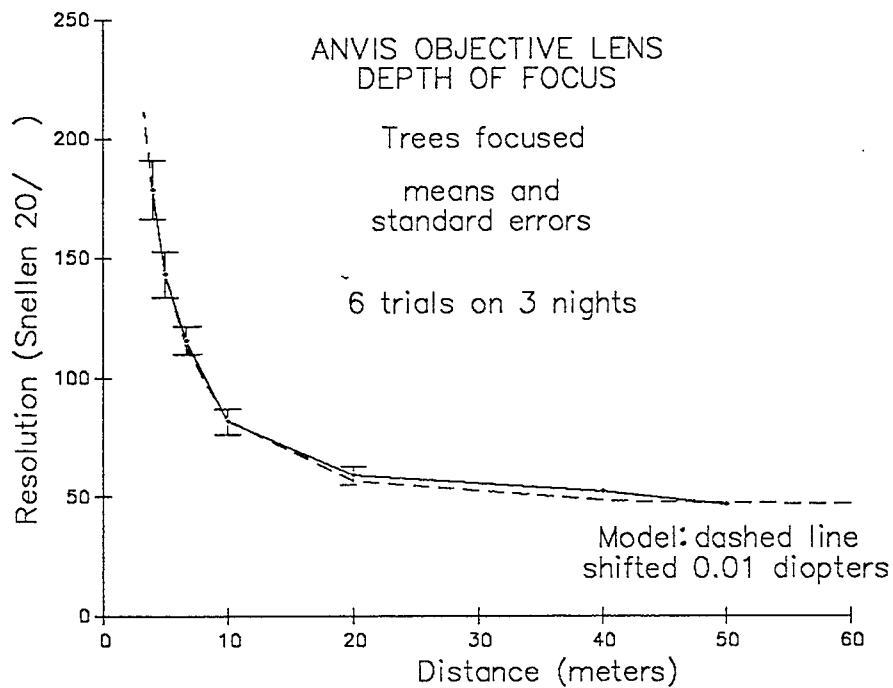


Figure 4. Trees focused; mean resolutions and model versus viewing distances.

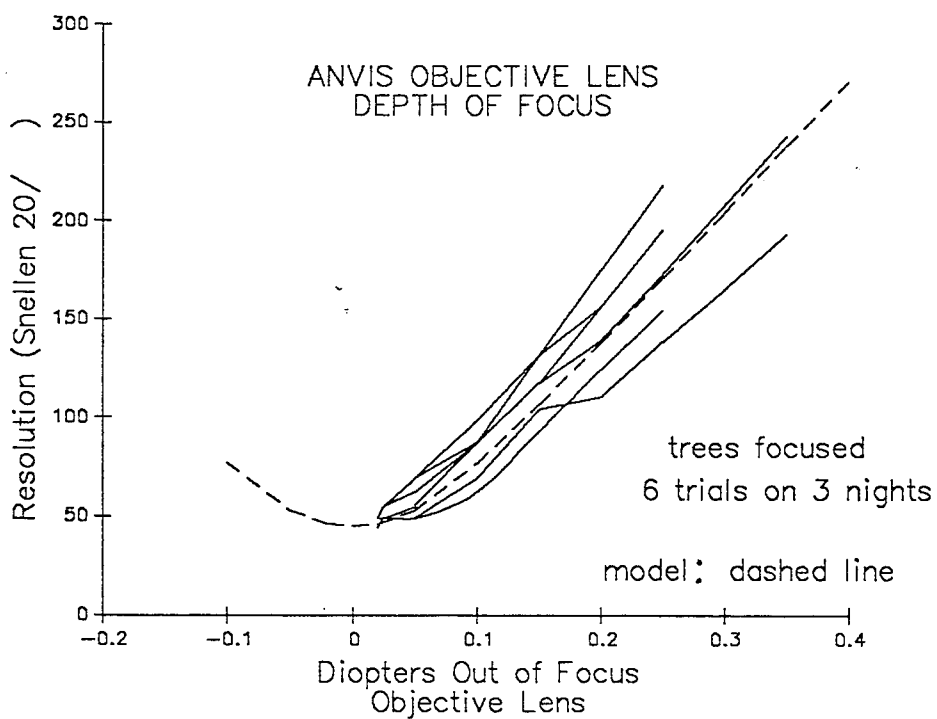


Figure 5. Trees focused; individual trials -- resolution versus diopters of blur.

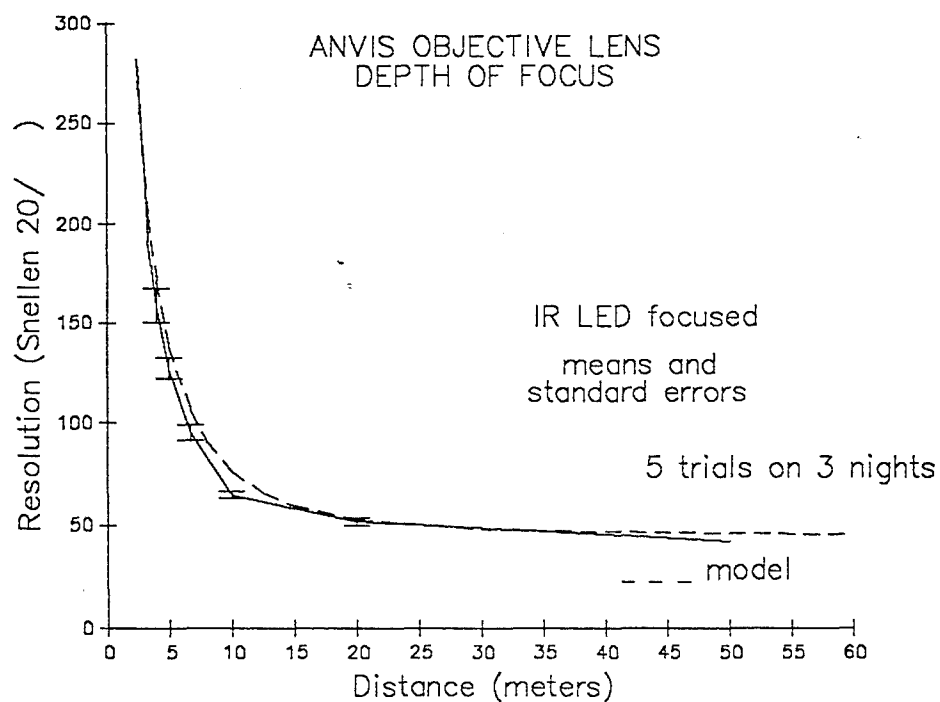


Figure 6. IR LED focused; mean resolutions and model versus viewing distances.

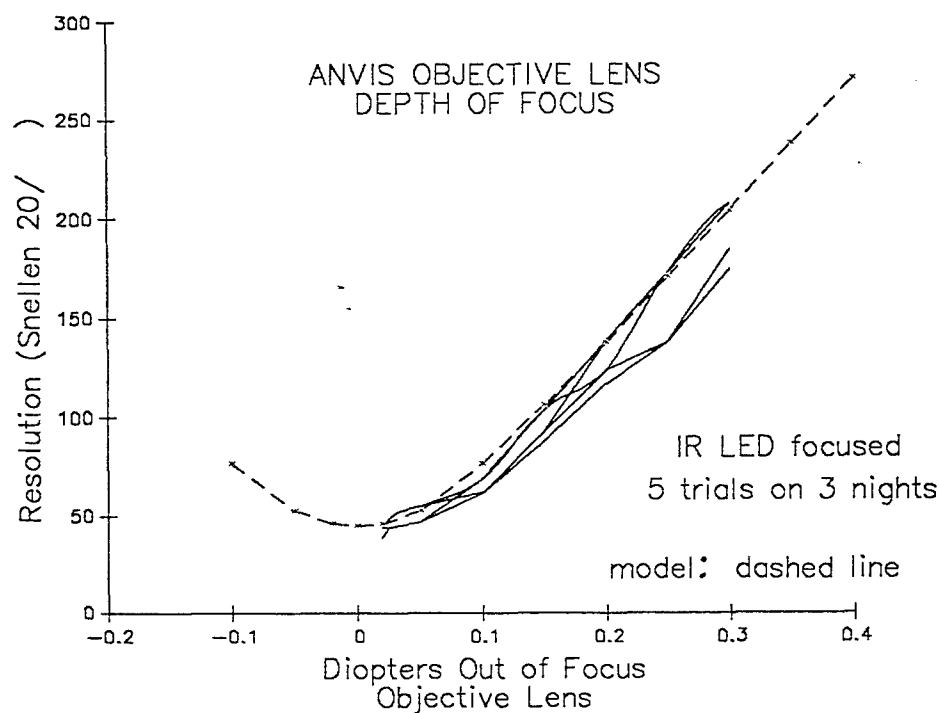


Figure 7. IR LED focused; individual trials -- resolution versus diopters of blur.

