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Image Quality of Monochrome Television Cameras

Law Enforcement
Equipment
Technology

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Image Quality of Monochrome Television Cameras

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Contents

FOREWORD

The Law Enforcement Standards Laboratory (LESL) of the National Bureau of Standards (NBS) furnishes technical support to the National Institute of Law Enforcement and Criminal Justice (NILECJ) program to strengthen law enforcement and criminal justice in the United States. LESL's function is to conduct research that will assist law enforcement and criminal justice agencies in the selection and procurement of quality equipment.

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 is a law enforcement equipment report developed by LESL under the sponsorship of NILECJ. Additional reports as well as other documents are being 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. Comments should be addressed to the Law Enforcement Standards Laboratory, National Bureau of Standards, Washington, D.C. 20234.

Jacob J. Diamond
Chief, Law Enforcement
Standards Laboratory

Executive Summary

The camera operating characteristics most frequently quoted by manufacturing of monochrome television cameras are: (1) limiting resolution, (2) signal-to-noise ratio, and (3) sensitivity. These characteristics are related to each other, and to the scene parameters: (1) spatial frequency, (2) contrast and (3) brightness. The camera characteristics are evaluated under optimum limiting conditions of the scene parameters, and hence define in a general way the quality of the image produced, but they do not give much information about the range of scene parameters over which the camera will produce useful pictures. The contrast transfer function and the responsivity curve of the camera give additional information about image quality. A sixth camera operating characteristic, relative spectral response, which is independent of the other camera characteristics and the scene parameters, also may affect image quality.

IMAGE QUALITY OF MONOCHROME TELEVISION CAMERAS

Joseph C. Richmond

The camera operating characteristics most frequently quoted by manufacturers of monochrome television cameras are the: (1) limiting resolution, (2) signal-to-noise ratio, and (3) sensitivity. These characteristics are coupled to each other and to the scene parameters: (1) spatial frequency, (2) contrast and (3) brightness. The camera characteristics are evaluated under limiting conditions of the scene parameters, and hence define in a general way the range of scene parameters over which the camera will produce useful pictures, but they do not give much information about the quality of the image produced. The contrast transfer function and the responsivity curve of the camera give more information about image quality. A fourth camera operating characteristic, relative spectral response, which is independent of the other camera characteristics and scene parameters, may also affect image quality.

Key words: Contrast; contrast transfer function; image quality; limiting resolution; relative spectral response; signal-to-noise ratio; square wave patterns; television cameras.

INTRODUCTION

The purpose of this report is to show how the performance characteristics of a television camera or system relate to the subjective perception of image quality. It will be shown that the camera characteristics usually quoted by manufacturers of television cameras do not fully describe image quality. These characteristics are: (1) limiting resolution, (2) signal-to-noise ratio and (3) sensitivity. Two additional characteristics, the contrast transfer function and the responsivity curve give much additional information about the image quality.

SUBJECTIVE VISUAL EVALUATION OF IMAGE QUALITY

Image quality is not easily defined.[1] If two photographs, of different image quality, are made of the same scene, almost anyone will be able to tell which has the better image quality, but he will probably not be able to clearly explain why one is better than the other. The adjectives used to explain the difference will probably be "sharper," "better contrast," or "better resolution."

Sharpness generally refers to the way in which edges in the scene, where a dark object is outlined against a light background or vice versa, are depicted in the image. In a sharp image the transition between dark and light occurs in a very short distance. In a less sharp image the transition requires a greater distance. Contrast refers both to the difference between the luminances of the lightest white and darkest black in the image and to the number of shades of gray that can be distinguished between them. The image with the best contrast is the one in which the shades of gray in the image best represent the brightnesses in the scene. Resolution refers to the size of the smallest detail in the scene that can be distinguished in the image.

