LAW ENFORCEMENT STANDARDS PROGRAM

SURVEY OF IMAGE QUALITY CRITERIA FOR PASSIVE NIGHT VISION DEVICES

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National Institute of Law Enforcement and Criminal Justice
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by

Joseph C. Richmond
Heat Division
National Bureau of Standards

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Survey of Image Quality Criteria for Passive Night Vision Devices

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FOREWORD

Following a Congressional mandate* to develop new and improved techniques, systems, and equipment to strengthen law enforcement and criminal justice, the National Institute of Law Enforcement and Criminal Justice (NILECJ) has established the Law Enforcement Standards Laboratory (LESL) at the National Bureau of Standards. LESL's function is to conduct research that will assist law enforcement and criminal justice agencies in selection and procurement of quality equipment.

In response to priorities established by NILECJ, LESL is (1) subjecting existing equipment to laboratory testing and evaluation and (2) conducting research leading to the development of several series of documents, including national voluntary equipment standards, user guidelines, state-of-the-art surveys and other reports.

This document, LESP-RPT-0301.00, Survey of Image Quality Criteria for Passive Night Vision Devices, is a law enforcement equipment report prepared by LESL and issued by NILECJ. Additional reports as well as other documents will be issued under the LESL program in the areas of protective equipment, communications equipment, security systems, weapons, emergency equipment, investigative aids, vehicles and clothing.

Technical comments and suggestions concerning the subject matter of this report are invited from all interested parties. Suggestions should be addressed to the Program Manager for Standards, National Institute of Law Enforcement and Criminal Justice, Law Enforcement Assistance Administration, U.S. Department of Justice, Washington, D.C. 20530.

Lester D. Shubin, *Manager*
Standards Program

*Section 402(b) of the Omnibus Crime Control and Safe Streets Act of 1968, as amended.

SURVEY OF IMAGE QUALITY CRITERIA FOR PASSIVE NIGHT VISION DEVICES

Abstract

Image quality is probably the single most important parameter in determining the utility of any optical device. For night vision devices, in particular, image quality is of paramount importance. In looking at two different photographs of the same scene, which are essentially two different images fixed by the photographic process, almost anyone can tell at a glance which has the better image quality, particularly if there is a significant difference in image quality. Objective evaluation of image quality in quantitative terms is not easy, because there are many variables that contribute to image quality, not all of which have been identified, or can be quantitatively evaluated.

This report is a preliminary survey of image quality evaluation techniques that have been described in the literature and discussion of their merits for use in a standard for passive night vision devices.

1. BASIC PROBLEMS OF IMAGE QUALITY ASSESSMENT

In the discussion that follows we will be using the radiometric terms radiance and irradiance. These are both measures of the spatial distribution of radiant flux or power, Φ, the time rate of flow of radiant energy, and are defined in appendix A.

A scene can be viewed because it varies in radiance, both spatially and spectrally [1]. A perfect optical system will reproduce in image space the radiance distribution that is present in object space. For each point in object space, there will be a corresponding point in image space, the location of which is determined by the laws of optics. Each element of area surrounding a point in object space will have a radiance in the direction of the optical system which will be essentially constant over the small solid angle subtended by the entrance pupil of the system from the point. The radiant power from the element of area will be the radiance times the projected area of the element times the solid angle subtended by the entrance pupil. The optical system will focus this radiant power, producing an irradiance on a second element of area surrounding the corresponding point in image space, whose area is related to the area of the element in object space by the square of the linear magnification of the optical system. In a lossless system this irradiance is related to the radiance in object space by the f-number of the optical system. With the optical system focused at infinity and viewing a large-area diffuse source of uniform radiance

$$E_i = 0.25\pi L_o f^{-2} \tag{1}$$

where E_i is the irradiance in image space, L_o is the radiance in object space and f is the f-number of the optical system. For real systems, focused on an object at a finite distance, the equation becomes

$$E_i = \pi L_o \tau \, [4f^2(M+1)^2+1]^{-1} \tag{2}$$

where τ is the transmittance of the optical system and M is the magnification, given by

$$M = F/(D-F) \tag{3}$$

where F is the focal length of the optical system and D is the object distance [2].

Unfortunately, all real detectors are essentially surfaces, and usually plane surfaces, and the image that is observed is the variation in irradiance on that plane. If the scene in object space is confined to a plane normal to the optic axis, a perfect optical system will form a perfect image at the image plane, which will correspond to the detector if the system is in perfect focus. If the scene is not confined to a plane, the image of those points not in the object plane will be blurred by defocusing.

No real optical system is perfect. There will always be losses due to reflection, scattering and absorption in the optical elements, various types of aberrations due to imperfections in the optics, and diffraction effects. All of these factors and the defocusing degrade the image, and the image is never a true representation of the scene. The objective of this report is to discuss the ways in which images formed by real optical systems and particularly those formed by image-intensifier night vision devices deviate from the ideal image, and in particular, how such deviations can be evaluated.

The image produced as the output of an imaging system may fail to faithfully reproduce the scene in object space in several ways. Most systems with which we will be dealing produce monochromatic images, that is, the image consists of areas of varying radiance, and the spectral, or color, information in the scene is lost. The extent of such loss may be observed by comparing color and black and white photographs of the same scene. In addition, (1) the magnification may be different in different parts of the image; this will produce a distorted image, although it may be of good quality otherwise; (2) the image will not resolve all of the detail that is present in the scene; and (3) the contrast in the image will be different from that in the scene. In other words, the full range of radiance present in the scene will not be present in the image. The reduction in resolution may be due to imperfect optics (aberrations of various types), grain in film, noise in electronics, the size of the resolution element in scanned systems, etc. The reduction in overall contrast may result from veiling glare in the optical system, the threshold and saturation limits of the detector, nonlinearity in the detector gain, etc. The two effects, loss in resolution and loss in contrast, are coupled. The loss in contrast increases with the spatial frequency in the image until the remaining contrast is so low that fine detail in the image is lost.

There are six related basic criteria that have been used by others in the past to quantitatively evaluate optical image quality. They are (1) the point spread function, (2) the line spread function, (3) the edge gradient, (4) the optical transfer function, (5) the contrast transfer function, and (6) the limiting resolution. Three additional factors that may degrade the quality of an optical image are veiling glare, flare, and distortion. In cases where the optical image is electronically processed before viewing, as in image-intensifier night vision devices and television, the electronics may further degrade image quality. The properties that may contribute to electronic degradation are dark current or light-equivalent background, light induced background, noise and nonlinear amplification.

2. POINT SPREAD FUNCTION [3,4,5,6,7]

The image of a point source will always have a finite area roughly circular in shape. The irradiance on the image plane will vary from a maximum at the center to essentially zero at some distance from the center and usually with secondary ridges and/or peaks [3,4,5]. Axial images generally have axial symmetry, while off-axis images generally have two-fold symmetry about a radius from the optical axis [6]. That is, the two halves of the image on either side of a radius through the center will be mirror images of each other. If the irradiance on the image plane is plotted as a function of position in that plane, the resulting three dimensional figure is the point spread function and contains information that completely describes the image forming characteristics of the system at that point [7].

However, the point spread function is not easy to evaluate, is difficult to represent graphically, and when so represented is not easy to interpret directly in terms of image quality; hence is apparently not much used for image evaluation.

3. LINE SPREAD FUNCTION [7,8,9,10]

If a line source is used instead of a point source, its image will be changed from a dot to a line of finite width in which the irradiance varies in a direction normal to its length. A plot of the irradiance of the line image as a function of position along a normal to the image is the line spread function. For an axial image, this function contains all of the information necessary to evaluate the quality of an image formed at that point. For an off-axis point, two line spread functions are required—one taken from a line source oriented along a radius from the optic axis, and one oriented normal to the radius [7].