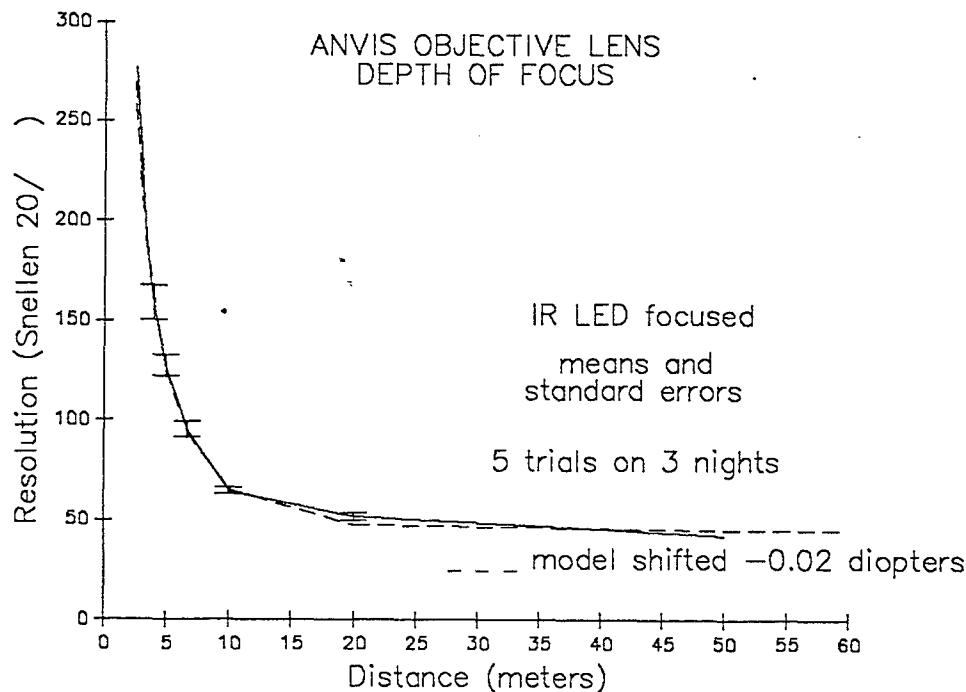


Figure 8. IR LED focused data shifted 0.02 diopter.

The solid line in Figure 9 shows the average resolution across all trials of infinity focus measurements using the stars and trees versus viewing distance in meters. Note that the variability bars are standard deviations instead of the standard error bars in the previous plots. The standard deviation was used at each range because of the difference in the number of trials at each point. The dashed line is the derived model from these data. The description of the model is found in Appendix D.

Focused at 5 meters

Figure 10 shows the mean resolutions and standard errors versus diopters of blur using the outside test site. Note that the average resolution values were slightly better than the model prediction for viewing distances beyond 6.66 meters (-0.15 diopter). However, the data points are based only on three trials. Figure 11 shows the mean resolutions and standard errors versus diopters of blur from five trials using the indoor hallways with an attenuating filter over the ANVIS objective lens. Note the approximate equal blur for both in-front-of and behind the five meter focused distance in diopters for the inside measurements of depth of focus. For the inside measurements of the depth of field, slightly different values for the best resolution and diopter coefficients in the model provided a better fit than the limited outside infinity series of trials.

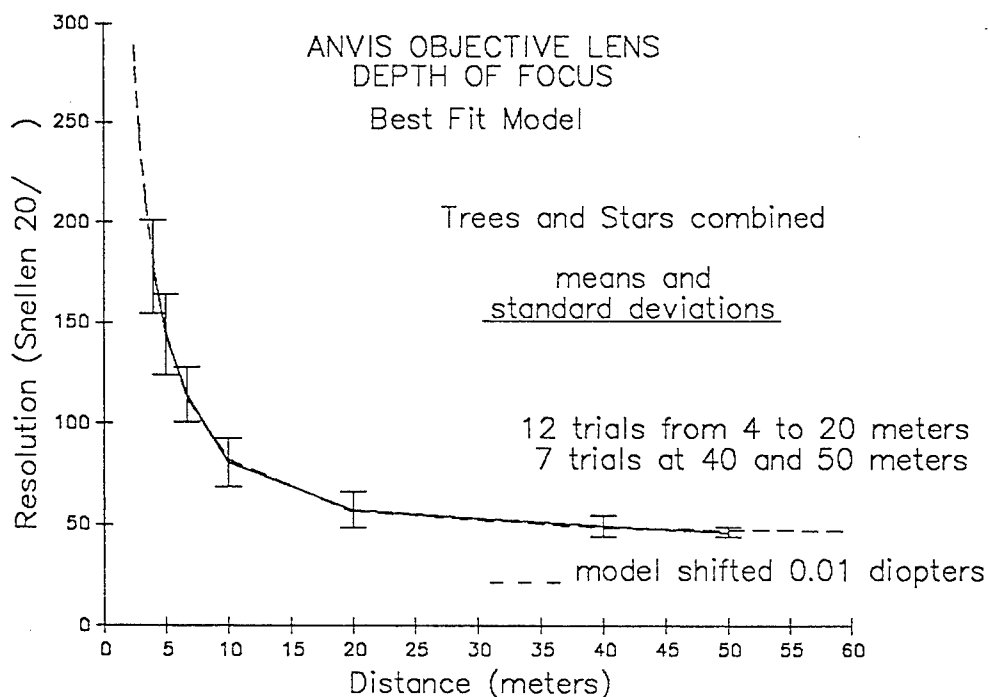


Figure 9. Stars and trees focused data averaged; resolution versus viewing distances.

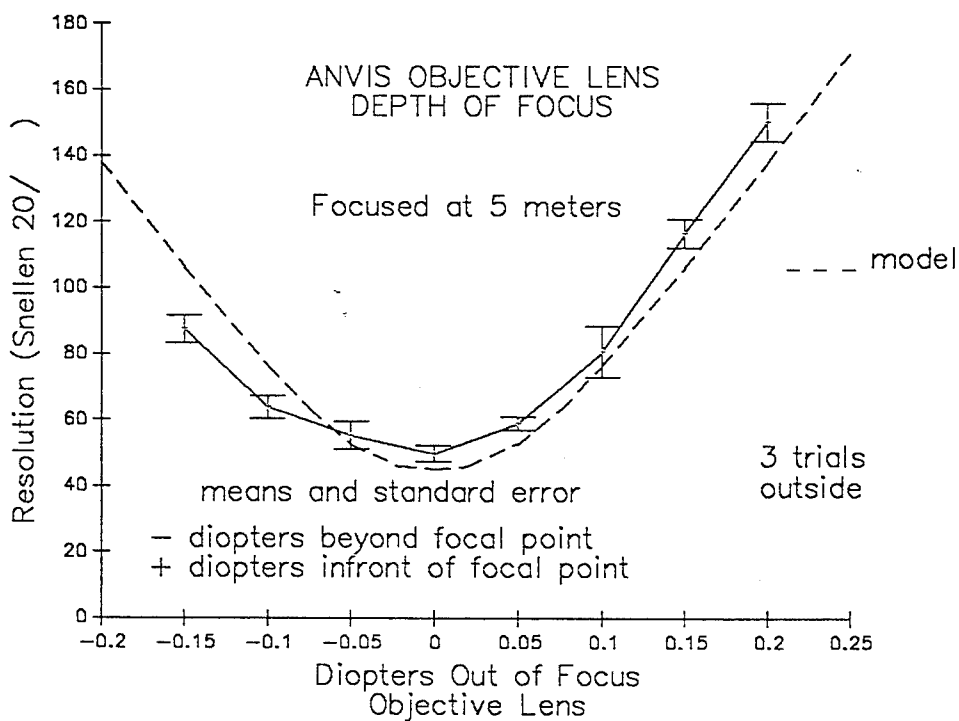


Figure 10. Resolution chart focused at 5 meters; outside site resolution versus diopters of blur.

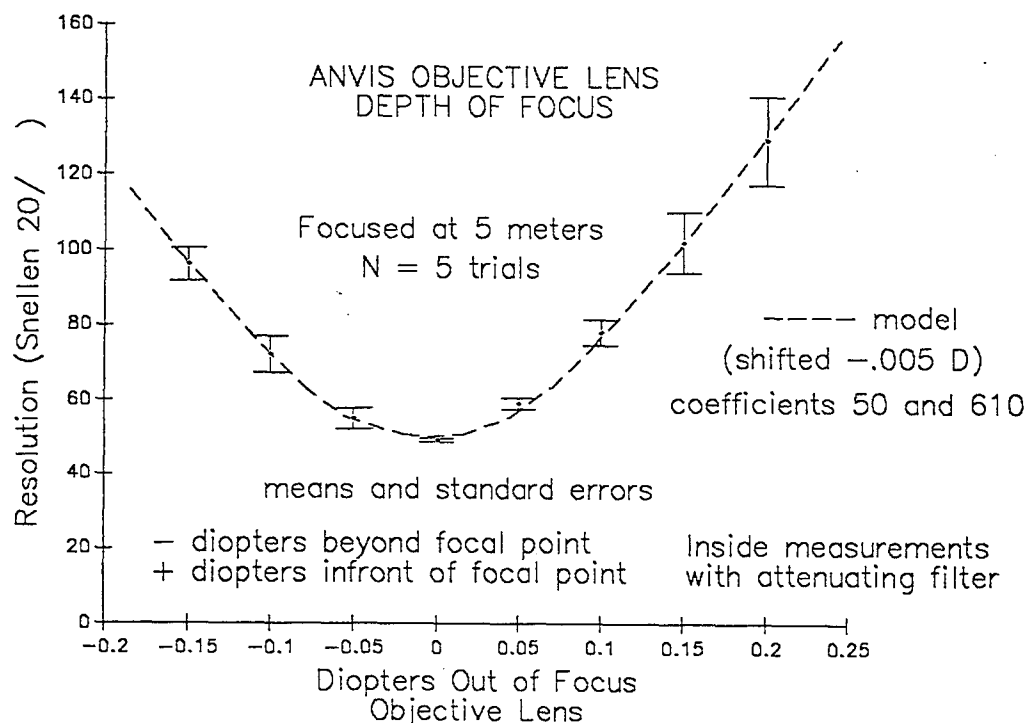


Figure 11. Resolution chart focused at 5 meters; inside site resolution versus diopters of blur.

