Photonics-Enabled Technologies

Imaging System Performance for Homeland Security Applications

OP-TEC

Optics and Photonics Series

Imaging System Performance for Homeland Security Applications

Photonics-Enabled Technologies

OPTICS AND PHOTONICS SERIES

OP-TEC: The National Center of Optics and Photonics Education

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PREFACE

This module is one of three pertaining to the role of optics and lasers in homeland security. OP-TEC treats the imagining component of homeland security as a *photonics-enabled* technology. The current OP-TEC series on photonics-enabled technologies comprises modules in the areas of manufacturing, biomedicine, forensic science and homeland security, environmental monitoring, and optoelectronics, as listed below. (This list will expand as the OP-TEC series grows. For the most up-to-date list of OP-TEC modules, visit http://www.op-tec.org.)

Manufacturing

Laser Welding and Surface Treatment

Laser Material Removal: Drilling, Cutting, and Marking

Lasers in Testing and Measurement: Alignment Profiling and Position Sensing

Lasers in Testing and Measurement: Interferometric Methods and Nondestructive Testing

Environmental Monitoring

Basics of Spectroscopy

Spectroscopy and Remote Sensing

Spectroscopy and Pollution Monitoring

Biomedicine

Lasers in Medicine and Surgery

Therapeutic Applications of Lasers

Diagnostic Applications of Lasers

Forensic Science and Homeland Security

Lasers in Forensic Science and Homeland Security

Infrared Systems for Homeland Security

Imaging System Performance for Homeland Security Applications

Optoelectronics

Photonics in Nanotechnology

The modules pertaining to each technology can be used collectively as a unit or separately as stand-alone items, as long as prerequisites have been met.

For students who may need assistance with or review of relevant mathematics concepts, a review and study guide entitled *Mathematics for Photonics Education* (available from CORD) is highly recommended.

The original manuscript of this module, *Infrared Systems in Homeland Security,* was prepared by Dr. Alan Ducharme.

CONTENTS

Introduction 1
Prerequisites 2
Objectives 2
Scenario 2
Basic Concepts 3
  Resolution of the Human Eye 4
  Resolution Criterion 5
Modulation Transfer Function (MTF) 10
  Blur Spots and Resolution 13
  MTF in Electro-Optical Systems 15
  Cascade Property of MTFs 18
MTF Measurement Methods 19
  Point Spread Function Method 19
  Knife-Edge Method 19
  Target Method 20
Applying MTF to Reconnaissance Systems 22
Laboratory 25
Exercises 28
References 29
Appendix—Fourier Transforms 30
Laboratory MTF Target 31

Imaging System Performance for Homeland Security Applications

INTRODUCTION

The National Strategy for Homeland Security and the Homeland Security Act of 2002 have mobilized a variety of agencies throughout our society. The primary function of the Department of Homeland Security is to utilize technology and information gathering capabilities to secure the United States against future terrorist attacks. An increasing effort has been made to monitor vital facilities and U.S. borders using video surveillance. Video reconnaissance utilizes a wide range of imaging systems operating in the visible and infrared spectrums to cover areas that would be difficult to cover using conventional armed forces. An example would be the perimeter of a water treatment facility. Video reconnaissance allows a single operator to monitor hundreds of video cameras. The performance of these video cameras is crucial to the effectiveness of these surveillance systems.

An imaging system is a collection of optical lenses or mirrors that form an image of a scene onto an observation or image plane. Systems that display this image directly on the human eye are referred to as *all optical.* An example would be a telescope or a pair of binoculars. Modern systems used for recording moving imagery utilize an electronic detector placed at the image plane. These systems are referred to as *electro-optical,* since they integrate electronic and optical technologies to produce high-quality images. Electro-optical imaging systems can be used to capture moving imagery typically called *video.*

Imaging systems do not generate perfect images or exact representations of scenes. This is due to a number of limitations—some complex, such as spectral range, and some simple, such as the diameter of the optics. This deviation between real images and perfect images can be thought of as how well the system can "see." In human beings, ocular maladies such as astigmatism or near- and far-sightedness decrease our ability to see objects and perform tasks such as reading or driving. Age tends to change the shape of the eye's lens, causing images on the retina to be defocused. The result is a reduction in the ability of the imaging system to see.

The concept of "seeing ability" is qualitative. In optical engineering, we measure imaging system performance quantitatively. One such measurement is *resolution,* which is determined by the size of the smallest feature that the imaging system can resolve. A more complex, but also more encompassing, measurement is *modulation transfer function* (MTF). These measurements provide a means of determining the ability of an imaging system to perform specified tasks.

In this module, you will study the measurements used to evaluate imaging system performance as they relate to homeland security. The concepts of resolution and MTF will be presented for optical and electro-optical systems. You will learn how to use industry standard methods in evaluating different systems based on resolution and MTF and how to predict the performance of a system for a particular application.

PREREQUISITES

The student should be familiar with the following before attempting to complete this module.