MONOCHROME IMAGES

In a monocrome imaging system such as black and white television the scene is reproduced as an image that varies in brightness only. All of the spectral, or color, information in the scene is lost. In addition, the image may differ in several ways from the scene as seen by the human eye. The system has a resolution limit, that is, some of the fine detail in the scene is not reproduced in the image. The resolution limit in the monochrome television system may be related to the size of the scanning electron beam in the camera tube or picture tube, to the bandwidth of the amplifier, or to the resolution of the objective lens of the camera. The range of brightnesses that can be produced in the image on the monitor

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[1] For a detailed discussion of image quality criteria see LESP-RPT-0301.00 Survey of Image Quality Criteria for Passive Night Vision Devices, GPO Stock No. 2700-00262, price 65 cents, U.S. Government Printing Office, Washington, D.C. 20402.

is limited. The brightest highlight in the image may be significantly darker than the brightest highlight in the scene and the darkest shadow in the image may be significantly lighter than the darkest shadow. Also the overall brightness in the image may be different than that in the scene. The image also contains noise, which may be visible as "snow," a grainy pattern of light and dark dots superimposed on the image. Finally, if the relative spectral response of the camera differs from that of the normal human eye, the relative brightnesses of areas of different colors in the scene will be different in the image.

The signal produced by the television camera can be modified by the monitor electronics in at least two ways. The "brightness" control can be used to vary the overall brightness in the image and the "contrast" control can be used to vary the contrast (gamma) of the image. By use of the two controls it is possible to increase the detail visible in the shadows or highlights of the image at a sacrifice of detail in other areas. Because of the modifications that may be introduced by the monitor electronics, it is generally preferable to evaluate the quality of the image produced by a television camera in terms of the video signal displayed on a waveform monitor, rather than in terms of the image displayed on a television monitor. In the discussion that follows, reference will be made to the appearance of the image on a TV monitor, but all measurements will be of the voltage of the video signal as displayed on a waveform monitor.

BASIC SCENE PARAMETERS

In order to relate the subjective visual parameters of the image to the performance characteristics of the imaging system, it is necessary to define the basic parameters of the scene and construct a simple scene in which these parameters can be varied. The basic parameters of the scene are brightness, contrast and spatial frequency. Brightness is the luminance of the scene or any part of it. Contrast is related to the difference in brightness of adjacent areas of the scene. Spatial frequency is related to the relative size of areas of nearly uniform brightness in the scene. Any scene can thus be represented as a series of parallel lines in which the brightness of a spot on the line varies with position. If the brightness is plotted as a function of position along the line, the resulting curve can be formed by the sum of the amplitudes of a large numbes of sine waves of diffesent frequencies, amplitudes and phases. Thus if we know how the camera reproduces a sine-wave pattern, in which the brightness in the direction of scanning varies sinusoidally, for patterns of all spatial frequencies, we know essentially all about the imaging characteristics of the camera or system. We can also learn a great deal about the imaging characteristics from the way in which the system or camera reproduces square-wave patterns of different spatial frequencies. Square-wave patterns are much easier to produce than are sine wave patterns.

SQUARE WAVE PATTERNS

The ideal square-wave pattern is a series of parallel dark lines on a light background. The space between lines is equal to the width of a line, and the length of each line is at least five times its width. Such a pattern can be completely described by three parameters: spatial frequency, which is related to the width of a line; contrast, which is a measure of the ratio of the brightness of the lines and spaces and the absolute brightness of the lines and spaces. Since most patterns are made to be viewed by diffusely incident illumination on the front of an opaque pattern or the back of a transparency, the last parameter can also be expressed as an illumination level times the reflectance or transmittance of the pattern.

The spatial frequency, *f*, is generally expressed in lines (lines plus spaces) per picture height. Normal U.S. Broadcast television is referred to as having 30 frames per second of nominally 525 scanning lines each. However, the maximum number of scanning lines displayed on the monitor screen is 489, the time required for the other 36 lines being required for the vertical blanking interval and control pulses. The height-to-width ratio of the television image is 3 to 4. If we know the number of pattern lines, N, just filling the width of the field of view of the camera, we can compute f as

$$f = 0.75\,N, \tag{1}$$

or, if we know the width of the field of view, W, and the width of a pattern line, w, in the pattern,

$$f = 0.75\,W/w. \tag{2}$$

The spatial frequencies of many resolution charts are reported in line pairs per mm. A line pair consists of one line and one space, and thus line pairs per mm is equivalent to cycles per mm. In the television industry, however, the units used for spatial frequency are pattern lines per picture height, in which a line pair (one dark and one light line) counts as two lines. It may also be confusing that the unit is in lines per picture *height,* although almost always measured as lines per picture *width*; hence the factor of 0.75.