The line spread function is somewhat easier to measure than the point spread function and can be represented in two dimensions. It is perhaps somewhat easier to estimate the resolution of a system from a line spread function than from a point spread function, but mathematical transformation is required to get quantitative data on the image quality of a system from the line spread function [5,7].

4. EDGE GRADIENT [5,7,10,11,12,13,14]

If an object having a sharp, straight edge and high radiance is outlined on a low-radiance background (thus having an abrupt discontinuity in radiance) and then is imaged, the transition in the image will not be as abrupt as that in the object. If the irradiance in the image is plotted as a function of position along a normal to the edge, the resulting curve is called the edge gradient. The derivative of such an edge gradient is the line spread function.

The edge gradient may be easier to measure than the line spread function. Such a measurement requires a source with a sharp discontinuity in radiance, which can be produced by a single knife edge, as compared to the line source required for the line spread function, which usually requires a narrow slit made from two knife edges parallel and close together [7]. The comments about the information content of the line spread function apply equally to the edge gradient.

A parameter called acutance [5,15,16,17,18] can also be obtained from the edge gradient. Acutance may be thought of as the sharpness of edges in an image and is a measure of image quality. For evaluating acutance, the negative log of the irradiance (the optical density of a photographic negative or the reflection density of a photograph) in the image of a knife-edge pattern is plotted as a function of distance, in micrometers, across the edge in the image [17]. The acutance is then the square of the slope of the density-vs-distance curve across the edge, averaged between the points on either side where the slope has a value of 0.005 density units per micrometer, divided by the density difference between the light and dark areas in the image. A typical edge gradient is shown in figure 1 for a knife-edge image recorded on film. The points A, at X_a and D_a, and B, at X_b and D_b, are where the slope has a value of 0.005. Expressed mathematically, the acutance $\langle G_x \rangle^2/DS$ is

$$\langle G_x \rangle^2/DS = \frac{1}{(D_b - D_a)(X_b - X_a)} \int_A^B (dD/dx)^2 dx \quad (4)$$

where G_x is the slope of the curve at point x, DS is the density difference between the light and dark areas, $D_b - D_a$, D is the optical density of the negative and x is the distance, in micrometers, normal to the edge.

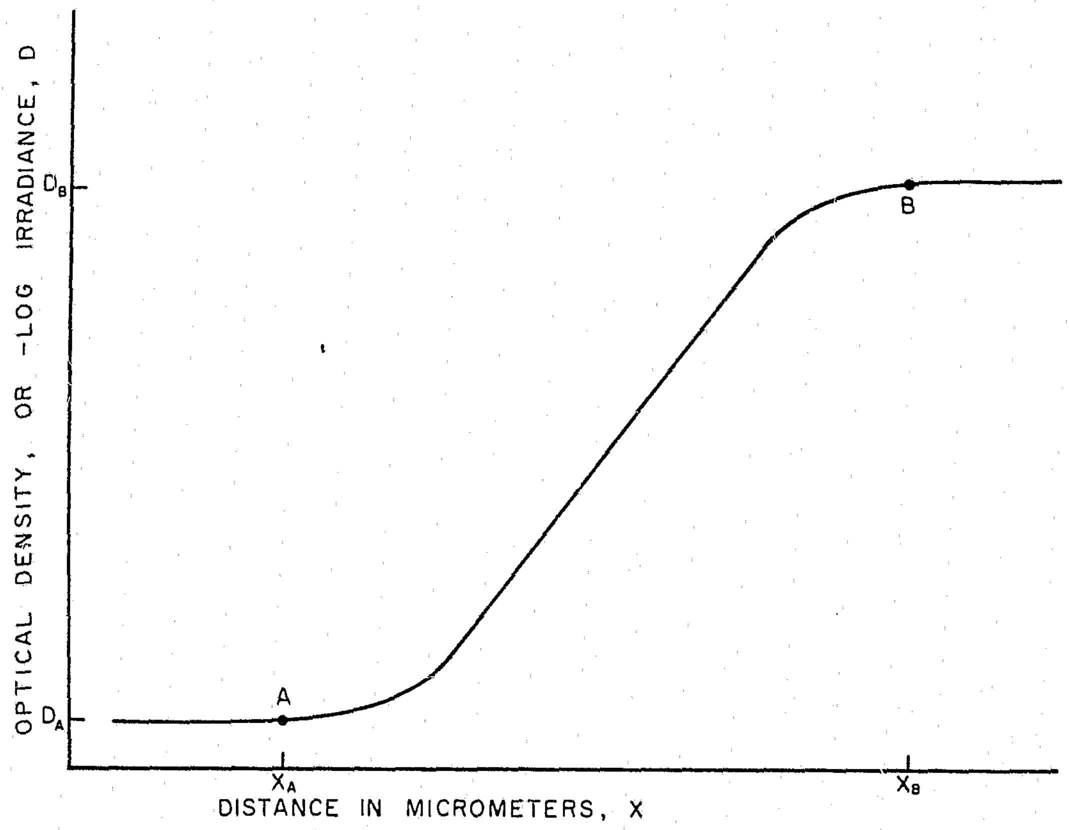

FIGURE 1. *A typical edge gradient, showing the points, A at X_a, D_a and B at X_b, D_b, where $dD/dx=0.005$, between which acutance is computed.*

5. OPTICAL TRANSFER FUNCTION [3,5,7-10,12,18-29]

The one-dimensional optical transfer function (OTF) is defined as the Fourier transform of the line spread function and can be computed from the measured edge gradient or line spread function. The mathematical derivation of the optical transfer function is given in appendix B. However, it may be easier to visualize what it represents from the way in which it is measured directly.

When a two-dimensional sine-wave pattern in which the luminance varies sinusoidally in one dimension is imaged, the image will also be a sine-wave pattern in which the spatial frequency (reciprocal of the wavelength) of the image will be that of the object pattern times the magnification factor of the optical system used to form the image. The amplitude, or contrast, of the image usually is less then that of the object and the image may be displaced relative to the image that would have been formed by a perfect imaging system [24]. The OTF relates the flux distribution (radiance or luminance) in the image to that in the object and consists of two parts—a real part, called the modulation transfer function (MTF), and an imaginary part, called the phase transfer function (PTF), as explained in appendix B.

The MTF is defined as the ratio of the contrast, or modulation, in the image to that in the object. The contrast, or modulation, C(f), at a spatial frequency f, is given as

$$C(f)=\frac{L_{max}-L_{min}}{L_{max}+L_{min}} \tag{5}$$

where L_{max} is the maximum luminance and L_{min} the minimum luminance in the pattern. The MTF(f) at spatial frequency f is then

$$MTF(f)=\frac{C(f)_i}{C(f)_o} \tag{6}$$

where the subscripts i and o refer to the image and object, respectively.

The PTF(f) is a measure of distortion and is the difference in phase between the image formed by the system under test and the image that would be formed by an equivalent error-free system. It is expressed as cycles, either as a phase angle ω, in radians or degrees, or simply as cycles. 2π radians $=360°=1$ cycle. When the PTF has an appreciable value, the line spread function is asymmetrical. The PTF is likely to be given only as a fraction of a cycle, in degrees or radians, the whole cycles being ignored. Some equipment used for evaluating OTF measures only the fractional phase difference, and not the number of complete cycles.

Both MTF(f) and PTF(f) usually vary with position in the image plane, and usually with orientation of the patterns at any one point [24]. For points away from the optic axis, they are usually measured in two orientations with the waves normal and parallel to a radius from the optic axis, respectively [21].

Both MTF(f) and PTF(f) are plotted as a function of spatial frequency to form the MTF and PTF curves for a system. Generally such curves are plotted for a point on the optic axis, and for a point away from the optic axis, usually about 2/3 of the distance from the center to a corner of the field.