Discussion

The slight apparent shifts of the data between trials, regardless of the object focused, imply that the range of focus for the ANVIS objective lens can vary up to approximately 0.05 diopter between trials under the best conditions. This is with a very experienced NVG user and experimenter, a telephoto lens on the camera, and a modified ANVIS objective lens that has a fine focus adjustment.

With a standard ANVIS objective lens, a rotation of approximately 2.2 degrees resulted in 0.10 diopter of focus change. With the modified objective lens used in this study, 27 degrees of lens rotation equated to a change of 0.10 diopter in focus position. With the standard coarse ANVIS objective lens focusing threads, we estimate approximately 30 degrees of rotational hysteresis. That means, if the user adjusts the objective lens beyond the focus point by 0.10 diopter, the objective lens focusing knob has to be reversed and rotated approximately 32.2 degrees to correct for the 0.10 diopter (30 degrees hysteresis and 2.2 degrees focus change). Any additional objective focusing knob rotation of 2.2 degrees will change the focus in increments of 0.10 diopter.

In the laboratory using the single tube ANVIS with the fine focus modification, we found that the focus could vary slightly from one side of the field of view to the opposite side by up to

approximately 0.07 diopter. This effect was found in all six tubes of our three standard ANVIS. The probable cause for a 0.07 diopter (50 micron) difference in focus between opposite edges in the field of view could be due to an approximate 0.1 degree tilt of the photocathode from a perpendicular plane to the objective lens optical axis.

This change in focus in different parts of the ANVIS field of view also may partially explain why the depth of field in diopters in the field evaluation appeared not to be equal in front of and behind the 5-meter focusing distance. In the field study, the camera and ANVIS tube always were aligned with the center of the resolution chart. When the measurements were made in the hallways at USAARL, the camera and ANVIS tube were aligned with the right hand side of the resolution chart which centered the previously found limiting resolution targets for the ANVIS.

In a previous study of ANVIS depth of field determination (Chyrek, 1995), it is not surprising that no statistically significant difference in ANVIS resolution was found at either 30 feet (9.14 meters or 0.109 diopter) or 200 feet (61 meters or .016 diopter). Lack of statistical significance probably was due to subject variability, the standard coarse focusing knob, and the use of the two tubes for the binocular ANVIS. By measuring and averaging ANVIS resolution both in front and behind the objective lens focal distance, the center and limits for the depth of focus can be more accurately determined.

As a follow up on the IR LED, where the data appear to show that the IR LED focused closer than the physical distance, we contacted Mr. John Hall, optical engineer, at the Night Vision Electronic Sensor Directorate, Fort Belvoir, Virginia, and asked if the ANVIS objective lens was color (wavelength) corrected at the 865-nanometer peak wavelength of the IR LED. Mr. Hall performed an optical analysis of the ANVIS objective lens using an optical computer program called "Code V" from a contractor supplied optical prescription, and found essentially no difference (less than 0.01 diopter) in the focal points for a broad band light source or the narrow band 865-nanometer LED.

The model suggests that the IR LED focal point is shifted approximately 0.02 diopter from the focal points for the trees and stars. There is a low probability that all five of the IR LED trials would appear to be focused at a nearer apparent distance than the best fit model for the stars and trees series. In the laboratory, we could not confirm or deny the apparent focus shift with the IR LED data, primarily because our sensitivity and variability for focus positions can be upwards of 0.05 diopter between trials.

This study examined only the objective lens depth of focus of the ANVIS. The focusing of the eyepieces will be examined in a future study, evaluating monocular and binocular focusing techniques with different types of objects used for focusing. When using the binocular focusing technique for the eyepieces, from personal experience, we believe that small point sources such as stars and distant lights are very poor binocular fusion stimuli when one image is in focus and the image in the other eye is slightly out of focus.

Conclusions

Since a slight reduction (17 percent for the model) in ANVIS resolution was shown with 0.05 diopter (20 meters) of blur, it is suggested that the viewing distance for focusing ANVIS for infinity be as great as practically possible, and not less than 50 meters (0.02 diopter).

In the course of evaluating the depth of field of the ANVIS objective, we found the following factors which may affect the final focus position and resultant resolution at a given focusing distance: (1) An experienced ANVIS user can be expected to adjust the objective lens within approximately ± 0.05 diopter of the viewing distance. (2) From multiple trials, ANVIS resolution was found to decrease from the objective lens focus distance with the 0.05 diopter blur increments used in this study. (3) High contrast luminous objects such as stars and distant visible lights are easier for the observer to focus the ANVIS objective lens than lower contrasting objects such as trees, and are at least equivalent and possibly easier to use than high contrast resolution charts. (4) Data from the narrow band near infrared light LED source (with a wavelength peak of approximately 865 nanometers) appeared to result in a focus at nearer optical distances with ANVIS than the actual viewing distance. However, we could not confirm this in the laboratory. (5) The ANVIS objective lens focus may vary within the field of view by approximately 0.07 diopter.

For estimation purposes (a rule of thumb) in estimating the Snellen resolution of ANVIS for a given amount of objective lens blur, the value of diopters of blur times 700 equals the Snellen resolution denominator (20/xx) is acceptable for values greater than 0.10 diopter of blur. For blur values of less than 0.10 diopter, a model using the ANVIS limiting resolution with the diopters of blur provides a good fit of the data obtained in this study (Appendix D).

As limiting resolution improves with more advanced ANVIS developments such as the "ultra tubes," accuracy in setting the objective lens with a low $f/\#$ will be more important in obtaining the best possible acuity for aviators for near infinity viewing distances. To accurately adjust and maintain this optimum objective lens focus, finer focusing threads with less hysteresis as used in this study and the latest U.S. Air Force model F4949 "Super ANVIS" are highly recommended.

For the ground-based infantry soldier who may need to quickly change focus between about 2 meters to infinity for clear vision while traversing over various terrain, the fine focus objective lens used in this study can be adjusted with one hand motion for lens rotation from 2 meters to infinity (approximately 135 degrees of rotation), albeit with 8 times more rotation than the standard NVG objective lens. However, if the soldier occasionally will be required to view objects at arms length from about 0.5 meters, and then quickly readjust the object lens back to near infinity (540 degrees of rotation or 1 ½ objective lens turns), the finer focusing objective lens may be contraindicated.

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Appendix A

List of Manufacturers

Canon, Inc.
P.O. Box 5050, Dai-ichi Seimei Building
Tokyo 163, Japan

Ilford Limited
Mobberly Cheshire, England

ITT Defense and Electronics
Electro-Optical Products Division
7635 Plantation Road
Roanoke, VA 24019

Appendix B

Description of U.S. Air Force 1951 3-bar resolution chart

The U.S. Air Force 3-bar high contrast resolution chart has been a standard for defining optical characteristics for many years (Boff and Lincoln, 1988; Farrell and Booth, 1984; Smith, 1990). The chart has three vertical and horizontal bar patterns which increase in size in approximately 1.12 to 1 ratio increments. There are six steps between a doubling of the 3-bar target size. The target sizes are coded using a group and element number where the size interval between group numbers is a factor of 2 and the interval between elements is the 6th root of 2. The group numbers correspond to the number of cycles per millimeter when the element number is 1. Increasing element numbers decrease the number of line pairs per millimeter.

The 3-bar pattern can be sized and coded from very small to very large, keeping the same size ratio between bar targets. The code (group, element) will determine the resolution in line pairs per millimeter. When the group number is negative, the resolution is usually expressed as the reciprocal of line pairs per millimeter, or millimeters per line pair. For a given viewing distance, the resolution can then be calculated in angular units such as milliradians, arc minutes, or Snellen resolution.

The following equation calculates the denominator of Snellen resolution for a given group, element, and viewing distance in meters:

$$20/R = \frac{(0.5)^X(0.891)^{(Y-1)}}{Z} \quad (34.4)$$

where: R = the denominator of the Snellen resolution

X = the group number (include minus sign if present)

Y = the element number

Z = the viewing distance in meters

The 3-bar targets on the chart used for this study ranged in size from -6,1 to -1,6 (group, element). The bar widths of the 3-bar target for the -6,1 subtend 2 arc minutes (20/40 Snellen) at 55 meters, and the -1,6 target bars subtend 2 arc minutes at approximately 1 meter.

An acceptable criterion for determining the end resolution on the 3-bar target is the smallest visible bar pattern that the observer can count the two spaces between the 3-bars. Eye limiting resolution with the 3-bar chart is approximately 70 sec arc compared to the 48 to 60 sec arc reported for Snellen letter charts or 35 sec arc/bar for grating orientation (Boff and Lincoln, 1988).

Appendix C

Data form

Date: _____ Start/End time: _____

Order: (Ascending) (Descending)

	Focus distance		Focus object	
	_____		<u>(3-bar)(stars)(trees)(IR)</u>	
	Distances (meters)	(diopters)	Measured resolution (group, element)	Calculated resolution (Snellen)
1.	50	0.02	_____	_____
2.	40	0.025	_____	_____
3.	20	0.05	_____	_____
4.	10	0.10	_____	_____
5.	6.667	0.15	_____	_____
6.	5	0.20	_____	_____
7.	4	0.25	_____	_____
8.	3.333	0.30	_____	_____
9.	2.857	0.35	_____	_____
10.	2.5	0.40	_____	_____

Appendix D

Simple ANVIS resolution predictive model

Model description

In developing a simple model for ANVIS resolution for different amounts of defocus of the objective lens under optimum conditions, it is preferable to use easily measurable visual components that can be generally understood by nonmathematicians rather than a complex optical description of focal lengths, $f/\#$ s, etc., which would then be integrated with a contrast sensitivity eye model. The two characteristics of the ANVIS selected for inclusion in the model as coefficients were limiting resolution under high light conditions using a high contrast target, and resolution with 1.00 diopter of blur.