Modulation contrast, C, is measured as

$$C = \frac{L_l - L_d}{L_l + L_d}\,. \tag{3}$$

The subscripts l and d refer to the light and dark lines respectively and the symbol L may be the luminance of the pattern or the image on a monitor, the radiance of the pattern, or the voltage in the video signal as evaluated by means of a waveform monitor.

Brightness is expressed as luminance for light of a color temperature of 2870 K (television industry standard) or a spectral distribution of CIE Standard Source A (color temperature 2856 K). Lights of these two spectral distributions are indistinguishable visually and nearly indistinguishable photometrically.

RESPONSIVITY

Responsivity is the voltage of the video signal produced per unit radiance (or luminance) in the scene or unit irradiance or illumination on the input face of the camera tube. It is usually measured with a uniform diffuse source of size large enough that the measured value is independent of source size. Such a source could consist of a single light line that fills the entire field of view of the camera. If the illumination on the pattern is zero, the image on a TV monitor will have some low brightness greater than zero. As the illumination is slowly increased, the brightness on the monitor will remain constant until a point is reached where an increase in illumination on the pattern can just be detected. This is the threshold level of the system. To characterize a system or a camera, it is expressed either in terms of the luminance or radiance of the pattern. To characterize a camera tube it is expressed as the irradiance or illumination on the input face of the camera tube. Some manufacturers of television cameras report the characteristics of the camera tube as being the characteristics of the camera. This can be misleading unless it is clearly stated that the characteristics apply to the camera tube and not the camera.

The illumination, E_i, in the optical image formed on the input face of the tube is related to L_s, the luminance in the scene, by the equation

$$E_i = \frac{\pi \tau L_s}{4(f/N)^2} \tag{4}$$

where f/N is the f-number of the lens, and τ is the transmittance of the lens.

As the illumination on the pattern is increased above the threshold level at a constant rate, the brightness of the monitor will increase at an increasing rate, as indicated near the bottom of the curve in figure 1. A region will soon be reached where the brightness in the image, L_i, is related to the brightness in the scene, L_s, by the equation

$$L_i = L_s^{\gamma} \tag{5}$$

in which the exponent γ is the "gamma" of the system. The "gamma" of many television cameras is less than one.

