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Examination of a Method for Improving Night Vision Device Depth of Field

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ABSTRACT
Night Vision Device (NVD) depth of field is extremely small when viewing objects close to the observer. An optical system's depth of field can be increased by reducing, or slowing, the system's f-number (*f/#*) which can be accomplished by adding restrictive apertures onto the front of the objective lens. This noticeably increases NVD depth of field but causes a significant reduction in the device's light gathering capability. This paper derives equations describing the phenomenon, assesses the tradeoffs that are involved in using apertures to increase depth of field, and discusses an experiment demonstrating improved depth of field resulting from decreasing the objective lens aperture.

INTRODUCTION
A problem with Night Vision Devices (NVDs) is their depth of field. When the device is focused far away, such as at infinity, objects close in are out of focus. This problem has little effect on pilots flying an aircraft, whose attention is on distant objects, but it presents a safety hazard for some crewmembers who must constantly move about the aircraft, refocusing their NVDs while trying to accomplish complicated tasks [3]. When focused close to the user, NVD depth of field is extremely small. If a user moves their head only a few inches, the image moves in and out of focus quite rapidly, complicating tasks. Frequent refocusing of the device may be unacceptable to the user who continually changes the point of their attention or has a heavy workload, such as a loadmaster, gunner, or medic [4]. This report examines one approach for improving NVD depth of field by using small apertures over the objective lens, and its potential limits of NVD performance.

Depth of field arises from the ability of an imaging device to accept defocus [5]. Ignoring objective lens aberrations, imaging array resolution is limited by the picture element (pixel) size. The pixels of the NVD under "bright" light conditions are the individual channels in the image intensifier (I^2) tube microchannel plate [2]. This paper concentrates on the bright light condition where the NVD is microchannel-plate limited. In dim light conditions where system performance is limited by the human eye, the treatment of the problem changes somewhat and will not be addressed here [2].

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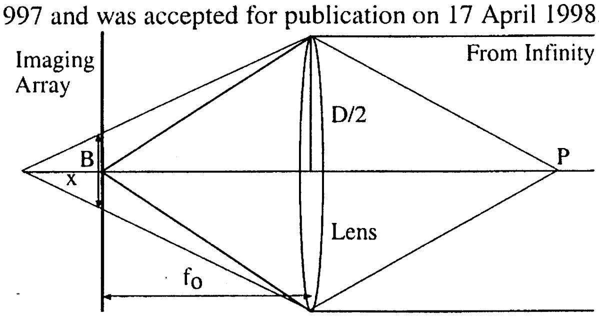

Figure 1. Geometry for derivation of hyperfocal distance.

Hyperfocal Distance
One should note that imaging system objective lenses are normally not single lenses but rather complex combinations of lens elements. For these complex lenses, the focal length of the lens, f_o, is the distance from the rear principle plane to the focal plane. To simplify the diagrams and to make the geometry more clear, complex objective lenses will be represented by a simple, single lens element.

An interesting condition can be derived from the geometry of a lens focused at infinity (Figure 1). Because it is focused at infinity, we know that the distance from the lens to the imaging array is exactly f_o, [5]. It is also known that because of the pixel size, or acceptable blur size, *B*, some points closer to the observer than infinity will be in acceptable focus. From this information, it is possible to determine the distance to the closest point that will appear in focus to an infinity-focused imaging system. From Figure 1, a point inside infinity, *P*, forming a blur circle of exactly *B* and appearing in focus to the imaging device, forms an image a distance *x* behind the photocathode. Given a lens of diameter D and a blur size B, x can be found by using basic geometry:

$$\frac{B/2}{x} = \frac{D/2}{f_o + x} \tag{1}$$

Solving for x:

$$x = \frac{Bf_o}{D - B} \tag{2}$$

Once x is known, the near edge of the depth of field for an infinity focused lens can be found by determining the plane in object space that is conjugate to the image distance $(f_o + x)$. This can be calculated by using the thin lens equation [5]:

$$\frac{1}{s} + \frac{1}{s'} = \frac{1}{f_o} \tag{3}$$

Where, s is the distance from the lens to the object and s' is the distance from the lens to the image. For this derivation, s' is equal to $f_o + x$. Substituting this into the thin lens equation and solving for s yields:

$$s = \frac{f_o(f_o + x)}{x} \tag{4}$$

Substituting the expression for x, Equation 2, into Equation 4 and simplifying yields an expression for the lens-to-object distance of:

$$HFD = s = \frac{f_o D}{B} \tag{5}$$

Where HFD is the hyperfocal distance. Objects beyond this distance are in focus for an infinity-focused lens. Note that the HFD is directly proportional to the diameter of the lens.

Depth of Field

Calculating HFD is not ideal for determining the largest potential NVD depth of field. It should be easy to see that when focused well inside infinity, an optical device's depth of field will have limits on both sides of best focus. Since the model in the previous derivation is already focused on infinity, it only exhibits a near side. There can be no far side when focused at infinity since it is impossible to have real objects farther away than infinity. Conceptually, the infinity focus condition only uses part of the viewing device's potential depth of field. Derivation of the equations locating the near and far edges of the depth of field is more involved than for HFD.

The lens in Figure 3 is focused on an object at some distance, placing a sharp image in the image plane. Points closer to the observer than the object whose

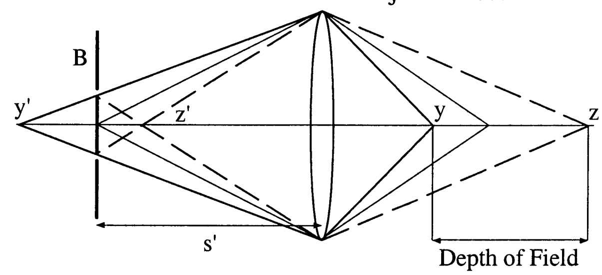

Figure 2. Basic depth of field geometry.

images are at the threshold for acceptable blur, image to a plane a distance y' behind the image plane. Points further from the observer than the object whose images are at the threshold for acceptable blur, image to a plane a distance z' in front of the image plane. Images that form anywhere up to a distance y' behind or a distance z' in front of the imaging array will appear in sharp focus to the observer. The longitudinal distance in object space from which these images come is the device depth of field, as in Figure 2.

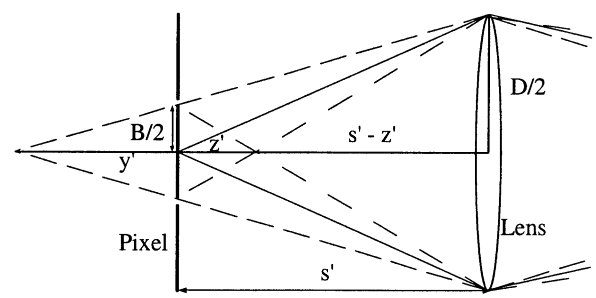

Figure 3. Geometry describing depth of field boundaries.

Two equations can be derived using the geometry of Figure 3: one for the depth of field's near edge and one for its far edge. Objects closer to the imaging system than the plane on which the imaging system is focused will form images behind the imaging array. Point objects closer to the observer than the focus distance that create blur circles with a diameter of exactly B will image a distance y' behind the imaging array. From Figure 3, it can be seen using the similar triangle approach that:

$$\frac{B/2}{y'} = \frac{D/2}{s' + y'} \tag{6}$$

And therefore:

$$y' = \frac{Bs'}{D - B} \tag{7}$$

Remember that s' is the distance from the lens to the image for a given focus distance. Using the thin lens equation, Equation 3, where the lens of focal length is f_o, and the focus distance is f_d. Solving for s' yields:

$$s' = \frac{f_o f_d}{f_d - f_o} \qquad (8)$$

Now, the location of objects that image to the plane y behind the imaging array must be determined. Rewriting the thin lens equation so that S' is the image distance and S is the object distance gives:

$$\frac{1}{S} + \frac{1}{S'} = \frac{1}{f_o} \qquad (9)$$

Solving for the object distance yields:

$$S = \frac{f_o S'}{S' - f_o} \qquad (10)$$

It is known that S' is equal to the image distance created by the lens for a chosen focus, s', plus the extra distance behind the imaging array at which acceptable images would form, y'. Therefore:

$$S' = s' + y' \qquad (11)$$

Substituting Equation 11 into Equation 10 yields:

$$S = \frac{f_o(s' + y')}{(s' + y') - f_o} \qquad (12)$$

Substituting Equation 7 for y' into Equation 12 and simplifying yields:

$$S = \frac{f_o D s'}{s' D - f_o D + f_o B} \qquad (13)$$

Substituting Equation 8 for s' and simplifying yields the equation for the near side of the depth of field.

$$S = DOF_N = \frac{f_o f_d D}{f_o(D - B) + f_d B} \qquad (14)$$

The derivation of the equation for the far edge of the depth of field closely follows the one for the near edge. Objects farther from the imaging system than the plane of best focus will come into focus in front of the imaging array. Those whose point objects create blur circles of exactly diameter B form images a distance z' in front of the imaging array. Using geometry and the first order imaging technique, it can be shown that the location of the far edge of the depth of field, DOF_F, is [6]:

$$DOF_F = \frac{f_o f_d D}{f_o(D + B) - f_d B} \qquad (15)$$

One should notice that the equation for the far edges of the depth of field can generate negative numbers if f_d gets large enough, implying that DOF_F is beyond infinity. These results should simply be ignored since in the real world, distances cannot be negative and objects cannot be located farther away than infinity. Negative DOF_F values should be treated as an infinity result.

Limits

Notice what happens to the near edge of the depth of field when focus goes to infinity. This can be determined mathematically by evaluating the limit of the above DOF_N equation as f_d gets very large using L'Hôpital's Rule.

$$\lim_{f_d \to \infty} \frac{f_o f_d D}{f_o(D - B) + f_d B} = \frac{f_o D}{B} \qquad (16)$$

This shows that for large focus distances;

$$DOF_N = \frac{f_o D}{B} = HFD \qquad (17)$$

When the imaging system lens is focused at true infinity, the near edge of the depth of field should converge to the system's hyperfocal distance.

Another important condition to note is the focus distance, f_d, at which the far edge of the depth of field goes to infinity. Mathematically, this happens when the denominator of Equation 15 goes to zero. Setting the denominator to zero and solving for f_d yields:

$$f_d = \frac{f_o(D + B)}{B} \approx \frac{f_o D}{B} \qquad (18)$$

Since D is much larger than B, this is essentially the hyperfocal distance. Therefore, when the imaging device's objective lens is focused at the device's HFD, the depth of field's far edge extends approximately to infinity. Recall that the near edge of its depth of field falls closer to the observer than the HFD. Since the depth of field's far edge extends to infinity for this particular focus condition, it is the condition for the maximum depth of field.

The near edge must be located to quantify the maximum depth of field. By substituting Equation 19 into the equation for the near edge of the depth of field, Equation 14, and simplifying, its position can be determined.

$$DOF_N = \frac{f_o(D + B)}{2B} \qquad (19)$$

Note that this is approximately one-half the HFD. So, if the device is focused at the HFD, the depth of field extends from one-half the HFD to infinity. Since DOF_N slowly converges to the HFD as f_d gets larger, focusing at the HFD will maximize device depth of field. This condition is the maximum depth of field for a particular imaging system since objects cannot be located beyond infinity. Focusing an NVD in any other plane will yield a smaller depth of field.

PROCEDURES

A brief experiment was conducted to examine the practicality of the concept. Apertures were placed over an NVD objective lens. Several subjects' visual acuities were measured at discrete distances without refocusing the NVD. It was anticipated that stopping down an NVD objective lens, increasing depth of field, should yield a noticeable improvement in subject visual acuity at different distances without refocusing the NVD.