To an experienced individual, the MTF curves will give a good qualitative evaluation of the quality of image produced, but no single value measure of image quality derived from an MTF curve has been generally accepted, although some have been proposed [30,31,32]. The PTF curve is not easily interpreted in terms of the distortion of the image and in most cases distortion is measured directly.

The measurement of OTF (MTF and PTF) for lenses and other purely optical systems is simpler then for photoelectronic imaging systems such as night vision devices and television, in which an optical (light) image is converted into an electronic image, which is amplified and converted back into an optical image for viewing. In the purely optical system, the photons pass through the system at the speed of light with essentially no time delay. In the photoelectronic systems, the speed of the electrons in that part of the system is significantly less than the speed of light, and the phosphor screen, used to recreate the optical image, has a significant decay time. The net result is that a rapidly moving image, that can be correctly focused by a purely optical system, will be smeared out and appear to have poor resolution in a photoelectronic system.

The less-expensive equipment for measuring OTF makes use of a moving square wave pattern, generated by a rotating disc with radial slots behind a fixed slit [33]. The spatial frequency of the pattern can be changed by changing the angle between the fixed and rotating slits. The moving image formed by the optical system under test is scanned across the entrance aperture (slit) of the detector in the image plane of the device, at a frequency of 1 KHz, and the output of the detector is filtered at the fundamental frequency, hence is directly proportional to the MTF of the system, and the phase difference between the input and output waves is the PTF. Equipment of this type is available in the $30,000 to $50,000 price range.

The above simple equipment cannot be used with photoelectronic systems, because the movement of the pattern is fast compared to the time constant of the system. For such systems the pattern in object space must move so slowly that the time constant of the system does not reduce the MTF, or a stationary pattern is scanned with a moving detector [25]. The second procedure is less desirable for image intensifier night vision devices, because the periodic pattern formed by the fiber optic plates may introduce perturbations when the image is scanned. Because of the difficulty in generating stationary sine-wave patterns with variable spatial frequency, many systems designed for use with photoelectronic devices use a line source, which consists of a very narrow slit [34]. The image of the line source is then scanned with a moving detector with a narrow slit aperture to produce the line spread function of the device, which is then processed by either analog or digital procedures to obtain the MTF. Because of the more elaborate processing of the output, such equipment is more expensive than that using moving images. The general price range for such equipment is $60,000 to $100,000.

The OTF is theoretically the best measure of the image-forming ability of a system, but practically such measurements leave something to be desired. Past experience has indicated that agreement from one laboratory to another, and from one type of measuring equipment to another, are likely to fail to agree by at least 5 percent, even on lenses, and discrepancies of 10 percent or more are rather frequent [21,24]. Even measurements made on the same lens with the same equipment at different times will frequently fail to agree. Errors with photoelectronic imaging devices are likely to be larger than those with lenses.

Because of the high cost of equipment and inconsistency of measurements of OTF in the past, it was decided that this method is not suitable for use in a standard at this time.

6. CONTRAST TRANSFER FUNCTION [9,14,15,22,23,28]

The major problem in measuring OTF is in generating the sine-wave pattern to be imaged, at all of the frequencies required. If the sine-wave pattern is replaced by a bar pattern, the measured quantity is the contrast transfer function, CTF. Measurement of CTF avoids the major disadvantages of MTF measurements and gives results of reasonable accuracy with much less expensive equipment, with only a small loss in information content [14,22,23]. Figure 2 shows the MTF and CTF of a typical lens.

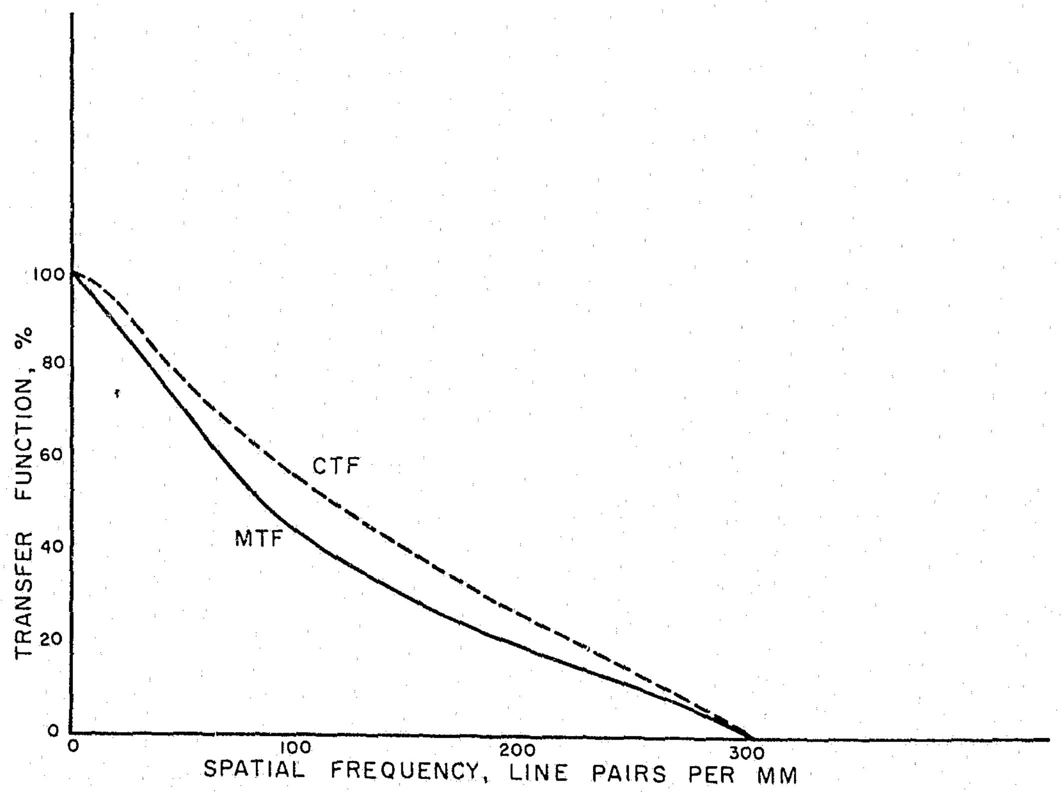

FIGURE 2. *Contrast transfer function (CTF) and modulation transfer function (MTF) curves for a typical photographic lens.*

7. LIMITING RESOLUTION [6,15,32,35]

Resolution in optical systems is a measure of the ability of the systems to separate images of two neighboring object points [36]. In astronomy, the object points are stars, and the limiting resolution is the angular separation of two stars that can just be seen as two and not one. In a spectroscope, the objects are spectral lines, and the resolution is the dimensionless ratio of the wavelength difference and the average wavelength of two lines that can just be separated [37].

When an imaging device is to be used to extract information from a scene, rather than to determine the relative positions of point or line sources, it has been found by experience that a recognition test gives a better evaluation of performance than the criteria mentioned above. A common example is the Snellen visual acuity test. The test chart [38] consists of lines of letters in which the height of the letters in each line decreases by a constant fraction from top to bottom. The person whose eyes are being tested is located a known distance from the chart, usually 20 ft, and is required to read the letters as far down as possible, and his visual acuity is rated on the basis of the smallest letters he can read. For this test the letters are black on white background so the object contrast is high, and the chart is well lighted.

Other charts that can be used for visual acuity tests of individuals who do not read consist of 1) a block letter E, the Snellen E [39]. Such a figure can be oriented with the opening, to the right when the E is in normal position, to the right, left, up or down. In this case the person being tested is required to give the direction of the opening; and 2) a Landolt C [39] which consists of a circular ring of width equal to 1/5 of its outer diameter, having a gap equal to the width of the ring. The ring can be oriented with the gap at any of 6 positions corresponding to 2, 4, 6, 8, 10, or 12 o'clock on a clock face. Again the person being tested is required to tell the direction of the gap.