1. High school mathematics through intermediate algebra and basics of trigonometry
2. CORD's Optics and Photonics Series Course 1, *Fundamentals of Light and Lasers*
3. CORD's Optics and Photonics Series Course 2, *Elements of Photonics*

   Module 2-1: *Operational Characteristics of Lasers*
   Module 2-2: *Specific Laser Types*
   Module 2-3: *Optical Detectors and Human Vision*

4. CORD Optics and Photonics Series, photonics-enabled technology module *Lasers in Forensic Science and Homeland Security*

OBJECTIVES

At the completion of this module, you should be able to do the following:

- Define the resolution of an imaging system for a variety of system types
- Define *aberration* as it relates to optical lens and mirror systems
- Read and understand an MTF measurement for optical and electro-optical components
- Describe how resolution and MTF are measured using procedures such as knife-edge and bar-targets
- Predict the expected performance of an imaging system using component MTF curves
- Choose between different detection systems based on a specific application

SCENARIO

Tauncie Smith has been working for several years for a U.S. Department of Defense contractor that specializes in mobile surveillance equipment. Traditionally, these systems have used electro-optical visible and infrared systems to detect imagery. The output of these systems utilized small liquid crystal display (LCD) screens so that the user could view scenery in real-time. With only 120×80 pixels, the resolution of the LCD was small and was consequently the limiting component of the entire system. Recently Tauncie's company was awarded a contract to modernize a particular armed force's long-range recognizance system for man-portable applications. The contract requires that these new systems have high-definition displays for real-time viewing. This requirement means that the optical and electronic components will need to have higher quality than previous systems, since they will not be limited by the output display. Tauncie's manager has decided that the company will invest in instruments that can measure the modulation transfer function (MTF) of the optical and electro-optical portions of the system. These instruments will be vital in both the design and manufacturing stages of the contract. This will require Taunice to learn and understand what MTF is and how it will relate to the overall performance of the system.

BASIC CONCEPTS

Determining the performance of an optical system requires the examination of several factors that impact the system's ability to generate an image. In this section, the concept of resolution will be discussed and the factors that influence it will be presented.

An imaging system consists of a lens and a detector. Figure 1 shows a simple optical arrangement that is used in these systems. The object plane is where the object being viewed is located; the image plane is where the lens creates an image of the object. The lens is used to direct radiation emanating from the object plane to the image plane.

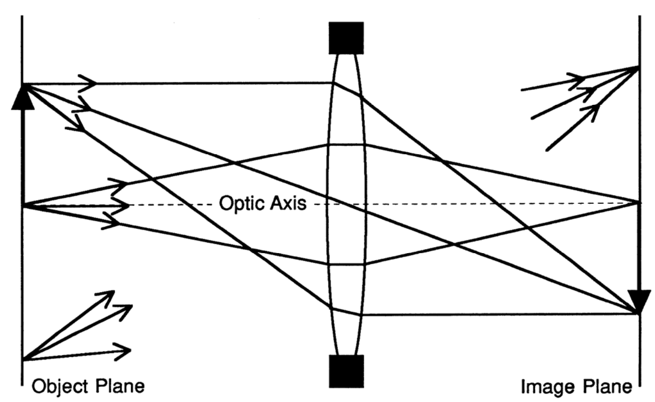


Figure 1 *Illustration of basic imaging system parameters*

The function of the imaging lens is to remap points on the object to analogous points on an image. Each point on the object has an associated amount of radiation strength or power that must also be transferred to the image plane. Ideally, the distribution of power on the object is replicated on the image plane, thereby, generating an image that is identically representative of the object. In other words, an object such as a person would be imaged by the lens onto the image plane and would retain all the visual characteristics of the person. A compete imaging system includes a method for detecting the radiation distribution at the image plane. This radiation detector transforms the radiation information into a signal that can be processed by an information recording system.

The human eye is an excellent example of a complete imaging system (Figure 2). It consists of a lens that images objects at varying distances onto the eye's detector called the *retina.* Focus is achieved by muscles in the eye that can change the shape of the eye and lens.

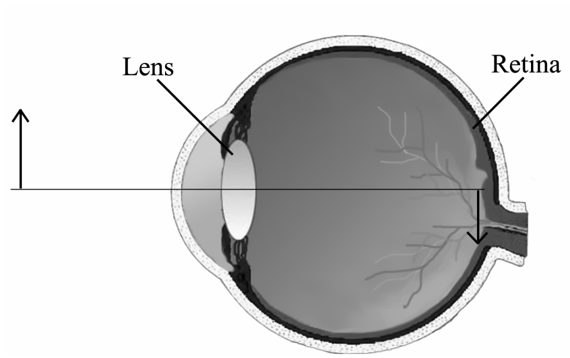


Figure 2 *The human eye represented as an optical imaging system*

Resolution of the Human Eye

"Resolution," in terms of an imaging system, refers to the smallest feature that can be seen or resolved. There are several factors that ultimately determine a system's resolution, but in the ideal case it is governed by the size of a single detector element.

Consider the human eye. The retina is made up of tiny cells called *rods* and *cones*. The rods are responsible for detecting a single color or blue-green light levels that relate to the magnitude of the light power. The shades of light between black and white are called *grayscales.* Rods report the grayscale values of the image to the brain. The cones are responsible for detecting color in the image. Chemical differences in the cones yield L-cones (red), M-cones (green), and S-cones (blue). The combined color information is collected by the cones and reported to the brain. The center of the retina or *fovea* has the highest density of cones—as many as 180,000 per square millimeter.

The standard Snellen eye chart is a collection of letters (ex., E, F, P, T, O, Z, etc.) used to measure your vision. A measure of reasonable eyesight is considered to be 20/20. This equates to being able to discriminate two points separated by one arc minute of angle or 1/60 degree. As you will see later in this module, this type of specification is one way of defining the resolution of an optical system.

The concentration of cones near the fovea is three cones per arc minute. Since it takes red, green, and blue (primary colors) to produce the colors in the visible spectrum, these three cones form a detector element. This detector element is called a *pixel*, which is similar to those found on television screens and LCDs.