In this experiment each subject was placed in a light tight room and allowed to dark adapt for 15 minutes. The subject was then given an F4949 ANVIS-type (Aviator's Night Vision Imaging System) NVD focused at 30 feet and asked to read square wave acuity targets at 30 feet, 20 feet, and 5 feet from the end of the NVD without refocusing the device objective lenses. Subjects were allowed to adjust eyepiece focus to optimize their visual performance. Three different apertures were selected for the tests: 23.5 mm, which corresponds to the normal NVD objective lens aperture, 7 mm, and 3 mm. Each subject was asked to read the targets once for each aperture.

The square wave acuity targets used in this research were modified versions of the NVD focusing target originally designed and fabricated by Armstrong Laboratory personnel for the aviators of Desert Shield [3]. Modifications were limited to changing the frequency of the target square waves to enable the technicians to make the anticipated measurements.

Light levels used in the tests were chosen to maximize luminance out of the NVD, thereby maximizing NVD aided human visual performance. For these tests, the luminance level was chosen between quarter and half moon, approximately $8.0X10^{-3}$ footLamberts (fL) for the open aperture, $9.0X10^{-2}$ fL for the 7 mm aperture, and 0.5 fL for the 3 mm aperture. This ensured constant NVD photocathode illumination for all three trials. The higher light levels for the 3 mm and 7 mm apertures were calculated by taking the ratio of the NVD lens area to the aperture area and multiplying by $8.0X10^{-3}$ fL.

RESULTS

<u>Theoretical</u>

Example calculations are helpful in emphasizing the significance of the resultant equations from the earlier derivation. An average NVD will be used, with an objective lens focal length of 27.03 mm, an *f/#* of 1.23, and a maximum resolution of 1.0 cycles per milliradian. Its exit pupil diameter can be calculated to be 21.98 mm using Equation 20 where f_o is the lens focal length and D is the lens diameter [5]:

$$f/\# = \frac{f_o}{D} \tag{20}$$

If *RES* is the maximum resolution in cycles per milliradian, then the blur circle size can be found using:

$$B = f_o Tan\left[\frac{1}{2000 \times RES}\right] \tag{21}$$

Where f_o is the objective lens focal length and B is the blur circle size. Substituting the appropriate values into Equation 21 yields a blur size, B, of 0.01352 mm.

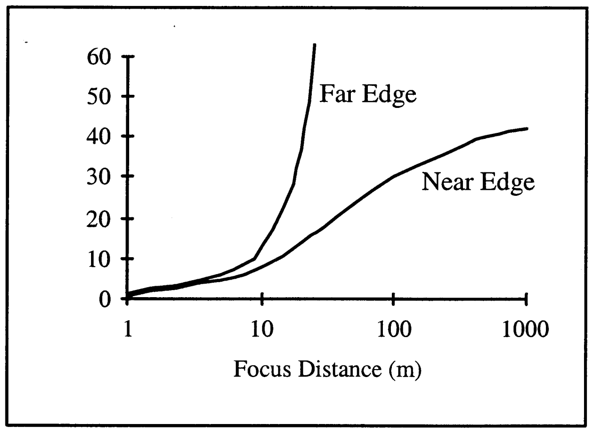

Figure 4. Near and far edges of depth of field vs. focus distance.

Now, recall Equation 5, the equation for the hyperfocal distance. For this system, f_o = 27.03 mm, D = 21.98 mm, and B = 0.01352 mm. Applying Equation 5 yields a HFD of 43.56 m. It should be noted that many systems available today exhibit resolution performance better than 1.0 cycles per milliradian. Improved resolution reduces B and consequently increases the HFD.

It is useful to examine how the equations behave as a function of f_d. When the location of the DOF_N and the DOF_F are plotted as a function of the focus distance, the results are shown in Figure 4. This figure has two interesting features. First, as f_d gets very large, as it would when the imaging system is focused at infinity, the near edge of the depth of field converges to the HFD. One should also note that as f_d approaches the HFD, DOF_F goes to infinity.