For a theoretically perfectly designed objective lens with no aberrations, a change in the film or image plane from the focal point of a point light source will proportionally increase the diameter of the blur circle. Figure D-1 shows this calculated relationship between blur circle diameter and diopters of blur. The size of the blur circle is directly proportional linearly to the resolution and highly correlated ($r = 0.9999+$) with diopters of blur above the limiting resolution for the device and/or the eye. With ANVIS in the laboratory during feasibility experiments with one trained subject, it was found that 1.00 diopter of blur from either a plus or a minus ophthalmic lens blank resulted in approximately 20/700 Snellen resolution using the high contrast 3-bar chart under simulated high moon conditions. With 0.50 diopter of blur, the resolution was approximately 20/350, as predicted by the proportional change in the size of the blur circle. However, as the value of diopters of blur approaches zero, the resolution with the image intensifier tube does not improve above approximately 20/45 for this tube and the criteria for this resolution chart.

With less than approximately 0.15 diopter of blur, the transition to the limiting resolution of the image intensifier is gradual rather than abrupt. (See Figure D-2). This gradual transition from blur circle size to a limiting resolution is probably due to a combination of uncorrected objective lens aberrations, the micro-channel characteristics such as spacing, phosphor screen point spread, aliasing of the fiber optic inverter, and, finally, the eyepiece optical contributions.

When combining two or more different limiting resolutions, such as from a camera lens and film print, the resultant resolution will always be equal to or slightly less than the poorer of the two resolutions. Various equations have been used to model the combination of two resolutions (Perrin and Altman, 1951), but the simplest ones use a variation of the root mean square of two components and change the values of the exponents and coefficients to fit the data.

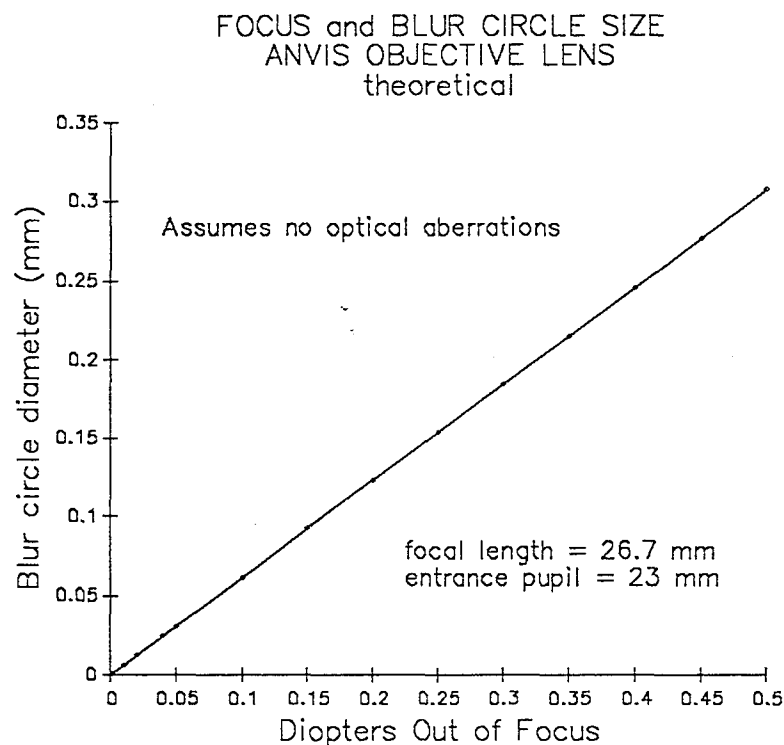


Figure D-1. Blur circle diameter proportional to distance from focal plane

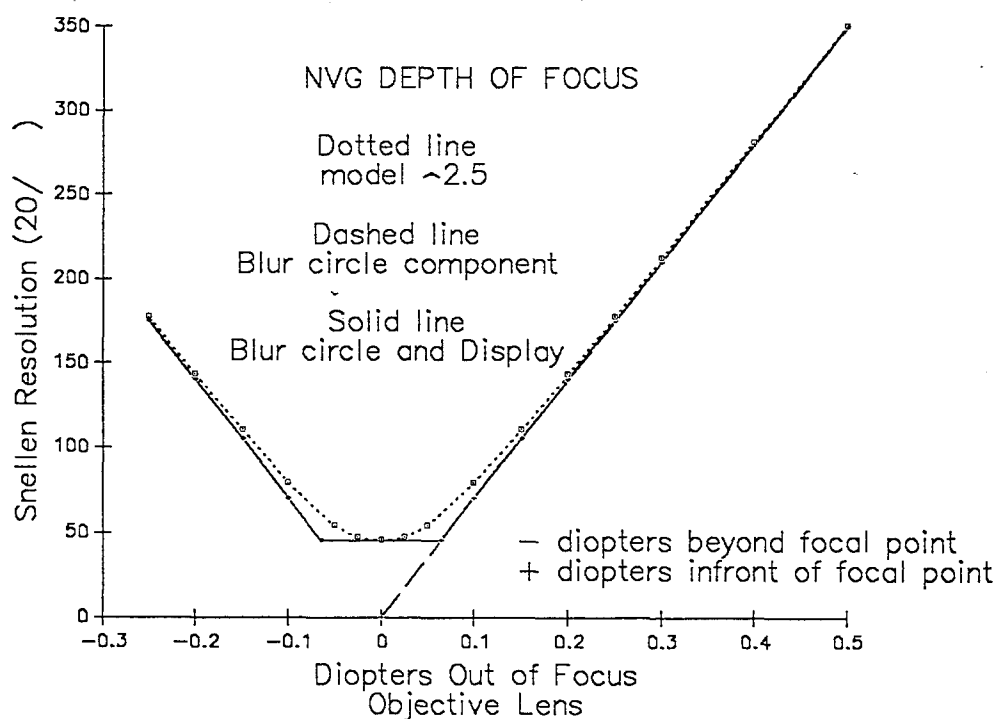


Figure D-2. Gradual change in resolution with decreasing amounts of blur near limiting resolution

The following equation was found to provide a good fit for the ANVIS resolution versus diopters of blur data in this study:

$$R_r = \sqrt[2.5]{(R_{mx})^{2.5} + (R_b \times D)^{2.5}}$$

where: R_r = the resultant Snellen resolution denominator. (e.g. 40 in 20/40)
 R_{mx} = the maximum or best resolution
 R_b = resolution with 1.00 diopter of blur
 D = diopters of blur

Note: Resolution units for each variable in the equation should be the same type. A few examples of resolution unit types are the following: (1) denominator of Snellen notation, (2) arc minutes of target dimensions, and (3) the reciprocals of lines/mm or cycles/milliradian or cycles/degree, etc.

Figure D-3 shows the effect of changing the exponents and roots (2.5 value shown in equation) from 1.0, 1.5 and 3.5, and assigning a value of 20/45 for the limiting resolution (R_{mx}) and 20/700 for the resolution with 1.00 diopter of blur (R_b). Increasing the root and exponent value flattens out the curve around the limiting resolution of 20/45, but notice that a greater change occurs between values 1.0 and 1.5 than between 1.5 and 3.5.

Figure D-4 shows the effect of changing the R_b values of 550, 700, and 800, which corresponds approximately to objective lens f -numbers of 1.44, 1.13, and 0.99, respectively. The root and exponents are 2.5 and R_{mx} is 20/45. With increasing diopters of defocus, the slopes increase with increasing R_b values and decrease with increasing f /#s.

Figure D-5 shows the effect of changing the R_{mx} value, which corresponds to an image intensifier tube optimum Snellen resolution from 20/25 to 20/65 in steps of 20. The root and exponents are 2.5, and the R_b value is 700. Note that the resolutions are approximately the same above 0.20 diopter of blur. This means that, if the 20/25 resolution goggle and the 20/65 resolution goggle are focused at infinity, and a resolution target is viewed at 5.0 meters (0.20 diopter), the resolutions between these two goggles will only vary between 20/141 and 20/147, respectively at this viewing distance. As the viewing distance becomes closer, the difference between the resolutions of the two goggles approaches the same value when both goggles are focused at infinity.