To summarize, the resolution of the human eye is determined by the size of cones used by the retina to detect light. One pixel of the eye represents the smallest feature that can be seen on the object. Good vision is the result of higher concentrations of cones, which can be as high as 180,000 cones per square millimeter. Poor vision is caused by a deformation of the crystalline lens. Corrective eyewear attempts to correct for these deformations.

All these elements in the human eye work together to allow us to see objects as sharp, well-defined images. Whether or not we are able to discern various details in this image is a resolution issue.

Resolution Criterion

A technical description of resolution was defined by Lord Rayleigh in 1879. He demonstrated that the resolution limit of a pure optical system is determined by *diffraction.* The phenomenon of diffraction occurs when light passes by the edge of an aperture. The light wave is disrupted by the edge and dispersed into a multitude of angles. This effect can be seen as a softening of the edges around a shadow. As light passes through a circular aperture, diffraction generates an Airy pattern (Figure 3).

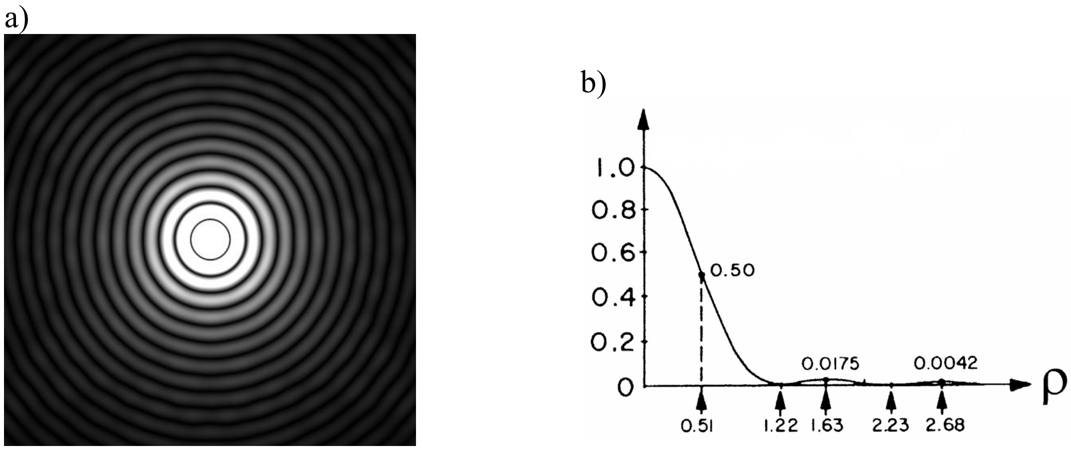


Figure 3 *Airy diffraction pattern produced by light passing through a circular aperture. a) Two-dimensional picture enhanced to accentuate the ring pattern. b) Profile of the intensity level across an Airy pattern*

The Airy pattern, like other types of diffraction patterns, provides insights into why optical systems have resolution restrictions. Optical systems are typically limited by a circular aperture since lenses are fabricated based on spherical surfaces. Light passing through the system undergoes diffraction and produces an Airy pattern. No matter how high-quality or large the lens becomes, the lens can never produce a single point of light. The image will always have the characteristic ring pattern seen in Figure 3.

The Airy pattern dimensions are governed by the focal length and diameter of the limiting aperture of the system. All lenses can be expressed in terms of their *f*-number, F/#. The F/# is calculated by dividing the focal length, *f,* of a lens by the diameter of the limiting aperture of the system, *D*.

$$\mathrm{F}/\# = \frac{f}{D}$$

The diameter of the center disc of the Airy pattern formed by a lens can be expressed as:

$$d = 2.44\lambda \mathrm{F}/\#$$

where λ is the wavelength of the radiation coming from the object.

So what does all this have to with resolution? Lenses produce Airy patterns and are thus said to be *diffraction-limited*. If two objects are located in the object plane of an optical arrangement, like the one shown in Figure 1, each will produce an Airy pattern at the image plane (Figure 4a). As the two objects move closer, their Airy patterns begin to overlap as seen in Figure 4b. When the two objects are moved close enough together so their center Airy pattern discs just touch (Figure 4c), we say these objects are at the limit of being distinguished as two separate objects. If the objects are brought even closer together, where their Airy discs overlap (Figure 4d), the two objects can no longer be distinguished from one another and appear as a single object.

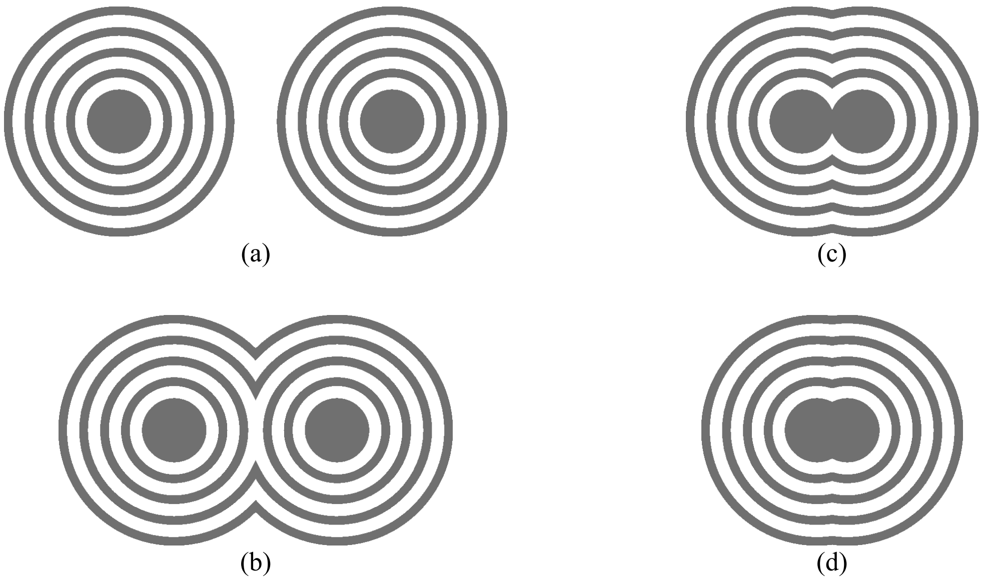


Figure 4 *Changes in the Airy pattern as two objects are brought closer together*