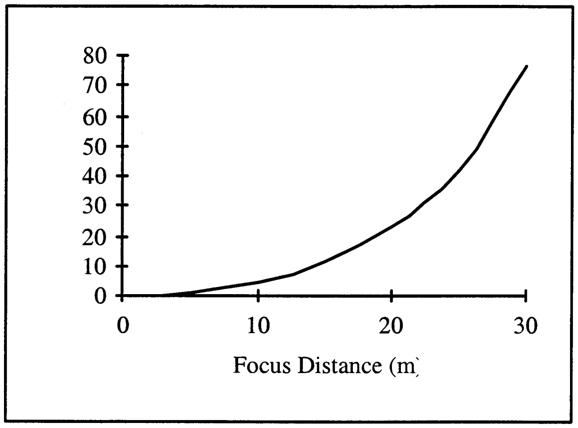

Figure 5. Depth of field vs. focus distance.

One should note that Figure 4 is a plot of the two edges of the NVD depth of field, not the depth of field itself. Calculating the difference between DOF_N and DOF_F and plotting it as a function of focus distance yields Figure 5. It is easy to see the trend that, for distances less than the HFD, the depth of field gets larger as the distance at which the NVD is focused increases.

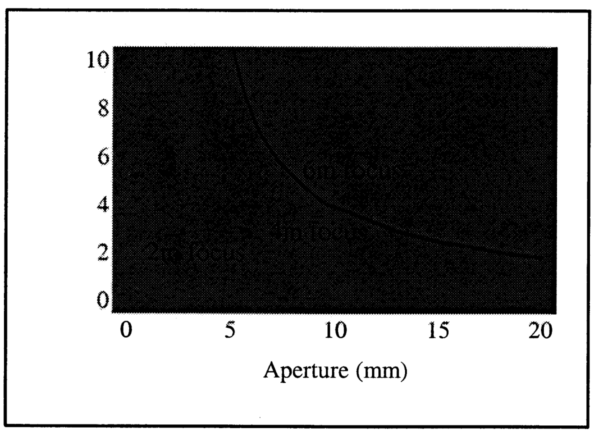

Figure 6. Depth of field vs. aperture size for various focus distances.

Figure 6 illustrates the effect of aperture size, D, on depth of field for several focus distances. Note that apertures above 10 mm have little effect but apertures below 5 mm show significant increases in depth of field. Also note that as focus distance gets longer, the curves move up and to the right, indicating that for longer focus distances, the user can achieve the same depth of field with a larger aperture. This effect gives rise to a significant tradeoff that will be discussed later. It should be emphasized that changing the focus distance also changes the location of the depth of field's near edge. While increasing focus distance increases depth of field, it also moves the depth of field's near edge father from the observer.

Figure 7 shows how depth of field changes with respect to NVD resolution performance for an F4949 ANVIS-type system where f_o = 27.03 mm and, without a limiting aperture, D = 21.98 mm. The trend indicates that high-resolution systems will have smaller depths of field. This is true in any two-dimensional imaging array. To achieve higher resolution, the pixels must be made smaller, making the overall system more susceptible to defocus. It should be noted that NVD HFD also increases for the same reason. A way around this effect, and recover the lost depth of field, is to shorten the objective lens focal length while maintaining a constant *f/#*. Unfortunately, this would increase the apparent angular size of the individual pixels and reduce the overall system resolution.

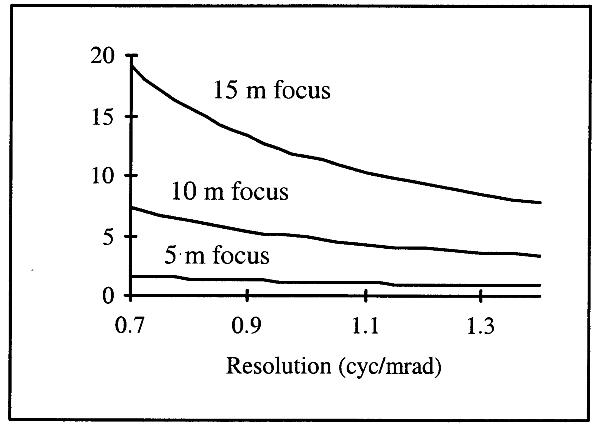

Figure 7. Depth of field vs. NVD resolution.