For limiting resolution tests of optical systems, line or bar patterns are frequently used [9,22,40]. A resolution bar chart usually consists of a series of patterns in which the size of adjacent patterns varies by a constant factor. Each pattern consists of several bars, separated by a distance equal to the width of a bar. Charts of this type vary in the length-to-width ratio of the bars, the number of bars in a pattern, and the ratio of sizes of adjacent patterns.

Other common patterns consist of bars that are wedge-shaped, varying in width and arranged in a fan, the space between the bars being of the same shape as the bars, [41] and of a single series of parallel bars in which the width of adjacent bars and of the space between bars is decreased by a constant factor [42-44]. Charts of these types are frequently seen in television test patterns.

One resolution chart that has been widely used in testing photographic lenses is the Air Force 1951 Resolution Chart [40]. In this chart the length-to-width ratio of the bars is 5, and the number of bars in a group is 3. A single pattern consists of two groups with the bars horizontal and vertical, respectively. A single group of three bars and two spaces is contained within a square. The ratio of the sizes of adjacent groups is $2^{1/6}$ or 1.122462. The patterns are available commercially as reflectance charts with a contrast, C(f), of about 0.97, and as transparencies having contrasts of 2.00, 0.80 and 0.20, expressed as density difference, or C(f) values of 0.99, 0.72 and 0.50, respectively.

A second well-known resolution chart is the NBS 1952 resolution chart for photographic lenses [45]. In this case the length-to-width ratio of the bars varies from about 10 to 36; there are again three bars in each group, and two mutually perpendicular groups in each pattern. The ratio of the sizes of succeeding patterns is $2^{1/4}$ or 1.189207. These charts were published as reflection charts in two degrees of contrast. 1.4 and 0.20 expressed as density difference, or C(f) values of 0.97 and 0.50, respectively.

A third widely used resolution chart is the NBS 1963 Microcopy Resolution Test

Chart [46]. In this chart, the length-to-width ratio is 24, and there are five bars in each group, and two mutually perpendicular groups in each pattern. The size ratio between adjacent patterns is again $2^{1/6}$. These charts are available only as reflection charts, with contrast C(f) of about 0.99.

Bar charts are not often used for visual acuity tests. Their principal use is in evaluating the limiting resolution of imaging devices.

For evaluating the limiting resolution of a visual optical device, such as a telescope, a microscope, or a lens, the chart can be viewed directly through the device. In the case of photoelectronic imaging devices, the image on the phosphor screen may be viewed directly or with the aid of a magnifying eyepiece. In the case of a photographic system, the image in the negative or print usually must be viewed through a microscope. In every case the image should be viewed through a magnifier if necessary to assure that the limiting resolution evaluated is truly that of the device and not that of the eye of the observer. The limiting resolution of the device being evaluated is the spatial frequency, in line pairs per mm, of the smallest pattern in the image that can be clearly identified as a line pattern. This will be the spatial frequency in the pattern on the chart divided by the magnification of the device. The magnification of the eyepiece, if any, does not enter into the computation.

Limiting resolution tests are quite widely used to evaluate image quality. This is unfortunate, because the limiting resolution in an image gives but little information about the quality of the image for most purposes. As mentioned previously, loss in resolution is coupled with loss in contrast, and information is needed on the contrast remaining at spatial frequencies lower than the limiting frequency, in order to evaluate the useful image quality.

The limiting resolution obtained with a given resolution pattern is influenced by the geometry of the pattern. For best precision, charts consisting of parallel lines separated by a distance equal to the width of a line are used. Even with charts of this type, the measured resolution increases with an increase in the length-to-width (aspect) ratio of the lines and the number of lines in a pattern, up to some limiting values on the order of 20 for length-to-width ratio and 10 for the number of lines. Even the measured CTF values are influenced by these factors, but to a much smaller extent than limiting resolution. Both limiting resolution and CTF are strongly influenced by the contrast of the test pattern.

The Air Force 1951 Chart has been selected for use in evaluating image quality (CTF) of night vision devices for several reasons. This chart has been used for over 20 years, and there is a large body of experience in its use. Charts are available from several manufacturers, as either reflectance charts or transparencies, and as positive or negative charts. As transparencies, 3 degrees of contrast are supplied. Charts are available in a wider range of pattern sizes than are most other charts.

8. DISTORTION [4,6,40]

In section 5, Optical Transfer Function, it was mentioned that the PTF is a measure of distortion in the image, but that the PTF curves are not easily interpreted in terms of the actual distortion present in an image.

Distortion is measured directly by viewing a chart with a square grid, large enough to fill the entire field of view, with the lines wide enough to be clearly visible in the image, and the size of the squares such that there are about 10 to 20 squares across the image [40]. To evaluate distortion quantitatively, a square grid chart with a distinctive mark at its center is set up so that its plane is normal to the axis of the device being tested, and the axis passes through the center of the chart. The viewing distance is adjusted until there are about 18 squares across the field. The image is then photographed with a distortion-free camera with a 1 to 1 magnification. The image, after processing, is measured with a travel-

ing microscope. The distortion is then measured as the deviation of the lines in the image from a true grid, expressed as a percentage of the distance from the axis. The percent distortion is then plotted as a function of the distance from the axis, and is classified as either pincushion or barrel type. The distortion varies significantly with position. In barrel type distortion the magnification is greater at the center than it is at the edges, and a straight line normal to a radius from the axis will be concave toward the axis. In pincushion type distortion, the magnification is less at the center than at the edges, and a straight line normal to a radius from the axis is convex toward the axis [47,48].

If a single value for distortion is desired, it is usually taken at some stated distance along a radius—a common value is 80 percent of the radius along a diagonal. In measuring the distortion along any radius from the axis, the grid should be oriented so that the lines on which distortion is measured are normal to the radius.

9. LIGHT-INDUCED BACKGROUND [20,21,40,49]

In any photoelectronic imaging system there is a uniform background signal over the entire image area. This uniform background is made up of two parts. One part, called light-equivalent background or dark current, is independent of the irradiance on the photocathode, and is discussed in the next section. The second part of the uniform background varies with the irradiance on the objective lens of the imaging device, and is called light-induced background.

The light-induced background is also made up of two parts, one originating in the objective lens, and one in the photoelectronic portion of the equipment. That portion originating in the objective lens is called veiling glare [21,40] and that originating in the photoelectronic portion of the equipment is called electronic light-induced background [49].

In any real imaging system, most of the light incident on the objective lens is regularly transmitted and focused. A small fraction of the light is scattered in the optical system, and is spread more or less uniformly over the plane. The fraction of incident light so scattered is called veiling glare. Veiling glare is thus a property of the objective lens, and evaluation of veiling glare is a part of the process of evaluating objective lenses, which will be covered in a separate report.

The electronic light-induced background is due to three factors. First, the accelerated electrons in the tube may collide with atoms or molecules of contaminating gas, and form electron-ion pairs. The electron of such a pair is accelerated by the electric field and attracted to the phosphor screen, and contributes to the background. The positively charged ion is also accelerated by the electric field, and attracted to the photocathode, where it may knock out additional electrons, which contribute to the background. Secondly, electrons may suffer collisions with atoms or ions in the tube, and be scattered from their normal paths, thus contributing to the background. Thirdly, some light from the phosphor screen may get back through the tube and be incident on the back of the photocathode, and liberate photoelectrons which contribute to the background.

The measured light-induced background will consist of the veiling glare of the objective lens plus the electronic light-induced background of the photoelectronic portion of the equipment, plus the light-equivalent background.