From this series of figures and the fact that "real" lenses are not perfect, the diameter of the Airy disc gives a good approximation of the minimum distance two objects can be separated and still be resolved (Figure 5) . The following equation defines this resolution:

$$\text{resolution} = 2.44\lambda F/\#$$

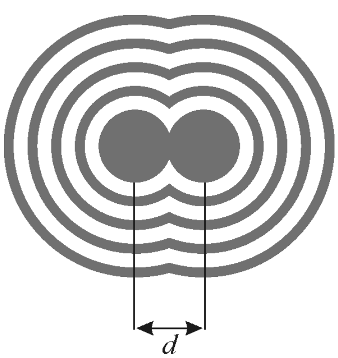


Figure 5 *Airy pattern disc diameter represents the smallest resolvable distance*

Example 1

Given: A lens with a focal length of 25.4 mm and a limiting aperture of 50 mm used at a wavelength of 632.8 nm

Find: The limiting resolution of this lens

Solution

$$
\begin{aligned}
\text{resolution} &= 2.44\lambda F/\# \\
&= 2.44\lambda \frac{f}{D} \\
&= 2.44(632.8 \times 10^{-9}) \frac{25.4 \times 10^{-3}}{50.0 \times 10^{-3}} \\
&= 0.784 \times 10^{-6} \text{ m} \\
&= 0.784\ \mu\text{m}
\end{aligned}
$$

Thus, for this lens system, two objects or two features on a single object will be distinguishable in the image as long as they are greater than 0.784 μm apart.

A diffraction-limited lens is one that images a tiny point of light, such as a star, as an Airy disc pattern. However, the diameter of this pattern is greater than the one predicted by the formula presented. This is because the diameter of the Airy pattern is a limit that is not achievable by real optical systems. Most systems image points of light as small circular patterns with diameters larger than the diameter of the Airy disc. This circular image is referred to as the *blur spot*.

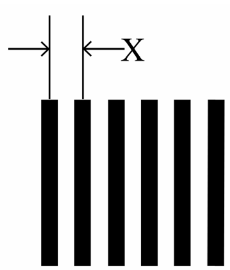
A blur spot is the result of imperfections in the optical design called *aberrations*. These aberrations can be caused by simple misalignments in the optics or more complicated imperfections inherent in the surface shape of the lens. The major classes of aberrations are categorized as first-order and second-order. The first-order aberrations are the result of mechanical problems in the system: tilt and defocus. The second-order aberrations are caused by the surface shape of the lens and depend on where the object is located with respect to the optical axis of the system. The second-order aberrations, also called *Seidel aberrations,* are listed in Table 1.

Aberrations in an optical system result in an increase in the blur-spot. High amounts of aberrations produce a large blur-spot whereas the total absence of aberrations produces a blur-spot with a diameter equal to the Airy disc. A larger blur-spot degrades the performance of an imaging system.

Table 1. Second-order (Seidel) aberrations

Aberration	Effect
Spherical	On-axis rays are focused at a different point than off-axis rays.
Coma	Rays passing through the center of the lens are focused to a different plane than rays passing by the edge of the lens.
Astigmatism	Rays in the vertical axis are focused to a different point than rays in the horizontal axis.
Distortion	Rays are non-uniformly distributed on the focal plane.
Curvature	Rays are focused on a curved focal plane.
Chromatic	Rays with different wavelengths are focused to different focal points.

Historically, resolution was measured using pairs of lines. A test engineer would image a target with consecutive white and black lines. The image was then viewed to determine whether the engineer could resolve the separate lines. The spacing between the lines was decreased until the engineer could no longer resolve separate lines and the target was uniformly gray in color. At this point in the measurement, the distance between the lines was taken to be the resolution of the system. Figure 6 shows an example of line pairs that are just resolvable by some optical system.



$$\text{Resolution} = \frac{1}{X} \text{ line-pairs/mm}$$

Figure 6 *Calculation of resolution from line pair target*

Historically, the units line-pair/mm (lppm or lpmm) have been replaced by cycles/mm corresponding to a *spatial frequency*.

When the concept of line pairs is used, the resolution of an imaging system can be found by placing line pair targets of a known size at the object plane. The most common method uses a bar-target. In 1951 the USAF standardized a target to measure the performance of an imaging system (Figure 7).