One can also see from Figure 7 that depth of field is larger for low resolution NVDs. If the user is willing to accept some resolution performance loss, depth of field will appear larger. If a user is trying to see large targets and adequate performance can be achieved with low resolution, user depth of field will appear to be larger.

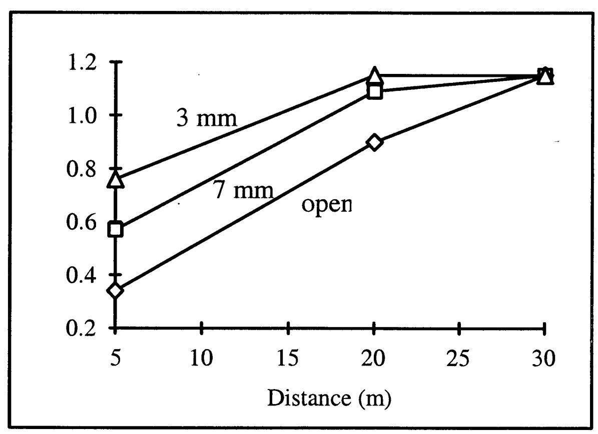

Figure 8. Resolution vs. target distance

Experimental

The data collected from the experiment described earlier appears in Figure 8. These data indicate that decreasing the objective lens aperture improves the subject's visual acuity as they view targets displaced from the plane of best focus. It also indicates that smaller apertures yielded greater acuity improvements than larger apertures. This is expected because of the anticipated increase in the device depth of field with a decrease in aperture size.

DISCUSSION

Radiometry of Small Apertures

As shown in Figure 6, it can be seen that depth of field increases dramatically as the limiting aperture diameter decreases. Unfortunately the light gathering capability of the device decreases as the limiting aperture gets smaller. When light is plentiful, this is not a problem. But in situations where one would use an NVD, light is scarce. The radiometry of the problem is very straight forward and described by the following equation [1]:

$$\Phi = LA\Omega \qquad (22)$$

In Equation 22, Φ is the radiant power or flux, L is the radiance of the source, A is the projected area of the detector, and Ω is the solid angle the source subtends from the point of view of the detector. The ratio of the radiant power collected by two different detectors is therefore given by:

$$\frac{\Phi_1}{\Phi_2} = \frac{L_1 A_1 \Omega_1}{L_2 A_2 \Omega_2} \qquad (23)$$

It is assumed that the two detectors are NVDs looking at the same scene, from the same point in space, but with different size apertures over their objective lenses. Therefore, they both see the same scene radiance, $L_1 = L_2 = L$, and solid angle, $\Omega_1 = \Omega_2 = \Omega$. When a lens is involved in radiometry, the area of the collecting lens is substituted for the area of the detector [1]. A_1 and A_2 now represent the areas of the two objective lens apertures. Equation 23 simplifies to:

$$\frac{\Phi_1}{\Phi_2} = \frac{A_1}{A_2} = \frac{\pi r_1^2}{\pi r_2^2} = \frac{r_1^2}{r_2^2} \qquad (24)$$

Where r is the radius of a particular aperture. Therefore, when using small apertures to increase depth of focus, device light gathering capability is reduced by the ratio of the squares of the radii of the apertures involved. For example, if a 3 mm aperture is placed over a 23.5 mm NVD objective lens, the NVD will see only 1.70% of the available light. This indicates that operations with small apertures over NVD objectives may require the use of auxiliary light sources. If such sources are not infrared, then the user may find it easier to simply take their NVD off and turn on conventional lighting. These calculations are made using the physical size of the NVD objective lens aperture, or lens entrance pupil, and not D, the exit pupil diameter, as in earlier calculations. Since the entrance and exit pupils are not necessarily the same diameter, the radiometry would not correctly describe the phenomenon if D were used.