The effect of background is to add a constant increment to both L_{max} and L_{min} in eq (2) for the contrast of the image, which thus reduces the MTF at all frequencies

$$Cf = \frac{(L_{max} + B) - (L_{min} + B)}{(L_{max} + B) + (L_{min} + B)} = \frac{L_{max} - L_{min}}{L_{max} + L_{min} + 2B} \qquad (7)$$

where B is background luminance. Because of the background, the MTF is never exactly unity even at zero spatial frequency. For this reason it is customary to normalize the MTF curve by substituting $C(O)_i$ for $C(f)_o$ in eq (6) (see app. B). In other words, the MTF at zero frequency is set equal to 1.00, and those at all other frequencies are adjusted by multiplying them by the ratio $C(O)_o/C(O)_i$.

10. BACKGROUND OR DARK CURRENT

In any photoelectronic device there will be a background signal that is produced in the absence of light. In the case of a photoconductive device this is appropriately termed "dark current" because it is the current that flows through the device under the influence of the bias potential, in the absence of light.

In the case of a photoelectronic imaging device, this phenomenon appears as the luminance of the phosphor screen when the device is activated, but the objective lens is capped, so that no light is incident on the photocathode. The term "dark current" is inappropriate in this case, since it is manifest as a luminous flux, rather than as an electric current. When this property is measured directly in terms of luminance of the phosphor screen, it is called background luminance. When it is evaluated in terms of the irradiance on the photocathode required to produce an equivalent luminance on the phosphor screen, it is termed "light equivalent background." The two terms are related by the optical gain of the imaging device.

The background is due primarily to electrons emitted by the photocathode spontaneously, as a result of thermal vibration of its molecules or atoms. Its amount varies with the temperature of the photocathode and the potential between photocathode and phosphor screen.

Light equivalent background can be measured directly, or can be computed from the measured luminance of the phosphor screen and the optical gain of the device, which is evaluated separately and is not considered as an essential parameter of image quality. When light equivalent background is evaluated directly, the luminance of the phosphor screen is evaluated with the objective lens capped. The cap is then removed, and the device is focused on a large-area source, whose radiance is slowly increased until the luminance of the phosphor screen is exactly doubled. The source radiance required to exactly double the luminance of the phosphor screen is then the light equivalent background [50].

11. FLARE [21,51,52]

Flare is a second type of defect in an image that may be produced by internal reflections in the optical system. Flare produces a ghost image and hence is localized, in contrast to light induced background, which is spread uniformly over the image area.

Flare is produced by a bright light source that is near an edge of or just outside the field of view of the device, but if outside, in a position where the light from the source is incident on the objective lens. It shows up as one or more bright areas on the image.

Circular images are usually caused by multiple reflections between the lens elements. Line images may be caused by reflection from the lens barrel. In any case flare, if present, can significantly degrade image quality in the areas where it is present. In a photoelectronic image device the flare from a red source may be significantly greater than that from a "white" source of the same luminance, particularly if the device has a S-1 or S-20 ER photocathode. The antireflection coating on the lens elements, particularly for photographic lenses, usually is not very effective in the red and near infrared, where the photocathode has its sensitivity peak.

Flare can be reduced by use of a lens shade that prevents light from outside the field of view from striking the objective lens, and by not looking at bright sources. However, this is not always possible, and the flare of the system should be evaluated as a part of the imaging properties of the system.

12. PERSISTENCE

While not directly related to image quality as such, persistence may degrade image quality of night vision devices when viewing a moving bright object, or when the image device itself is moved while viewing such an object, so that the image moves on the output screen.

Persistence is most noticeable as a streak or tail trailing behind the moving image of a bright object. It may be considered as a blurring of an image in time, comparable to the blurring of an image in space produced by the optical elements of the system. It may be measured as the time required for the image of a bright area to decay to some predetermined low value, such as 0.1 percent of the initial value. Persistence becomes significant only when the decay time is signficantly greater than the integration time of the eye, which is usually taken as 0.2 sec.

13. DISCUSSION

Any resolution test evaluates the resolution of the entire system, including the detector. In all of the visual tests described above, particularly in section 7, the human eye is used as the detector, hence the visual acuity of the individual observer making the test is a part of the evaluation. Visual acuity varies not only from one individual to another, but for the same individual from day to day and from hour to hour, depending on his general health, the state of adaptation or fatigue level of his eyes, his general bodily fatigue level, his diet during the previous few days, his emotional state and the level of alcohol in his blood, to mention only a few of the variables that are difficult to control. Among the significant variables that are more easily controlled are the contrast of and irradiance on the test chart, the luminance level of the phosphor screen for a photoelectronic device, and the time allowed for a determination. The general conclusion is that visual tests are not likely to have the degree of precision and accuracy that is desired in a standard test method.

In the methods that require a scanning microphotometer, such as the various transfer functions, the scanning device forms a part of the system being evaluted, and the line spread function, edge gradient, MTF or CTF evaluated is that of the combination of the imaging device and the scanning microphotometer. It is thus essential that the MTF or CTF of the scanning device be high at all spatial frequencies at which the imaging system is to be evaluated. This means that the scanning aperture should be small compared to the period of the highest spatial frequency being measured, or that the slit function of the scanning device should be much narrower than the line spread function of the imaging device being evaluated.

If the above criteria are met, the effect of the transfer function of the scanning device can be largely corrected for by use of eq (6). The transfer function of the scanning device remains constant, and need be evaluated only once.

The following conclusions about the test described in sections 2 through 8 appear justified. (1) Limiting resolution gives but little information about image quality for most purposes. (2) The line spread function and edge gradient both contain complete information about the imaging characteristics of an imaging system, but not in a form that is easy to interpret. (3) The optical transfer function contains all of the information that is present in the line spread function and edge gradient. The MTF is in a form such that it is easier to interpret, in terms of image quality, than the other image criteria, but the PTF is not easy to interpret in terms of distortion. OFT tests require expensive equipment, are somewhat time consuming to make and the accuracy and precision of such tests leave something to be desired. (4) The contrast transfer function is much easier to evaluate than the MTF, and provides similar information. (5) Distortion and background tests give additional quantitative information that is helpful in evaluating image quality. And, (6) flare, if present, can significantly degrade images, but there is no convenient way to evaluate flare in quantitative terms.

From the above analysis it appears that the tests required for evaluating the image quality of an imaging system should include: 1) CTF measurements at spatial frequencies from near zero frequency to the frequency at which the CTF approaches zero, 2) distortion measurements, 3) light-induced background measurements, and 4) a qualitative evaluation of flare.

14. SUMMARY AND CONCLUSIONS

It appears that no single parameter adequately describes the image quality of even a simple visual instrument such as a microscope or telescope. In the more complex case of a photoelectronic imaging device such as an image intensifier night vision device, at least five parameters are required to describe the image quality. These are (1) CTF, (2) distortion, (3) light induced background and (4) light equivalent background, all of which can be quantitatively evaluated, and (5) flare, which can only be evaluated qualitatively.

Two of the parameters that can be evaluated quantitatively, CTF and light induced background, vary with the level of irradiation on the target, and must be evaluated at several levels of irradiance covering the range of values to be expected in actual service. Distortion should be nearly free from variation due to irradiation level. Flare will be affected both by the radiance of the source producing the flare and the general level of irradiance on the primary target area, and should be roughly proportional to the ratio of the radiance of the flare source to that of the target area. However, since flare is not subject to easy quantification, it will probably be sufficient to evaluate it on a qualitative basis for a single high ratio of flare source radiance to general target radiance.

This report has included discussion of only those parameters of a night vision device that affect image quality. Other important parameters, such as optical gain and durability, will be discussed in subsequent reports.

APPENDIX A—Nomenclature

Irradiance, E, (at a point on a surface)—Quotient of the radiant flux incident on an element of the surface containing the point by the area of the element [53].