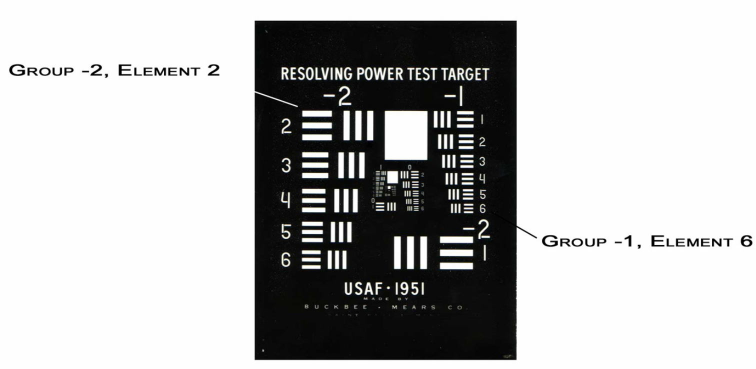


Figure 7 *The 1951 USAF resolving power test target MIL-STD-150A (This image is licensed under the Creative Commons Attribution ShareAlike License v. 2.5.)*

The USAF resolving power target consists of groups of 3-bar targets. The inverse of the separation distance between bars in a single pattern is equal to *spatial frequency* expressed as cycles/mm. Each group consists of six individual 3-bar patterns called *elements* that are numbered 1 through 6 vertically. The group number (–2, –1, 0, 1, and 2) is shown above each column of elements. The spatial frequency of any 3-bar element can be calculated by applying the following formula:

$$\text{Spatial frequency} = 2^{\text{Group}+\frac{(\text{Element}-1)}{6}}$$

Example 3

Given: A USAF 1951 target is imaged by a system under test. The technician observes the recorded image and determines that she can resolve bars for element 5 in group –1, but not for element 6 in group –3.

Find: The spatial frequency of the resolvable target and the resolution of the imaging system

Solution

$$\begin{aligned}\text{Spatial frequency} &= 2^{\text{Group}+\frac{(\text{Element}-1)}{6}} \\ &= 2^{-1+\frac{(6-1)}{6}} \\ &= 0.89 \text{ cycles/mm}\end{aligned}$$

Since this spatial frequency indicates that the target bars are 0.89 mm apart, this distance is the measured resolution of the imagining system. This means that the tested imaging system can resolve two objects or two distinct details on a single object as long as they are not closer than 0.89 mm.

The value of resolution is a single number that is often calculated and used incorrectly. An example would be when the optical system is used in conjunction with a detector array.

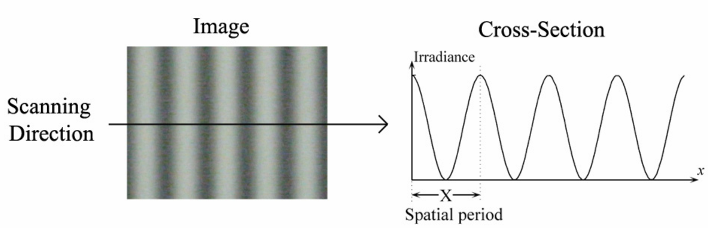
Engineers often assume that the blur-spot of the optical system is smaller than a single pixel. So they calculate the limiting resolution of the system by doubling the pixel width and taking the inverse of this number. However, this method does not take into account the noise and other factors resulting from the electronics part of the detector system that also degrade system resolution.

Another abuse of the term *resolution* stems from the misconception resolution defines the overall performance of an optical system. Resolution is a single value and only describes how the system performs at a single spatial frequency. In order to get an overall measure of performance, the system must be measured over a range of spatial frequencies. The modulation transfer function (MTF) takes into account this range of spatial frequencies and is a better way of gauging the performance of an optical imaging system.

MODULATION TRANSFER FUNCTION (MTF)

The term *modulation* refers to a periodic change in the amplitude of a signal. The term *periodic* means that varying features in the signal repeat regularly with constant spacing called the *period*. In electronics, an example of a periodic signal would be a sinusoidal voltage observed over time. The reciprocal of the period is equal to the frequency and, in the case of a time-varying signal, is expressed in units of 1/seconds or hertz, Hz.

Modulation in a two-dimensional image produced by an optical system is the periodic change in irradiance (power per unit area, W/cm^2) as the image plane is scanned. The spatial frequency of irradiance modulation is the reciprocal of the spatial period of the modulation (Figure 8).



$$\xi = \text{SpatialFrequency}\left[\frac{\text{cycle}}{\text{length}}\right] = \frac{1}{X}$$

Figure 8 *Relationship between period and spatial frequency*

Transfer function is a concept used in many fields of engineering. It is used to predict what the output of an arbitrary system will be based on set of input conditions.

For example, consider an audio signal with a voltage that varies over time. A low-pass filter is a system of electronic components assembled to yield a transfer function that attenuates signals greater than a cut-off frequency, $f_{\text{cut-off}}$.

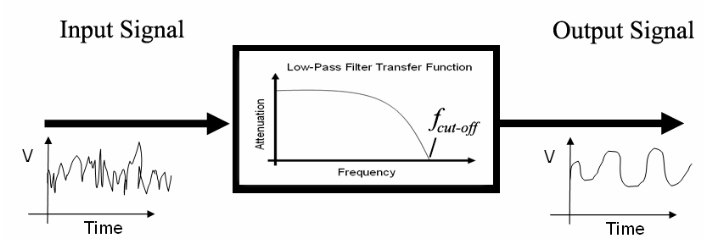


Figure 9 *Example low-pass filter for time-varying voltage signal*

The "input signal" contains a range of frequencies from low to high. The low-pass filter allows the low-frequency portion of the signal to pass while attenuating the higher frequencies. The "output signal" contains only the low frequencies present in the "input signal." This type of filter would be used by an audio amplifier to route only low-frequency content to a bass speaker.