During the depth of focus study, it was apparent when the data were plotted that the actual point of focus for a given trial could vary up to approximately 0.05 diopter. The values of the resolutions at a given viewing distance or the amount of diopters of blur were averaged for this study. Figure D-6 shows how the resolutions could vary at a given diopters of blur point

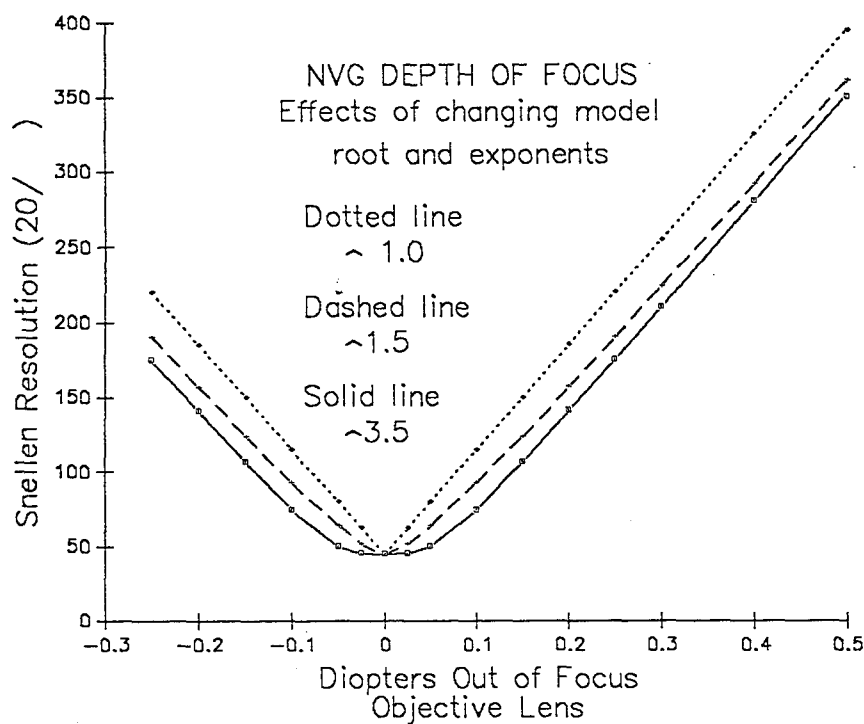


Figure D-3. Model effects from changing root and exponent values.

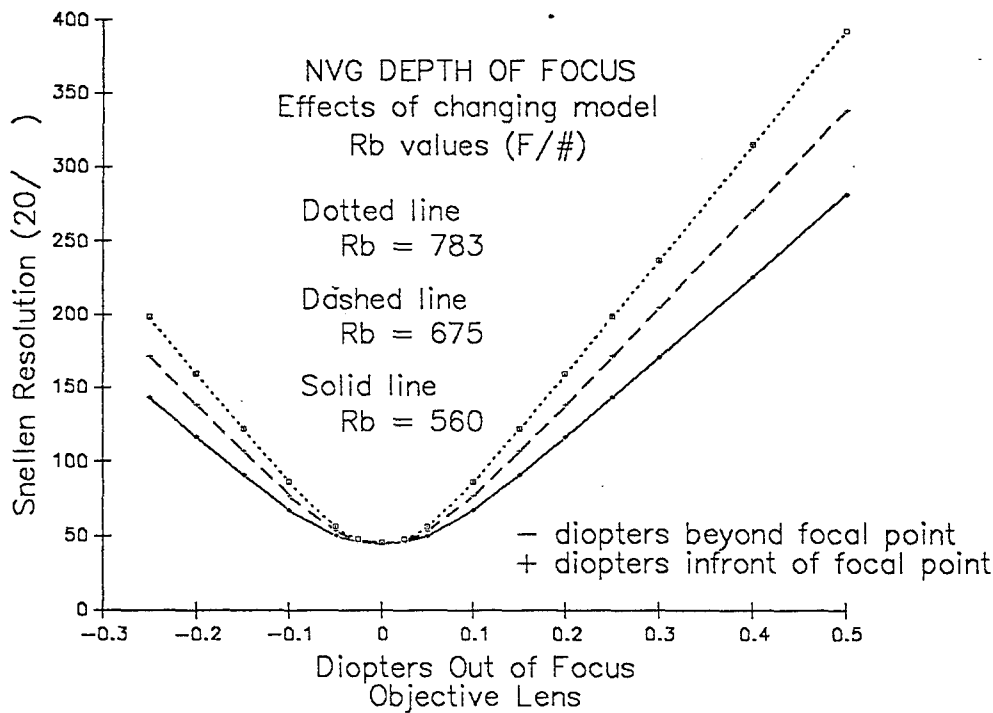


Figure D-4. Model effects from changing coefficient of diopters of blur.

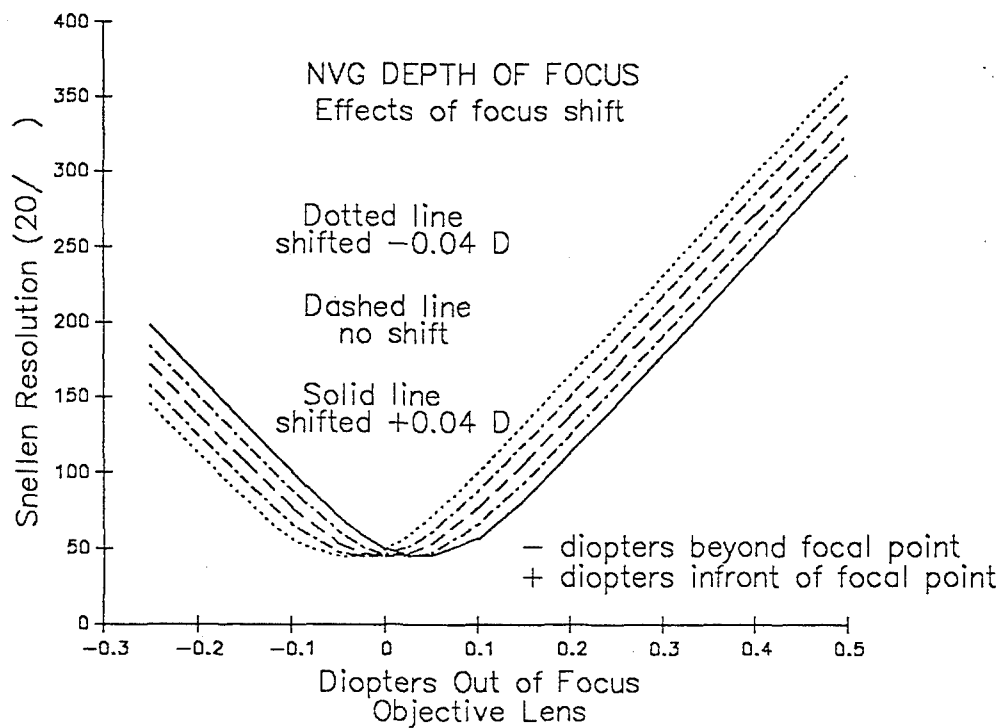


Figure D-5. Model effects from changing coefficient of best resolution.

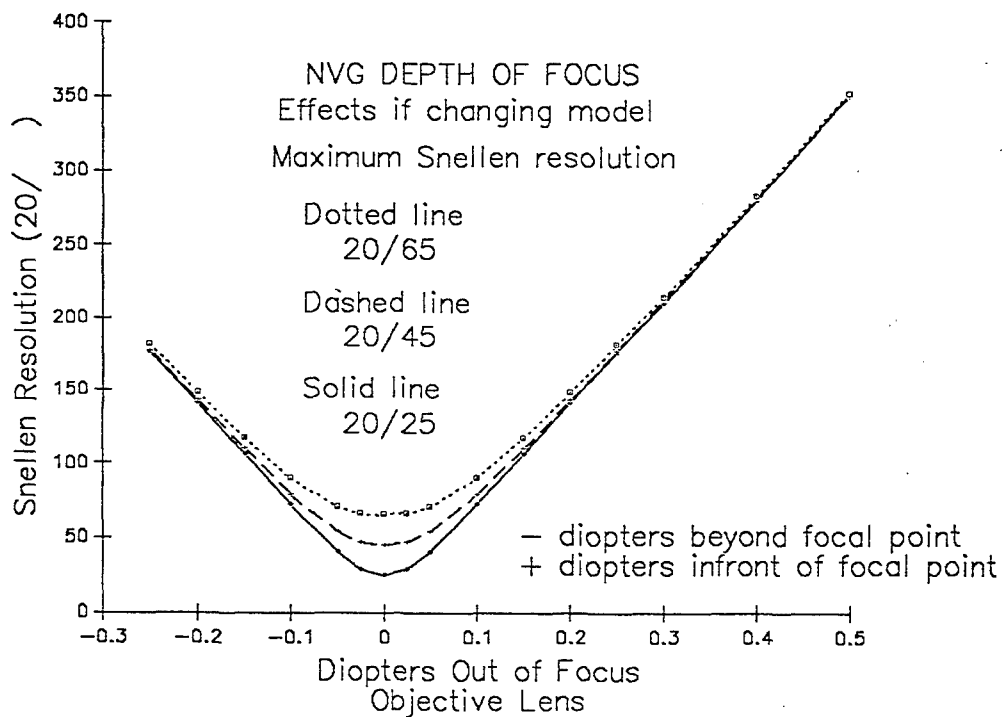


Figure D-6. Effects of slight diopter shifts in optimum focal point.

with focus shifts of the model from -0.04 to +0.04 diopter. In Figure D-7, the average of these five focus shift plots are shown with the model centered at zero diopters. Note that the only apparent differences between the two plots occur between ± 0.10 diopter, with the average values of the shifted curves being slightly larger than the model in the trough of the curve. Therefore, an average of multiple trials where the actual focal point varied slightly, will have basically the same model coefficients and exponent components as a single focused trial with the best resolution coefficient slightly larger (47.2 for the average of 5 trials versus 45 for the model or lowest value in each trial).

Figure D-8 shows the effect on the model components from the evaluator's criteria for the limiting resolution at a given value of blur. The difference between element sizes in the Air Force 3-bar chart is the sixth root of 2 or approximately 1.12 to 1 size ratio. Using the base line coefficients of 45 and 675 with the root and exponents a constant of 2.5, a one element smaller (better) response by the evaluator would change the coefficients to 40 and 600, where a response of one element larger produces coefficients of 50.6 and 757.