Radiant flux, Φ,—Power emitted, transferred or received in the form of radiation [53].

Radiance, L, (in a given direction, at a point on the surface of a source or a receptor, or at a point on the path of a beam)—Quotient of the radiant flux leaving, arriving at, or passing through an element of surface at this point and propagated in directions defined by an elementary cone containing the given direction, by the product of the solid angle of the cone and the area of the orthogonal projection of the element of surface on a plane perpendicular to the given direction [53].

Expressed mathematically

$$E = d\Phi/dA \qquad \text{(A-1)}$$

where dA is the element of area surrounding the point. The unit is $W \cdot m^{-2}$.

$$L = d^2\Phi/d\omega dA\cos\theta \qquad \text{(A-2)}$$

where ω is the solid angle of the elementary cone and θ is the angle between the normal to the surface and the given direction. The unit is $W \cdot m^{-2}\,sr^{-1}$.

Figure 3 may help to understand the concept of radiance. The point P is the point at which radiance is measured, and ΔA is the plane area surrounding P. The line P-P′ defines the given direction from P′ to P. The area ΔA′ surrounding P′ is in a plane normal to P-P′ and subtends the solid angle Δω from P. The solid angle is not shown in the figure. N is the normal to surface ΔA at P and θ is the angle between A and P-P′. The radiation field is represented by the arrows. That portion of the radiation field passing through ΔA′ and ΔA in that order constitutes the flux ΔΦ. Then

$$L(P,P' - P) = \Delta\Phi/(\Delta\omega\Delta A\cos\theta) \qquad \text{(A-3)}$$

Note that eq (A-3) differs from eq (A-2) in the use of finite flux, ΔΦ, solid angle, Δω, and area, ΔA, instead of the differential quantities in eq (A-2), since all real measurements involve finite quantities, not differentials.

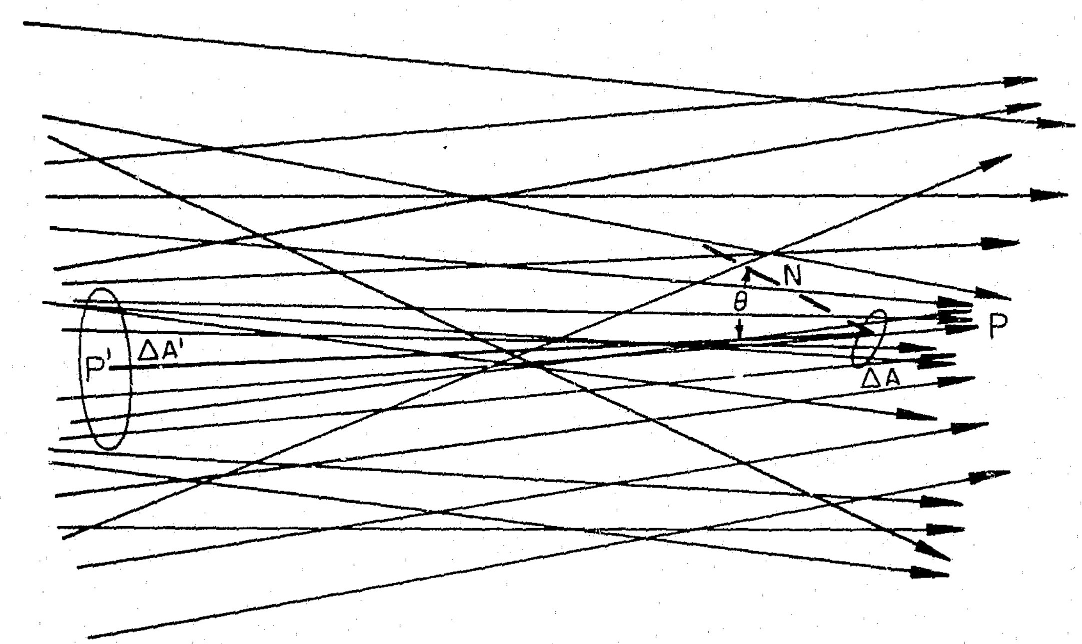

FIGURE 3. *The concept of radiance.*

In the absence of diffusion, it can be demonstrated that the optical extent, product of the geometric extent of an element of a beam and the square of the refractive index of the medium of propagation, is an invariant along the length of the beam, whatever the deviations which it undergoes by reflection or refraction ($dG \cdot n^2 = $ constant). In consequence, the basic radiance, quotient of the radiance by the square of the refractive index, is invarient along the length of an element of beam if the losses by absorption or by reflection are taken as zero ($L \cdot n^2 = $ constant) [44].

The values of irradiance and radiance to be used are weighted by the spectral response of the detector used to measure the radiant flux or power. If the human eye is used as the detector, the spectral response of the CIE Standard Observer [45] is used as the weighting function and the irradiance becomes the illuminance, E, and the radiance becomes the luminance, L.

Flare—A defect in an optical system which produces ghost images of a bright source due to reflections in the system. Light from the source must strike the outer surface of the objective lens, but need not be in the field of view. The images may be of almost any size or shape, but circular or elliptical discs, circular or elliptical lines, or portions of either are the most common form.

Veiling glare—A defect in an optical system which produces a relatively uniform background over the entire image area. The background is due to scattering in the system. Note: The term "flare" is sometimes used in the literature to mean "veiling glare" as defined above, or the combination of both "flare" and "veiling glare."

Modulation Transfer Function—The ratio of the modulation contrast in the image to that of the object imaged, when imaging a pattern whose radiance varies sinusoidally in one dimension, plotted as a function of the spatial frequency in the image.

Contrast Transfer Function—A modulation transfer function measured with a square-wave pattern as the object, instead of a sinusoidal pattern. Note: "Modulation transfer function" is sometimes used in the literature to mean "contrast transfer function" as defined above.

APPENDIX B—Optical Transfer Function [55]

An imaging system views the radiance of objects in object space, and focuses the radiance on a surface, usually plane, in image space. The irradiance on this surface is detected by the eye in visual systems, by photographic film in cameras or by various types of detectors in photoelectronic imaging systems. In any one system the irradiance on the image plane is proportional to the radiance in object space, and the proportionality constant can be computed from the geometry of the system. In the discussion that follows I_o represents the radiance in object space and I_i the irradiance on the image plane. The proportionality constant is omitted from the equations because the transfer functions are independent of the absolute values of radiance or irradiance.

The basic mathematics of the optical transfer function requires a linear system—one in which, for incoherent illumination, the irradiance adds linearly. In such a system the optical image is a linear superposition of impulse responses summed over the entire object plane. This simple relation is best expressed as a convolution of the object radiance, $I_o(\mu)$, and the impulse response of the imaging element(s),

$$I_i(x) = I_o(\mu) f(x-\mu)\, d\mu \tag{B-1}$$

where, since we are dealing with the problem in one dimension, f(x) is the line impulse response (line spread function). Thus, if we consider the delta-function (a line source) as an object, its image is the impulse response (line spread function), i.e.,

$$\begin{aligned} I_i(x) &= \int \delta(\mu) f(x-\mu)\, d\mu \\ &= f(x) \end{aligned} \tag{B-2}$$

We can characterize the impulse response (line spread function) as the complex product of two *amplitude* impulse responses.

$$f(x) = \phi_a(x) \cdot \phi_a^*(x) = |\phi(x)|^2 \tag{B-3}$$

By combining this with eq (B-1), we obtain

$$I_i(x) = \int I_o(\mu)\phi_a(x-\mu)\,\phi_a^*(x-\mu)\, d\mu \tag{B-4}$$

Because we are treating a linear system, the spectrum of the image is given by its Fourier transform. The tilde ~ is used to designate a Fourier transform. Then,

$$\tilde{I}_i(\sigma) = \int\int I_o(\mu)\phi_a(x-\mu)\phi_a^*(x-\mu)\, d\mu\, e^{-2\pi i\sigma x} dx \tag{B-5}$$