Now we can put the concepts of *modulation* and *transfer function* together for optical imaging systems. In an optical system, the modulation transfer function (MTF) is defined as the prediction of system performance based on inputs at different spatial frequencies. In general, most optical systems behave as low-pass filters. Observe in Figure 10 how an imagining system might process a set of bar target elements as their sizes decrease (equivalent to increasing spatial frequency).

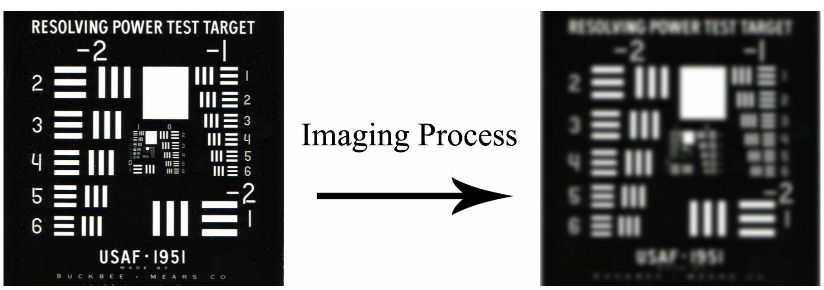


Figure 10 *Example of low-pass filter behavior in optical systems*

As the spatial frequency of the bar target elements increases, the space between the white bars in the image begins to "fill-in" until only a grey box is observed. This is a result of the real imaging ability of the optical system. The smallest target that can be resolved is the limiting resolution. The MTF describes the resolving ability of an imaging system over a range of spatial frequencies.

Figure 10 also shows how an optical system acts as a low-pass filter. For the low-frequency targets, information contained in the targets is resolved and made available, or "passed," to the observer. Conversely, the high-frequency targets are not resolved and the information they contain is not "passed" to the observer. This is equivalent to the audio example in which the low-pass filter only makes available, or "passes," bass sounds to the listener.

The MTF is always normalized to its value at zero spatial frequency. All measurement data and plots shown will include this normalization. The dependent variable, ξ, is used to represent the spatial frequency axes. The MTF is inherently a two-dimensional function but is typically plotted with respect to only one axis using one-dimensional plots.

The MTF value at any spatial frequency is equal to the attenuation of the input modulation. This attenuation is represented as *modulation depth* in the image. Modulation depth is evaluated by observing a cross-section or profile of the image irradiance such as the one shown in Figure 11 (generated in a similar manner to Figure 8).

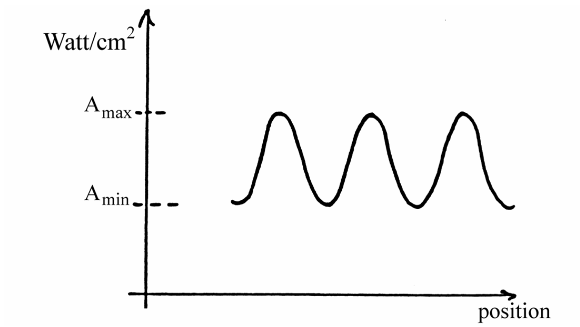


Figure 11 *Profile of image irradiance*

The modulation depth in the image is calculated using,

$$M = \frac{A_{\max} - A_{\min}}{A_{\max} + A_{\min}}.$$

The following procedure is used to generate an MTF curve for a specific imagining system. The imagining system observes an object that has a set of targets on it of varying spatial frequencies. The range of these spatial frequencies is chosen so that the intended application of the imaging system is fully tested. The top graph in Figure 12 shows the irradiance profile of the object. This graph indicates that the target's spatial frequency is increasing from left to right. The middle graph in Figure 12 shows the profile of the image as it appears on the imagining plane of the system. This graph highlights the fact that *M* decreases with increasing spatial frequency. The bottom graph in Figure 12 shows the MTF curve that results for this imagining system.

The MTF curve in Figure 12 is determined in the following way. For each cycle of the middle graph, an *M* value is calculated. This *M* value is associated with a specific spatial frequency. The *M* value and spatial frequency form an ordered pair, (M, ξ). The ordered pair for each cycle is plotted and a curve is formed from these points to produce the MTF curve. As mentioned earlier, this curve is normalized to 1 at a spatial frequency of 0.

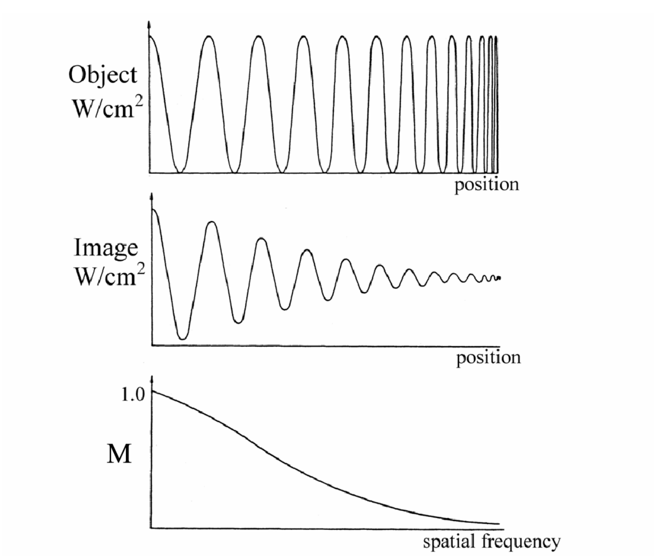
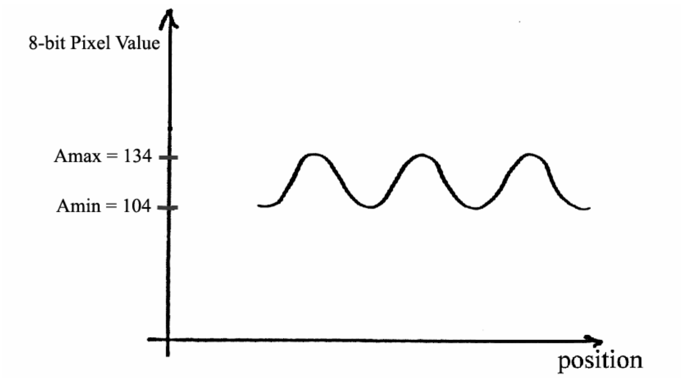