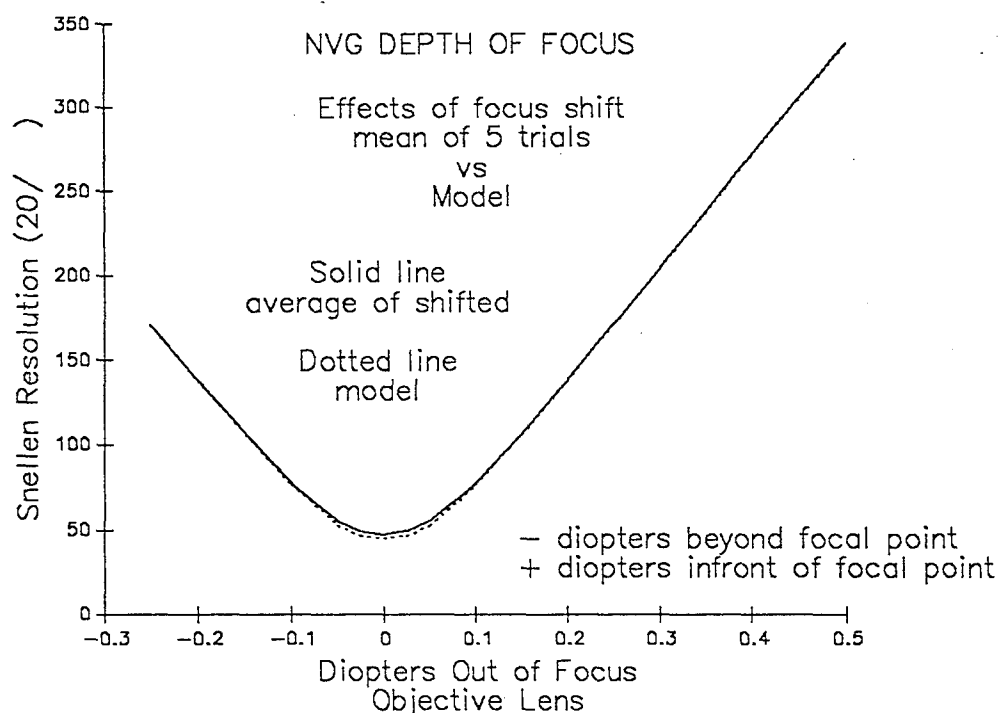


Figure D-7. Effects of averaging resolution with focal point shifts.

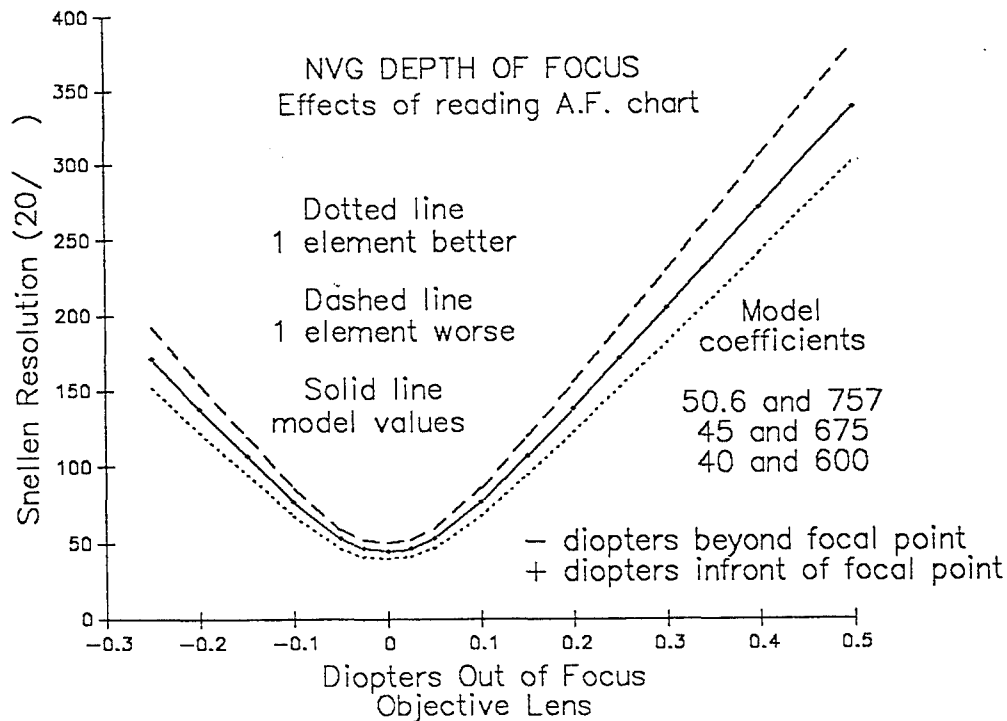


Figure D-8. Model effects of the evaluator's resolution criteria for the U.S. Air Force 3-bar chart.

Applications of the model

Field resolution

Issue: If an infantry soldier focuses his NVG (AN/PVS-7) at one distance (6.667 meters for this example), what is his best resolution under optimum conditions at other distances from infinity to 2.5 meters? (Assume the AN/PVS-7 and ANVIS objective lenses are the same.)

Solution Using the model with the following values, a plot of resolution versus viewing distance in diopters is shown in Figure D-9:

$$\begin{aligned} \text{root and exponents} &= 2.5 \\ R_{\max} &= 20/45 \\ R_b &= 20/675 \end{aligned}$$

Diopters of blur were calculated using the following equation:

$$D_b = (1/M_f - 1/M_v)$$

where: D_b = diopters of blur
 M_f = focus distance in meters
 M_v = viewing distance in meters

Note that the predicted resolution is poorer than 20/100 at infinity and at distances closer than 3.33 meters.

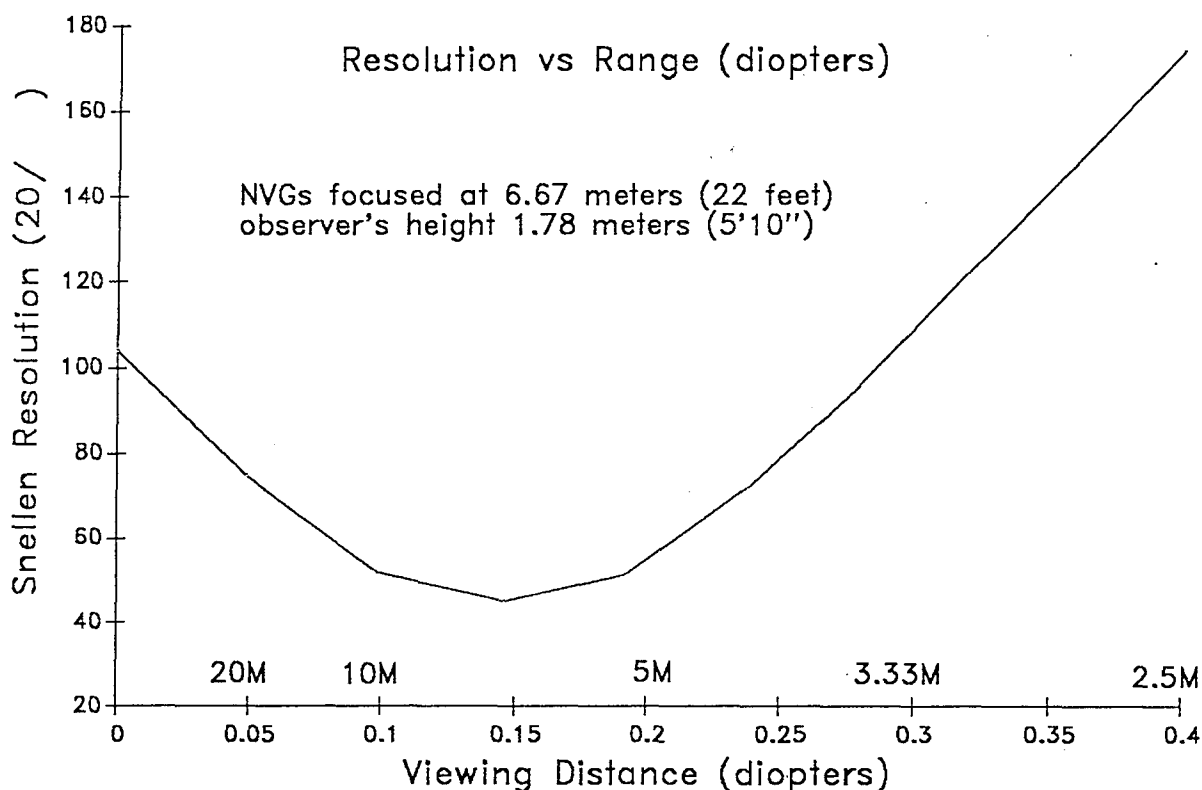


Figure D-9. Resolution versus viewing distance from an infantry perspective.

Blur circle diameter vs. resolution

Issue: What is the relationship between the apparent size of a blur circle with a given amount of defocus using a point source of light and the measured resolution with a high contrast U.S. Air Force 3-bar chart for ANVIS under high moon illumination?

Background: If we can determine the ratio between the size of the blur circle and measured angular resolution for a given diopter amount of defocus of the objective lens, we could estimate the R_b component (resolution with 1.00 diopter of blur) in the model before an image intensifier device is developed. The R_{max} component can be predicted using modulation transfer functions of the optical and intensifier tube parameters.

We know that increasing the $f/\#$ of the objective lens of an image intensifier (i.e. reducing the diameter of the entrance pupil) increases the depth of field, producing smaller blur circles for a given viewing distance, but at the expense of lower goggle gain which will reduce resolution under low ambient conditions such as star light. Objective lenses with lower $f/\#$ s (larger diameters) should have better low light performance and less depth of field, but also will have proportionally larger blur circles for light points for a given amount of defocus.