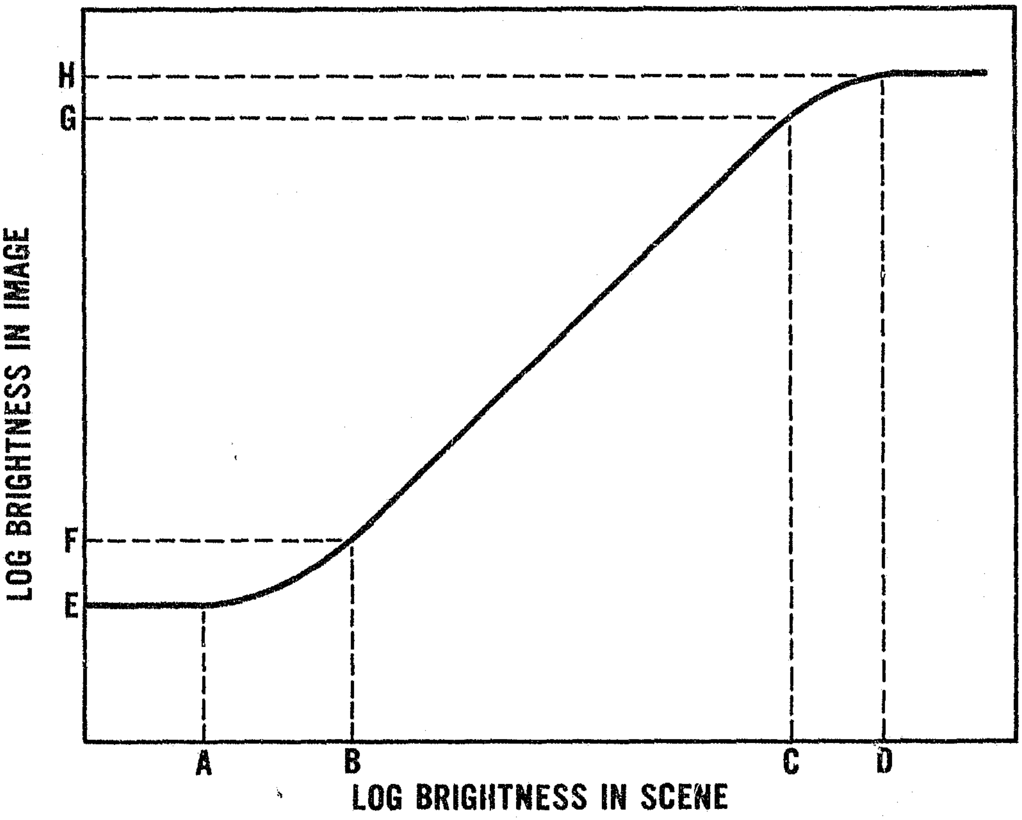

FIGURE 1. *The responsivity of a television system, evaluated in terms of the brightness of the image produced by the television monitor.*

As the illumination on the scene is increased further, the brightness of the image will follow that of the scene as predicted by equation (5) for a while, then at a slower and slower rate, until an upper limit of the brightness of the image is reached as shown in figure 1. Above this upper level of scene brightness the brightness of the image remains constant, regardless of the brightness of the scene. The limit of scene brightness above which image brightness remains constant is called the saturation level.

If the logarithm of the brightness of the image is plotted as a function of the logarithm of scene brightness, the resulting curve will look like the one in figure 1.

Scene brightness should be evaluated in units of radiance [$W \cdot m^{-2} \cdot sr^{-1}$]. However, it is the practice of the photoelectronic industry to use units of luminance [$lm \cdot m^{-2} \cdot sr^{-1}$].

Such units are valid for evaluating the response of a device having a relative spectral response that is different from that of the normal human eye only if the spectral distribution of the light is known. The photoelectronic industry specifies the spectral distribution of the light as being that of a tungsten filament lamp at a color temperature of 2870 K. The spectral distribution of such a source is reasonably well known out to a wavelength of about 1.5 μm. The photoelectronic industry also evaluates scene brightness in units of luminance, even though the spectral distribution is unknown.

The units used for luminance are the nit [$\text{cd} \cdot \text{m}^{-2}$] and footlambert [$\text{cd} \cdot \pi^{-1} \cdot \text{ft}^{-2}$] and for illumination the lux [$\text{lm} \cdot \text{m}^{-2}$] and footcandle ($\text{lm} \cdot \text{ft}^{-2}$].

In figure 1 the point A,E represents the threshold level of the system and the point D,H the saturation level. A is the logarithm of scene brightness or the logarithm of the irradiance or illumination on the input face of the camera tube at the threshold level and D is the logarithm of the same quantity at the saturation level.

The points B,F and C,G represent the ends of the straight line portion of the responsivity curve. Scene brightness in the range represented by B-C will be reproduced on the monitor in the luminance range F-G as computed by use of eq (5) if the gamma of the monitor is set at 1.00, and the brightness control of the monitor is set at the proper level. The exponent γ of eq (5) is evaluated as the slope of the straight line portion of the sensitivity curve:

SIGNAL-TO-NOISE RATIO

The threshold level of luminance of the TV monitor, E, is determined by background or noise. The principal source of noise in vidicon cameras is the shot noise in the scanning electron beam. A signal is produced at scene brightness levels lower than A, but it is so small compared to the noise that it cannot be detected. Thus the noise effectively sets the threshold level of the system. While the signal can be amplified indefinitely, the noise is also amplified, and hence the signal-to-noise ratio must be above some lower limit to produce a useful signal.