Diffraction Limit

Even if adequate light is available for conducting NVD operations with very small apertures to increase depth of field, there is another limit that cannot be overcome: the objective lens diffraction limit. It is possible to try to operate with an aperture on a NVD that is small enough to create a diffraction spot larger than the limiting resolution of the I^2 tube. When this happens, the benefit of the larger depth of field is significantly reduced by the loss of system resolution. Theory indicates that the diffraction limited spot size, in microns, of an optical system is give by [8]:

$$\textit{Spot Size} = 2.44\,\lambda\, f/\# \qquad (25)$$

Where λ is the wavelength of light, expressed in microns.

Note that ANVIS-type NVDs, such as the F4949, are equipped with a minus-blue filter to shape the I^2 tube photocathode response and block most visible light. These filters pass light at numerous wavelengths. In this analysis, the filter response was reduced to a single wavelength by averaging the filter cut-on wavelength and the photocathode cut-off wavelength. Minus-blue filter cut-on wavelengths are 0.625 μm and 0.665 μm for Class A and Class B filtered goggles respectively. The cut-off wavelength of the photocathode is approximately 0.900 μm for the third generation I^2 tube's photocathode [7]. This yields average wavelengths of 0.763 μm for Class A filters and 0.783 μm for Class B filters.

Using the expression of *f/#* listed earlier, the spot size equation can be rewritten:

$$\textit{Spot Size} = \frac{2.44\lambda f_o}{D} \qquad (26)$$

Note that as the aperture becomes smaller, the diffraction limited spot size becomes larger. When the aperture is small enough, the diffraction limited spot size becomes greater than the resolution limit of the I^2 tube. When this happens, the maximum resolution of the device becomes equal to the diffraction spot size, decreasing NVD performance and reducing the benefit of a large depth of field. For the example system used earlier, (Spot Size = 13.52 μm and f_o = 27.03 mm) this happens when the lens limiting aperture shrinks below 3.7 mm with a Class A filtered response, and below 3.8 mm with a Class B filtered response. However, because of the energy distribution of the diffraction spot and an appropriate point resolution criterion, this phenomenon will not become significant until apertures about half as large as the calculated values are employed [8]. Therefore, apertures smaller than 3 mm were ignored in the experiment.

CONCLUSIONS

Objective lens focal length, objective lens diameter, system resolution, and the distance at which the system is focused all influence the depth of field of an imaging system like the NVD. Adjusting any of these parameters will yield a noticeable change. The amount of improvement possible in an application is determined by the image quality the user requires.

Adding apertures to reduce the objective lens diameter can significantly increase NVD depth of field. However, limitations reduce the usefulness of this approach. Apertures dramatically reduce the light gathering capability of the device. Supplemental illumination, such as auxiliary infrared lights, may be necessary to achieve the desired system performance. It is also possible to reduce the aperture to such an extent that imaging performance, or resolution suffers. Reducing the lens aperture slows the system *f/#* and increases the diffraction spot size. Once the minimum spot separation, determined by the diffraction spot size and the appropriate resolution criterion, exceeds the maximum resolution of the system, imaging performance starts to suffer.

Other parameters can be adjusted to increase NVD depth of field. Accepting lower system resolution performance will make device depth of field appear larger. This may be difficult to accept for some users whose duties require high resolution NVDs. Shortening the objective lens focal length while maintaining objective lens *f/#* will lead to a larger depth of field but will reduce the system's overall resolution performance. Objective lens focus distance can be optimized to yield a greater depth of field by focusing at the device's HFD. However, this is only practical when infinity focus is required. Poor objective lens positioning mechanisms make this approach difficult to implement.

Some performance characteristics can be sacrificed or traded to optimize NVD depth of field. These tradeoffs must be examined on the basis of individual situations or applications to determine the most acceptable compromise between depth of field, resolution performance, and light gathering before this idea can be implemented.

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