Figure 12 *Determination of MTF using an input target with increasing spatial frequency*

Example 4

Given: The image irradiance profile shown below



Find: The modulation depth in the image. The values of the profile are given as digital 8-bit pixel values. This equates to a range of digital grayscale values from 0 to 255. This type of data is typical, since most data are captured digitally and stored in a computer.

Solution

$$M = \frac{A_{\max} - A_{\min}}{A_{\max} + A_{\min}} = \frac{134 - 104}{134 + 104} = 0.126$$

The modulation depth, *M*, is a key factor in determining the performance of an optical system. It can be shown mathematically that the value of *M* is greatest when the difference $A_{\max} - A_{\min}$ is greatest. A large difference in these two values also demonstrates better system performance, because this difference is an indicator of how much attenuation occurs in the input modulation. The larger the value of *M,* the less is the attenuation. As *M* gets smaller, the attenuation gets greater. This attenuation is directly related to the ability of an imagining system to distinguish between optical signals coming from the object and noise sources that are present in the imaging system. A system with large attenuation, small value of *M*, will often not be able to distinguish signals from one another. When that happens, the image produced does not provide an accurate reproduction of the object. Conversely, a system with a small attenuation, large value of *M*, will be able to distinguish the two signals and generate an image that more accurately reproduces the object. In general, the higher the value of *M*, the better is the system performance.

Blur Spots and Resolution

The blur spot described above can be used to determine the resolution of an optical system. The blur spot can also be used to determine the overall performance of a system by translating it from the space to the frequency domain and plotting it as an MTF curve. Before describing how this translation is done, we will take a closer look at the effect of blur spot size on the final image produced by the system.

An object can be broken down into a collection of points. The brightness of each point is determined by the object brightness where each point was defined. The corresponding point in the image, after passing through the system, is enlarged to the size of the blur spot. The final image is the summation of all of the image points. The result is that the final image is blurred by the optical system. This is explained graphically in Figure 13.

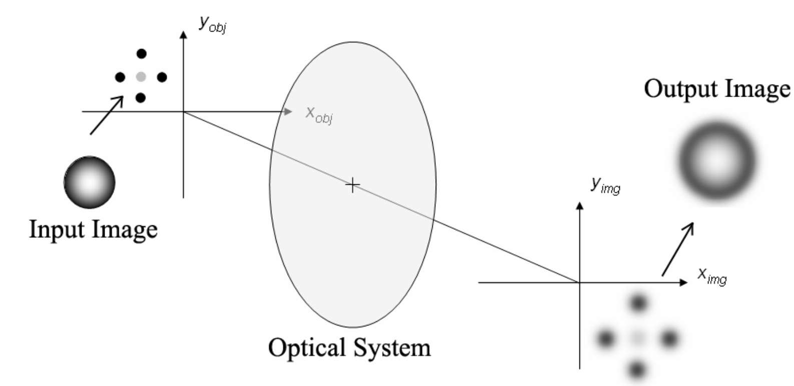


Figure 13 *Graphical explanation of how blur spot reduces image quality*

It is evident from Figure 13 that the larger the blur spot, the more degraded the image quality becomes. This is why technicians strive to keep the blur spot size as close to the diffraction limit as possible.

The blur spot can be described by a mathematical term called a *point spread function* (PSF). The PSF indicates how "blurred" an image becomes after being processed by an imaging system. A full description of this function and its relationship to the resolution of an imaging system requires the use of a mathematical tool called *Fourier analysis*.

Simply stated, Fourier analysis allows functions in the spatial domain to be translated into the frequency domain. The PSF is a spatial function. When analyzed using a fast-Fourier transform (FFT), it yields the MTF, which is a frequency function. The rigor of this analysis is beyond the scope of this module. However, the results of this analysis as it applies to the PSF and MTF will be discussed. Also in the appendix of this module an instrument-based method for doing FFTs is presented.

The relationship between the PSF and MTF is shown in Figure 14. In Case 1, the PSF is narrow and does not extend over a large spatial region (x). This indicates that the system that produced this PSF generates a relatively sharp image. Conversely, in Case 2, the PSF for another system is wider (more spatially spread out), causing the image to be less sharp. When these two PSFs are analyzed using an FFT, two different MTF curves result. As would be expected, the resolution of the system with the narrow PSF yields a higher resolution (ξ) than the system with the broader PSF.