We could approximate the size of a blur circle for a given amount of diopters of defocus for a given lens with a known focal length and $f/\#$, assuming minimal lens aberrations, using simple geometric optics. However, the ANVIS objective lens is actually composed of 8 lens elements with aperture diameter restrictions from 26 to 7.7 mm, and has an axial length of approximately 45 millimeters for an effective focal length of approximately 27 mm. The objective lens also induces approximately 8 percent barrel distortion, which is then compensated by the 8 percent induced pincushion distortion of the eyepiece.

Method: After several calculations of the blur diameters for a given amount of defocus for the ANVIS using simple geometric optics, it was decided to use a ray trace computer program to analyze the maximum spot sizes for the objective lens prescriptions, which included the indices of refraction for seven wavelengths from 546 nanometers to 876 nanometers. Using the same ray trace program, I determined the spot size equivalents for the ANVIS eyepiece and converted the linear millimeter units into angular arc minutes for a given diopters of blur.

Results: Figure D-10 shows two functions. One plot is the derived model of resolution in arc minutes versus diopters of ANVIS objective lens defocus, and the other function is a series of plots of the diameters of the blur circles for a point source of light in arc minutes for 3 different wavelengths versus the diopters of objective lens defocus. The arc minutes of resolution are the distances between bars, and not line pairs or cycles. That is, one arc minute represents 20/20 Snellen acuity. Note that the blur circle diameters are approximately 2 times the limiting measured resolutions above approximately 0.1 diopter of blur (Figure D-11).

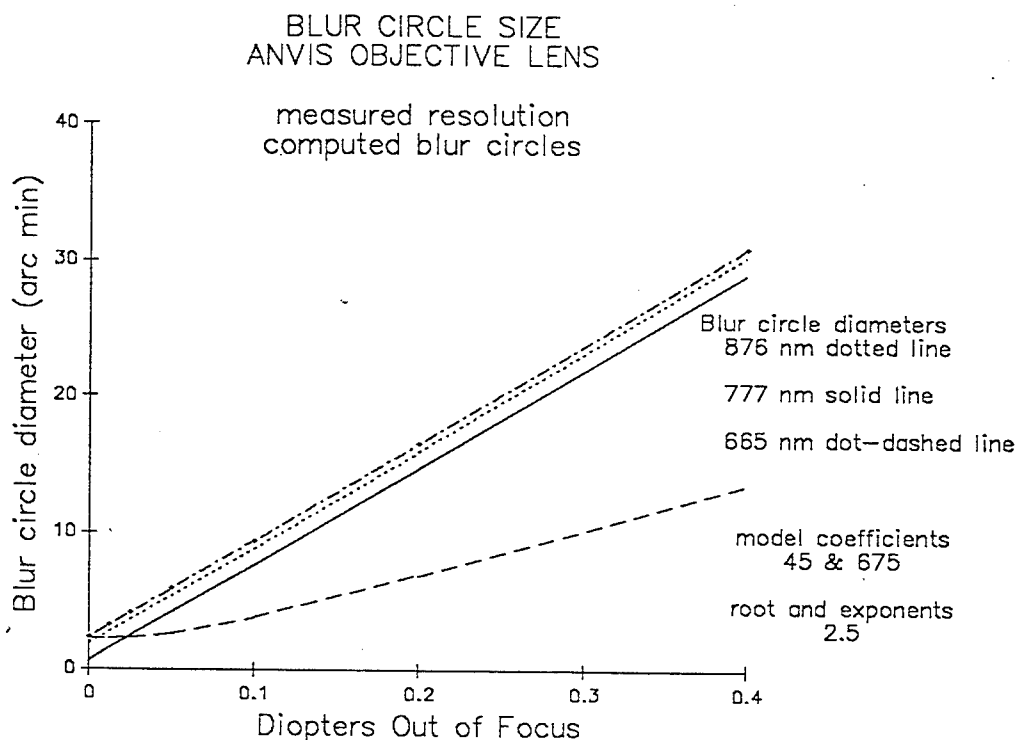


Figure D-10. Blur circle diameters for different wavelengths in arc minutes versus modeled resolution.

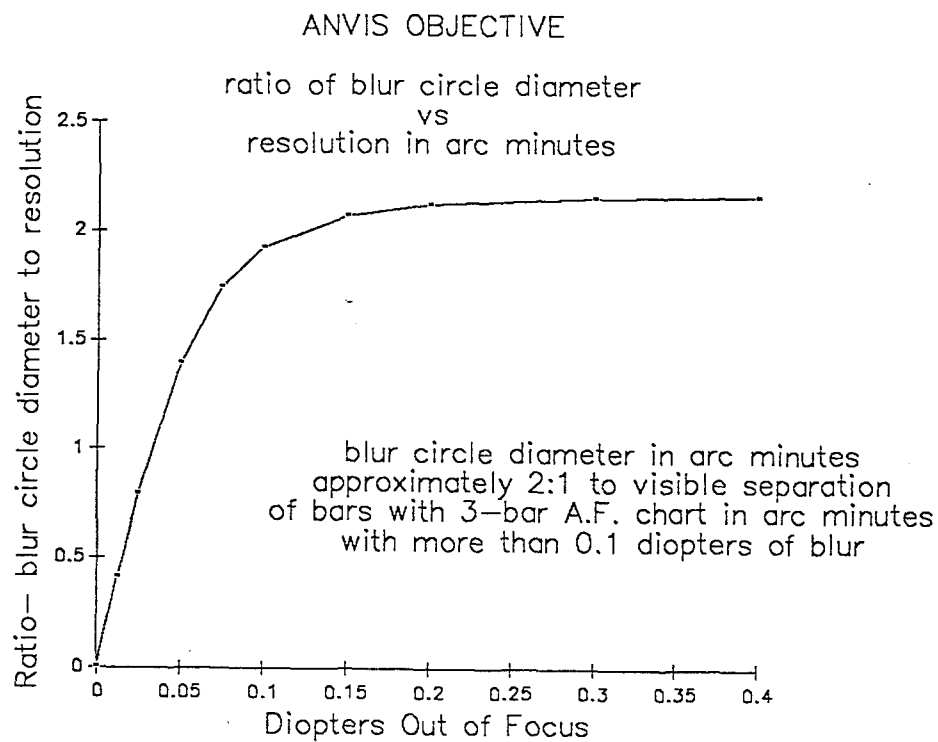


Figure D-11. Ratio of blur circle diameter versus resolution in arc minutes, ANVIS objective lens.

Appendix E

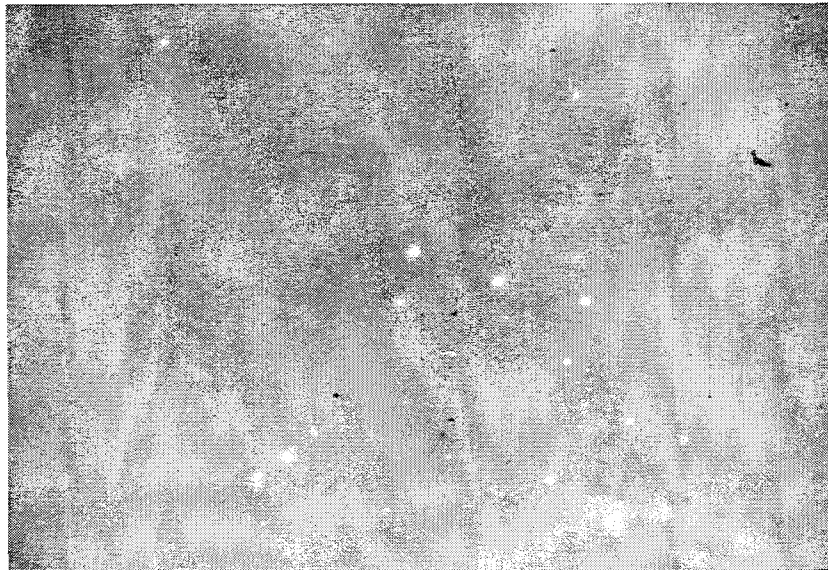
Sample prints of photographs used in depth of field study

Description

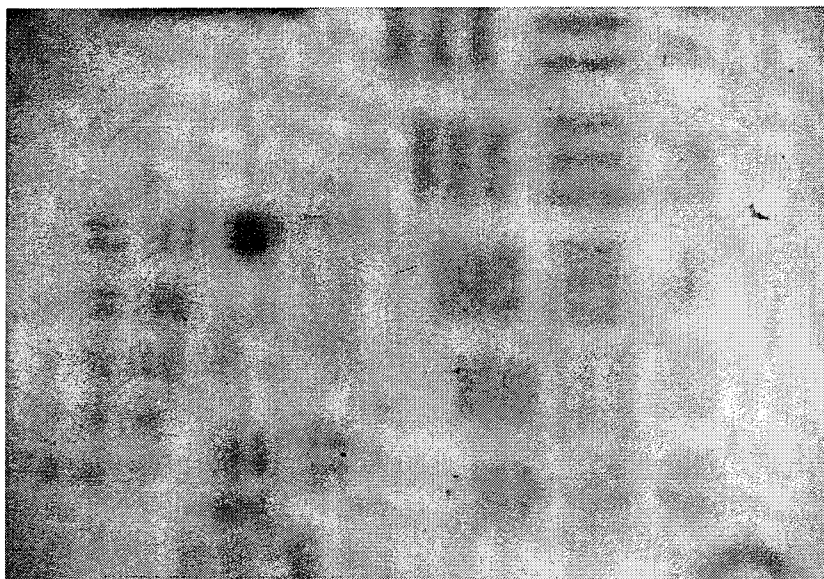
The photographs that follow were taken 15 April 1995 under full moon illumination. The stars shown in the first photograph were used to adjust the ANVIS objective lens focus. The Air Force 3-bar chart was then photographed from different distances without readjusting the focus. For comparison purposes, the ANVIS objective lens was then refocused for each of the previous viewing distances. Each page of the sample photographs shows a different viewing distance using the 3-bar chart.