The signal-to-noise ratio reported by the manufacturer is that at the upper end of the responsivity curve. It is thus a rough indication of the useful range of the camera, represented by the range B-C in illumination on the input face of the camera tube.

As scene brightness decreases the signal-to-noise ratio decreases from the maximum value at the input represented by C, until it is so low that no satisfactory picture can be produced. The signal-to-noise ratio of the system is thus directly related to input light level or scene illumination.

Signal-to-noise ratio is usually reported in units of decibels, dB.

$$S/N = 10 \log s/n \text{ [dB]}, \tag{7}$$

where s is the peak power in the video signal and n is the root-mean-square power in the noise. The noise has a very broad frequency band. The TV monitor does not respond to very high frequencies. Hence it is customary to use a filter, which passes the lower frequencies to which the TV monitor responds, before measuring noise.

Noise is usually not apparent in the picture displayed on the monitor until the signal-to-noise ratio decreases to a value on the order of 10. or about 10 db. Most cameras are reported by the manufacturer to have signal-to-noise ratios on the order of 40 dB or 10,000 to 1. For much of the discussion that follows noise will be ignored, because images formed at high light levels, where noise does not contribute significantly to image degradation, will be discussed.

CONTRAST AND RESOLUTION

When a square wave pattern is illuminated at a level such that the brightness of the light lines in the pattern is slightly less than C and that of the dark lines slightly greater than B in figure 1, the contrast in the image will be less than that in the pattern. The ratio of the contrast in the image to that in the pattern is defined as the contrast transfer function (CTF) of the system or camera. However, it is customary to take as the contrast of the pattern the measured contrast in the image at zero frequency (usually identical to that obtained when two lines fill the total field of view). The CTF (*f*) is plotted as a function of spatial frequency, *f*, to obtain the CTF curve of the camera or system. A typical CTF curve is shown in figure 2. The CTF (*f*) at frequency *f* will decrease with increasing spatial frequency.