Aided by the General Fourier Theorem, this becomes

$$\tilde{I}_i(\sigma) = \tilde{I}_o(\sigma) \cdot \tilde{f}(\sigma) \tag{B-6}$$

where

$$\tilde{f}(\sigma) = \int \tilde{\phi}(k-\sigma)\,\tilde{\phi}^*(-\sigma)\, d\sigma \tag{B-7}$$

$f(\sigma)$ is called the transfer function, and, since the transform of the amplitude impulse response is the aperture (pupil) function, is seen to be the convolution of the aperture function with its complex conjugate, the fundamental definition of optical transfer function. As with all truly linear systems, eq (B-6) shows that image spectrum is "object spectrum times transfer function." An alternate representation of the transfer function stems from eq (B-7), by application of the convolution theorem; it is seen to be the Fourier transform of the impulse response,

$$\tilde{f}(\sigma) = \int f(x) e^{-2\pi i\sigma x} dx \tag{B-8}$$

We now consider the effect of the transfer function (and its determination) on an image. We choose a radiance distribution which is cosinusoidal in the μ-plane. This allows us to consider a physically realizable (and measureable) object of a single frequency: all parameters are known and/or can be measured without ambiguity. Thus,

$$I_o(\mu) = A(1 + m\cos 2\pi\sigma\mu) \tag{B-9}$$

where A and m are constants. The image is given by eq (B-1), with a change of variable,

$$\begin{aligned} I_i(x) &= A\int f(\mu)\, d\mu \\ &\quad + Am\int f(\mu)\cos 2\pi(x-\mu)\, d\mu \\ &= A\int f(\mu)\, d\mu \\ &\quad + Am\cos 2\pi\sigma x \int f(\mu)\cos 2\pi\sigma\mu\, d\mu \\ &\quad + Am\sin 2\pi\sigma x \int f(\mu)\sin 2\pi\sigma\mu\, d\mu \end{aligned} \tag{B-10}$$

We commonly normalize the transfer function to unity at the origin, using the area under the impulse response (line spread function) as the normalizing factor. Thus, the normalized transfer function is written

$$\tilde{f}(\sigma)=\frac{\int f(\mu)e^{-2\pi i\sigma\mu}d\mu}{\int f(\mu)d\mu} \qquad \text{(B-11)}$$

We now define the normalized Fourier Cosine and Sine transforms by

$$\tilde{f}_c(\sigma)=\frac{\int f(\mu)\cos 2\pi\sigma\mu d\mu}{f(\mu)d\mu} \qquad \text{(B-12)}$$

and

$$\tilde{f}_s(\sigma)=\frac{\int f(\mu)\sin 2\pi\sigma\mu d\mu}{\int f(\mu)d\mu} \qquad \text{(B-13)}$$

Then, by incorporating (B-12) and (B-13) in (B-10), the *normalized image irradiance* is obtained:

$$I_i(x)=A+Am\{\tilde{f}_c(\sigma)\cos 2\pi\sigma x+\tilde{f}_s(\sigma)\sin 2\pi\sigma x\} \qquad \text{(B-14)}$$

For a given frequency, $f(\sigma)$ has a numerical value. To condense (B-14) accordingly, let

$$\tilde{f}_c(\sigma)=\eta\cos\theta$$
$$\tilde{f}_s(\sigma)=\eta\sin\theta \qquad \text{(B-15)}$$

Then eq (B-14) reduces to

$$I_i(x)=A+\eta mA\cos(2\pi\sigma x-\theta) \qquad \text{(B-16)}$$

By taking the ratio of $f_s(\sigma)$ to $f_c(\sigma)$, we find that

$$\theta=\tan^{-1}\frac{\tilde{f}_s(\sigma)}{\tilde{f}_c(\sigma)} \qquad \text{(B-17)}$$

When we square and add eq (B-15), we obtain

$$\eta^2\cos^2\theta+\eta^2\sin^2\theta=\{\tilde{f}_c(\sigma)\}^2+\{\tilde{f}_s(\sigma)\}^2 \qquad \text{(B-18)}$$

and

$$\eta=|f(\sigma)|=[\{\tilde{f}_c(\sigma)\}^2+\{\tilde{f}_s(\sigma)\}^2]^{1/2}. \qquad \text{(B-19)}$$

Then η is the modulus of the complete transform, and θ is the relative phase angle. Finally, the normalized image intensity is given by

$$I_i(x)=A\{1+m|\tilde{f}(\sigma)|\cos(2\pi\sigma x-\theta)\} \qquad \text{(B-20)}$$

Since

$$|\tilde{f}(\sigma)|\leq 1,$$

comparison of (B-9) and (B-20) shows that a sine wave is imaged as a sine wave with (at most) its modulation attenuated and phase shifted. Thus, for a linear system, a measure or

characterization of performance is the optical transfer function (OTF). When phase shift is not present (or neglected, for one reason or another) the system attenuates only modulation, and (B-11) is called the modulation transfer function (MTF). These terms are often used interchangeably, and the basic meaning and implication should always be determined before conclusions are reached. η, plotted as a function of spatial frequency, forms the MTF curve, and θ plotted as a function of spatial frequency forms the PTF curve.

APPENDIX C — References

[1] Ronchi, V., "Definition of the Concept of Image" in NATO Symposium on Image Evaluation, Munich, Germany, 1969, pp. 223-231 (H. W. Leibowitz, Director, Penn. State Univ.).

[2] Miller, L. D., "Transfer Characteristics and Spectral Response of Television Camera Tubes," Photoelectronic Imaging Devices, Vol. 1, Chapter 12, pp. 267-290 (L. M. Biberman and Sol Nudelman, editors, Plenum Press 1971).

[3] Stoelzner, W. E., "The Application of Fourier Techniques to Image Evaluation," Air Force Report SAMSO-TR-71-20, AD718095 (October 1971).

[4] O'Neill, Edward L., Introduction to Statistical Optics, figure 5-11, pp. 84, (Addison-Wesley Publishing Company, Reading, Mass., 1963).

[5] Birch, K. G., "A Survey of OTF Based Criteria Used in the Specification of Image Quality," National Physical Laboratory Report, Optical Metrology Division, Vol. 5, (April 1969).

[6] Born, Max, and Wolf, Emil, Principles of Optics, 3rd edition, Chapter IX, "The Diffraction Theory of Abberrations," (Pergamon Press, New York, 1965).

[7] Shack, R. V., "Characteristics of Image-Forming Systems," J. Research NBS, Vol. 56, No. 5, pp. 245-260 (May 1956).

[8] McCamy, C. S., "The Evaluation and Manifestation of Photographic Images," Picture Processing and Psychopictories, pp. 57-74 (B. S. Lepkin and A. Rosenfeld, editors, Academic Press, 1970).

[9] Franke, Georg, Physical Optics in Photography, pp. 184 (The Focal Press, New York, 1966).

[10] Attaya, W. L., et al, "Study of Image-Evaluation Techniques," AFAL Tech. Report AFAL-TR-66-343, AD803459 (November 1966).

[11] Frieser, H., "Untersuchungen Uber die Wiedergabe Kleiner Details Durch Photographische Schichten (II) und (III)" Phot. Korr. Vol. 91, pp. 51-60 (1955) and Vol. 92, pp. 183-190 (1956).

[12] Smith, P. L., "A New Technique for Estimating the Modulation Transfer Function of an Imaging System from its Edge Response," Air Force Report SAMSO-TR-72-66, AD739550 (October 1971).

[13] Cox, A., "Image Evaluation by Edge Gradients," NBS Circular 526, pp. 267-272 (April 1954).