With the telephoto lens used with the 35-mm camera, the images through ANVIS will appear blurred, and only 15 horizontal degrees of the ANVIS 40 degree field of view can be shown. The prints are approximately 3 by 4 1/2 inches. To equate the print image size to the 15 horizontal degrees photographed through the ANVIS, the reader should view these prints at approximately 34 inches, or slightly beyond arms length.

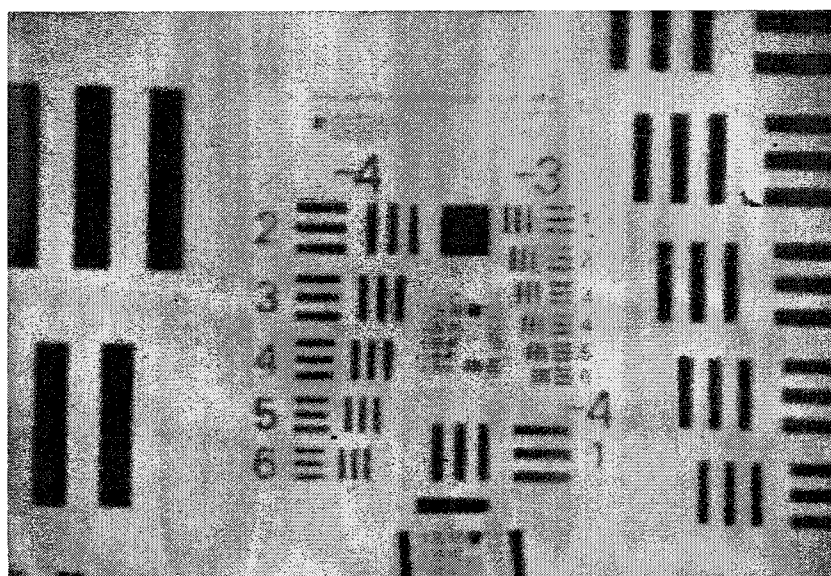
As mentioned in the methods section, the resolutions for the data analysis were determined from the film negatives and not the prints. The reader should understand that the photographs in this report are copies of prints from the printing process, which will further reduce the limiting resolution compared to that on the film negatives. However, the purpose of these photographs is to show the principle of depth of field for the ANVIS objective lens when focused at infinity.



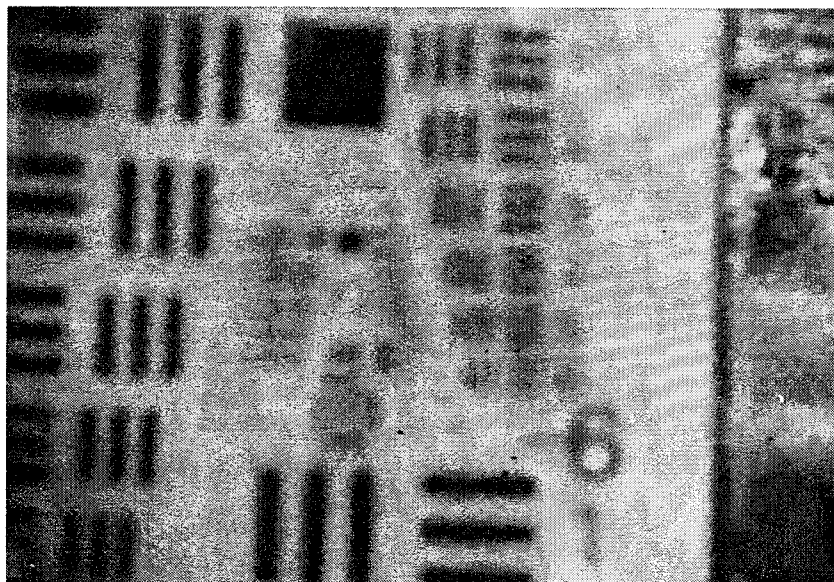
Focused at infinity using stars



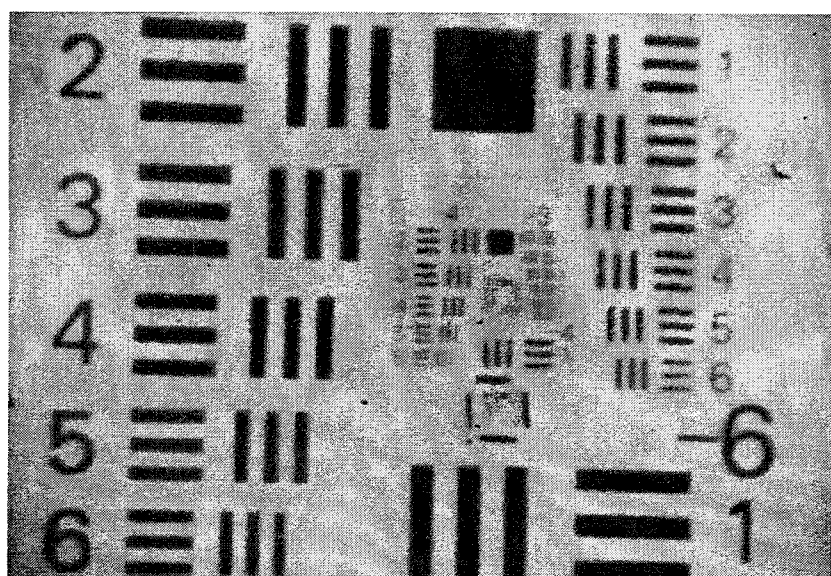
Focused at infinity using the stars; viewed at 2.5 meters



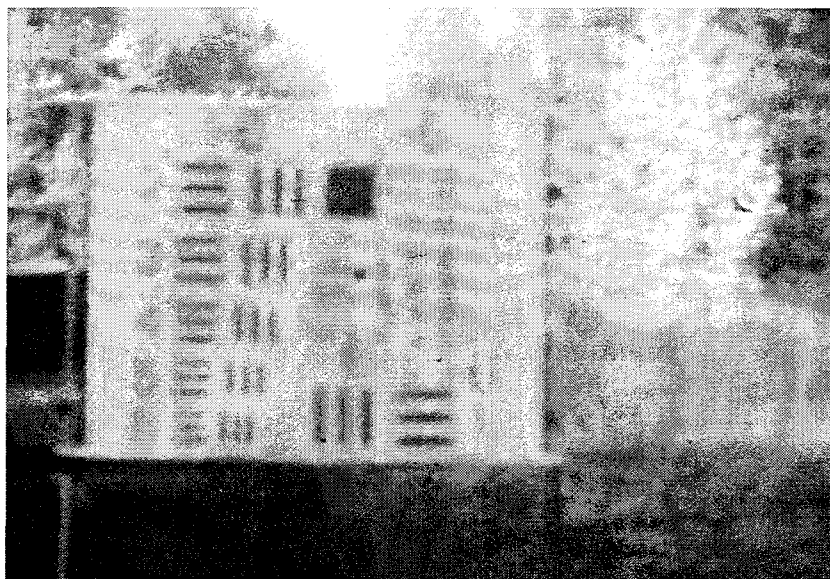
Focused at 2.5 meters



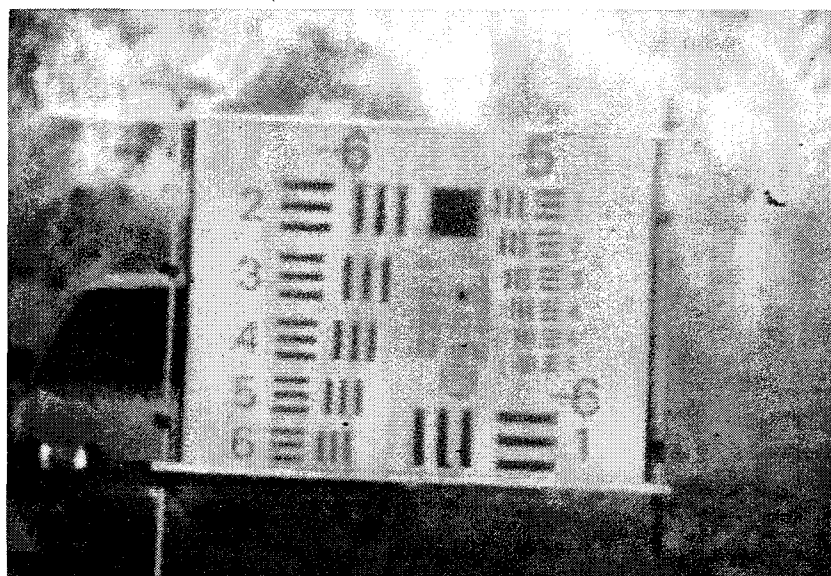
Focused at infinity using the stars; viewed at 5 meters



Focused at 5 meters



Focused at infinity using the stars; viewed at 10 meters



Focused at 10 meters



Focused at infinity using the stars; viewed at 20 meters



Focused at 20 meters



Focused at infinity using the stars: viewed at 40 meters



Focused at 40 meters