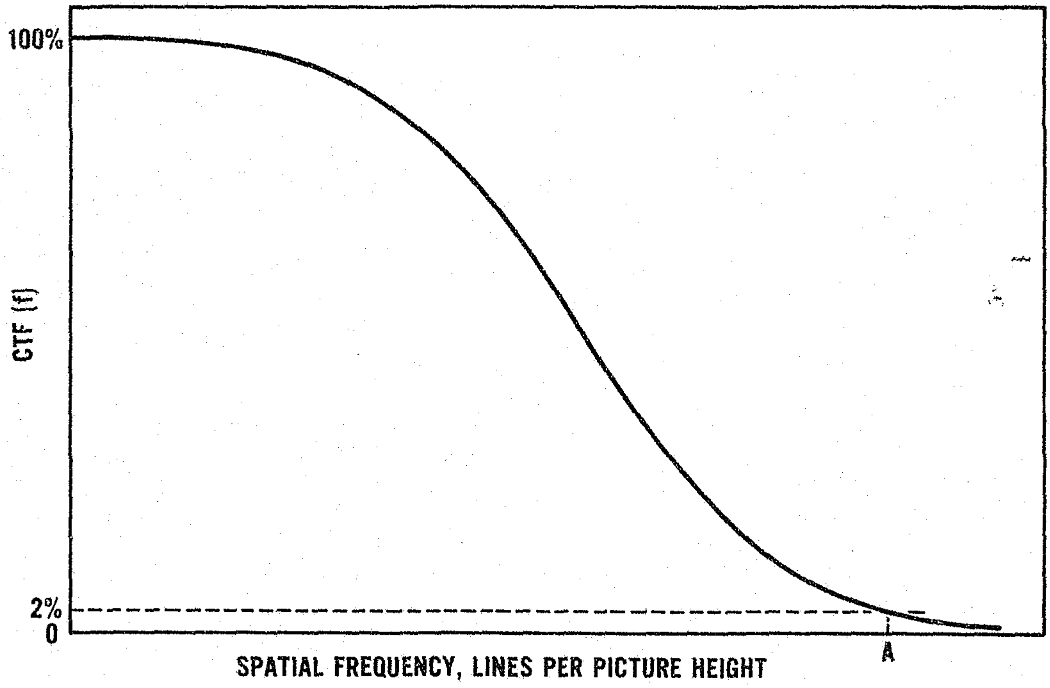

FIGURE 2. *A typical Contrast Transfer Function (CTF) curve for a television camera.* The dotted line at two percent contrast is the limit below which a linear pattern is usually not detected.

When the contrast of the image drops to about 2 percent, the image will appear to be uniformly gray and the lines of the pattern cannot be distinguished as such. The spatial frequency at which this occurs, indicated by A on figure 2, is the limiting resolution of the camera or system.

The limiting resolution is thus a measure of the smallest detail that can be visually distinguished in the image of a scene with maximum contrast under ideal lighting conditions. It is reported in units of pattern lines per picture height, even though it is horizontal resolution. The limiting resolution conveys no information about image quality at lower spatial frequencies.

CTF gives a much better evaluation of image quality than limiting resolution. In general, the overall subjective impression of image quality is well correlated with the area between the CTF curve and the 2 percent line shown in figure 2 for scenes with good contrast and adequate lighting.

CTF, and hence limiting resolution, decreases with both a decrease in the contrast of the scene viewed, and with a decrease in the signal-to-noise ratio. The signal-to-noise ratio decreases as the light level decreases.

SPECTRAL RESPONSE

Relative spectral response is a measure of the degree to which the camera or system responds to light of different wavelengths. The relative spectral response curve of a camera or system is a plot of the logarithm of the relative response of the system to spectrally narrow bands of light of different wavelengths, plotted as a function of the peak wavelength of maximum illumination for each band, for all wavelengths at which there is significantly response.

If the relative spectral response of the camera is a good match to that of the normal human eye, the image will portray the relative brightness of the various colors as the eye sees them and the image will look correct. In the image produced by a camera that has peak responsivity in the violet end of the spectrum, the blues and violets will appear too light and the yellows and reds too dark. If the peak is near the red end of the spectrum, the violets, blues and greens will appear too dark and the yellows and reds too light.

Cameras with peak responsivity well into the infrared may produce images of some scenes that appear unreal. For instance, facial blemishes may be accentuated, dark skin may look light, dark green foilage may appear white, and white snow may appear dark.

SUMMARY

The three characteristics generally reported by the manufacturers of television cameras to indicate image quality are: (1) limiting resolution, in lines per picture height, (2) signal-to-noise ratio, in decibels, and (3) sensitivity, in terms of scene illumination and/or faceplate illumination required for a usable picture and for a full video signal. In addition, they may or may not report relative spectral response.

Unfortunately the first three characteristics are each evaluated under conditions that give the most favorable value for that characteristic. Limiting resolution is evaluated for a high-contrast target at near-maximum light level and is reported as a maximum spatial frequency. Signal-to-noise ratio is evaluated at a near-maximum light level and a minimum spatial frequency. Sensitivity is evaluated at the minimum light levels required to produce a usable picture and a full video signal. These parameters thus roughly delineate a volume in three-dimensional space within which a usable image will be formed; the axes are light level or signal-to-noise ratio, spatial frequency and contrast.

Additional information is contained in the total responsivity curve and the CTF curve, which more clearly establish the boundaries of this space. These curves also give some additional insight into some of the interrelationships between the three factors within the boundaries.

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I have discussed this matter with Frances Whitlock of NCJRS.

Sincerely yours,

Jacob J. Diamond

Jacob J. Diamond, Chief
Law Enforcement Standards Laboratory

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