[14] Shack, R. V., "A Proposed Approach to Image Evaluation," NBS Circular 526, pp. 275-286 (1954).

[15] Lewis, N. W., and Hauser, T. V., "Microcontrast and Blur in Imaging Systems," J. Photographic Science, Vol. 10, pp. 288-301 (1962).

[16] Kuehn, Rudolph L., "Image Analysis," Display Systems Engineering, Chapter 5, pp. 137-164 (A. R. Luxemburg and R. L. Kuehn, editors, McGraw-Hill, 1968).

[17] Higgins, G. C., and Jones, L. A., "The Nature and Evaluation of the Sharpness of Photographic Images," Journal of Motion Picture and Television Engineers, Vol. 58, pp. 277-289 (April 1952).

[18] Brock. G. C., "Reflections on Thirty Years of Image Evaluation," Photographic Science and Engineering, Vol. 11, No. 5, pp. 356-362 (1967).

[19] Rosenhauer, K. and Rosenbruch, K., "Flare and Optical Transfer Function," Applied Optics, Vol. 7, pp. 283-287 (February 1968).

[20] Hall, J. A., "Evaluation of Direct-View Imaging Devices," Photoelectronic Imaging Devices, Vol. 2, Chapter 3, pp. 53-76 (L. M. Biberman and S. Nudelman, editors, Plenum Press, New York, N.Y., 1971).

[21] Hopkins, Robert E., "Lens Test Standardization Study," AFAL-TR-70-93, AD710633 (July 1970).

[22] Limansky, Igor, "A New Resolution Chart for Imaging Systems," Electronic Engineer, pp. 50-55 (June 1968).

[23] Coltman, J. W., "The Specification of Imaging Properties by Response to Sine Wave Input," Journal of the Optical Society of America, Vol. 44, No. 6, pp. 468-471 (June 1954).

[24] Kelsell, D., "Application of the Optical Transfer Function in Electro-Optical Systems," ESD-TR-70-166, AD708602.

[25] Scott, F., and Frauenhofer, D., "The Modulation Transfer Function and Methods of Measurement," Photoelectronic Imaging Devices, Vol. I, Chapter 13 (L. M. Biberman and S. Nudelman, editors, Plenum Press, New York, N.Y. 1971).

[26] Murata, K., "Instruments for the Measuring of Optical Transfer Functions," Progress in Optics, Vol. V, pp. 199 (E. Wolf, editor).
[27] Brouwer, W., "Sine Wave Testing," Optical Spectra., Vol. 1, No. 4, pp. 76-79 (1967).
[28] Nudelman, S., "Intensity: Detector Quantum Efficiency, Efficiency Contrast Function and the Signal-to-Noise Ratio," Advances in Electronics and Electron Physics, Vol. 28 (J. D. McGee, et al, editors).
[29] Franz, K., Kochmann, G., and Lahmann, R., "Modulation Transfer and Background of Various Image Intensifier Output Screens," 5th International Symposium on Photo-Electronic Image Devices (London, England, September 1971).
[30] Granger, E. M., and Kupeny, K. N., "An Optical Merit Function, SQF, Which Correlates with Subjective Image Judgements," Photographic Science and Engineering, Vol. 15, No. 3, pp. 221-230 (1972).
[31] Schade, O. H., "A New System of Measuring and Specifying Imaging Definition," NBS Circular 526, pp. 231-258 (April 1954).
[32] Kelly, D. H., "Spatial Frequency, Bandwidth and Resolution," Applied Optics, Vol. 4, No. 4, pp. 435-437 (April 1965).
[33] Scott, F., and Frauenhofer, D., "The Modulation Transfer Function and Methods of Measurement," Photoelectronic Imaging Devices, Vol. 1, Chapter 13, pp. 298-299 (L. M. Biberman and S. Nudelman, editors, Plenum Press, New York, N.Y. 1971).
[34] Hall, J. A., "Evaluation of Direct-View Imaging Devices," Photoelectronic Imaging Devices, Vol. 2, Chapter 3, pp. 69 (L. M. Biberman and S. Nudelman, editors, Plenum Press, New York, N.Y., 1971).
[35] Ronchi, V., "The Energetic Theory of the Resolving Power," in NATO Symposium on Image Evaluation, Munich, Germany, 1969, pp. 232-259 (H. W. Leibowitz, Director, Penn. State Univ.).
[36] Born, Max, and Wolf, Emil, Principles of Optics, 3rd edition, pp. 414 (Pergamon Press, New York, 1965).
[37] Born, Max, and Wolf, Emil, Principles of Optics, 3rd edition, pp. 333 (Pergamon Press, New York, 1965).
[38] Biberman, L. M., "Specification for Electronic Image-Forming Devices," Photoelectronic Imaging Devices, Vol. 1, Chapter 11, pp. 245-265 (L. M. Biberman and S. Nudelman, editors, Plenum Press, New York, N.Y. 1971).
[39] Kuehn, Rudolph L., "Image Analysis," Display Systems Engineering, Chapter 5, pp. 148 (A. R. Luxemburg and R. L. Kuehm, editors, McGraw-Hill, 1968).
[40] "Photographic Lenses," MIL-STD-150A (May 12, 1959).
[41] Crowell, M. H. and Labuda, E. F., "The Silicon Diode Array Camera Tube," Photoelectronic Imaging Devices, Vol. 2, Chapter 15, pp. 343;341-343 (L. M. Biberman and S. Nudelman, editors, Plenum Press, New York 1971).
[42] Franke, Georg, Physical Optics in Photography, pp. 181 (The Focal Press, New York, 1966).
[43] McGee, J. D., "The Spectracon," Photoelectronic Imaging Devices, Vol. 2, Chapter 21, pp. 521 (L. M. Biberman and S. Nudelman, editors, Plenum Press, New York, 1971).
[44] Washer, F. E., "Resolving Power of Airplane-Camera Lenses," NBS Circular 526, pp. 214 (1954).
[45] Washer, F. E., and Gardner, I. C., "Method for Determining the Resolving Power of Photographic Lenses," NBS Circular 533 (1953).
[46] "Revised Microscopy Resolution Test Charts," NBS Technical News Bulletin, Vol. 48, No. 12 (1964).
[47] O'Neill, Edward L., Introduction to Statistical Optics, pp. 56 (Addison-Wesley Publishing Company, Reading, Mass., 1963).
[48] Birch, K. G., "A Survey of OTF Based Criteria Used in the Specification of Image Quality," National Physical Laboratory Report, Optical Metrology Division, Vol. 5, pp. 217 (April 1969).
[49] Sackinger, W. M. and Gislason, G. A., "Ion Feedback Noise in Channel Multipliers," 5th Symposium on Photoelectronic Imaging Devices, Imperial College, London, England (September 1971).
[50] Hall, J. A., "Evaluation of Direct-View Imaging Devices," Photoelectronic Imaging Devices, Vol. 2, Chapter 3, pp. 60 (L. M. Biberman and S. Nudelman, editors, Plenum Press, New York, N.Y. 1971).
[51] Bodenstein, B., and Keppler, H., "Camera Flare: The Real Enemy?" Modern Photography, Vol. 36, No. 1, pp. 86-89 (1972).
[52] Goldberg, N., "The Fight to Conquer Flare," Popular Photography, Vol. 71, No. 3, pp. 68-71, 126 and 129 (September 1972).
[53] International Lighting Vocabulary, 3rd edition CIE No. 17 (E. 1.1) (Bureau Central de la CIE, Paris, France, 1970).
[54] ASTM Method 308, "Standard Recommended Practice for Spectrophotometry and Description of Color in CIE 1931 System," ASTM Book of Standards, 1972 edition, pp. 983-1000. The $\lambda(\nu)$ curve in table 4, pp. 998 is the photopic response function.
[55] Swing, R. E., private communication.

END