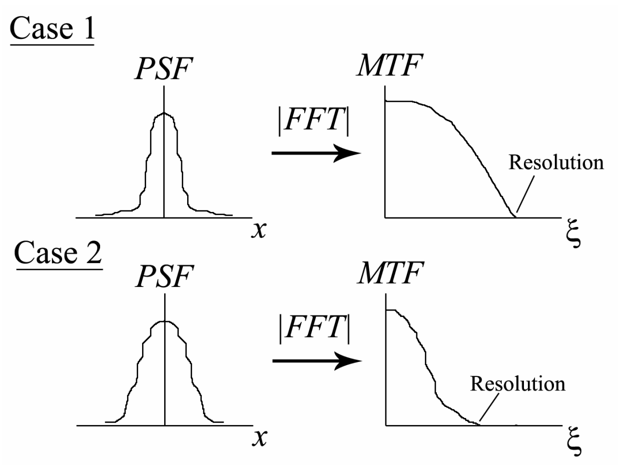


Figure 14 *Illustration of the relationships between PSF, MTF, and resolution for two cases*

The resolution value in Figure 14 is the point at which the MTF falls to an attenuation value of zero.

MTF in Electro-Optical Systems

Reconnaissance systems such as video cameras utilize an electronic detector array coupled to an imaging system. When these systems are combined, the overall system is referred to as an *electro-optical system*. The addition of the detector array affects the overall MTF of the system because the detector elements are typically larger than the blur spot of the imaging system. The MTF for the detector array is determined from detector element sizes and spacing.

Detector element sizes, called *footprints,* are expressed in w-by-w dimensions (assuming square detectors). The width of the detector is provided by the manufacturer and is typically between $2\text{–}10^{-6}$ m and 20×10^{-6} m, depending on the technology used. In general, infrared detectors are larger than visible detectors. The associated MTF for the detector array is denoted as $MTF_{footprint}$. A plot for a theoretical infrared system $MTF_{footprint}$ is shown in Figure 15.

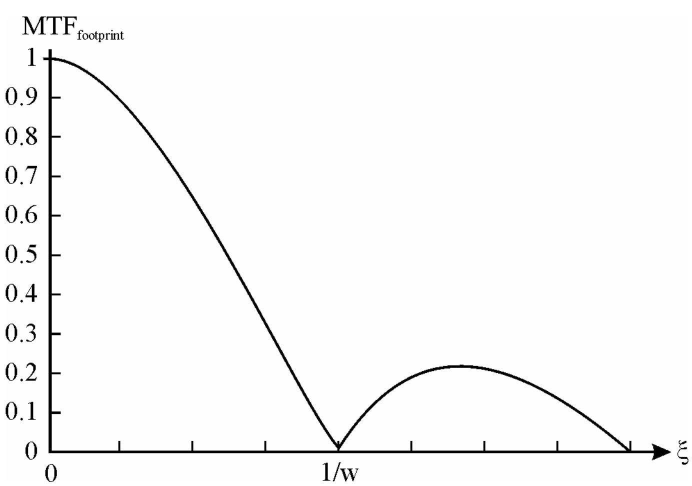


Figure 15 *Plot of the $MTF_{footprint}$ for a detector array with pixel width equal to w*

This plot falls to zero at 1/w and then increases again. The reason for this zero value is shown in Figure 16. The top two illustrations show that adjacent detector elements are able to discern differences in the irradiance from the object being observed. Each adjacent element "sees" a different average value of irradiance. This causes details about the thermal signature of the object to be distinguishable. However, in the bottom illustration, where the spacing between detector elements is 1/w, each detector "sees" the same average irradiance and no details are distinguishable. This is similar to what occurs when an imaging system can no longer differentiate individual bars in a bar target. It is at this point that the MTF of the system goes to zero (see Figure 15). We can also understand this from the mathematical definition of *M,* because at this spatial frequency, 1/w, the magnitudes of $A_{\max}$ and $A_{\min}$ are equal, thus making M equal to 0. As the spatial frequency increases, the variation in irradiance between adjacent detector elements once again becomes observable and the detector is able to resolve details in the object's thermal signature. The plot finally goes to zero at the resolution limit of the imaging system.

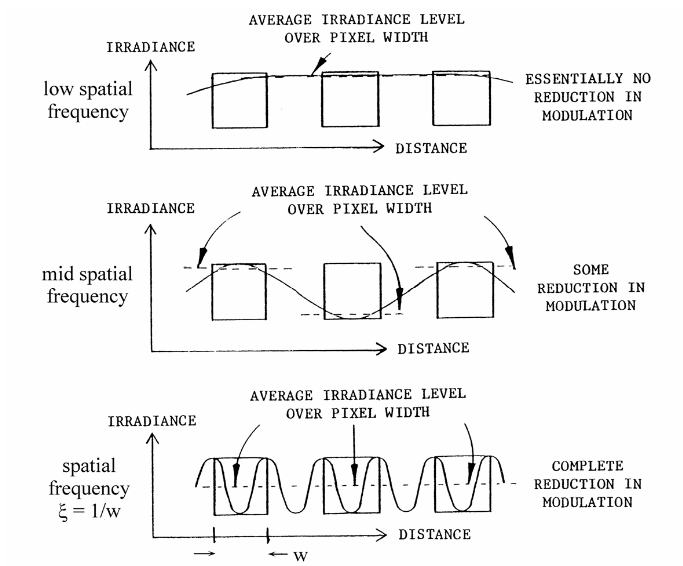


Figure 16 *Graphical explanation of the "1/w" zero value for* $MTF_{footprint}$

The center-to-center spacing of the detector elements is known as the *sample period, X*. This is shown in Figure 17. The sample period also has an associated MTF denoted as $MTF_{sampling}$. The effect of sampling is the same as for the detector footprint. A plot for the theoretical $MTF_{sampling}$ is shown in Figure 18. This plot falls to zero at 1/X for the same reason shown in Figure 16.

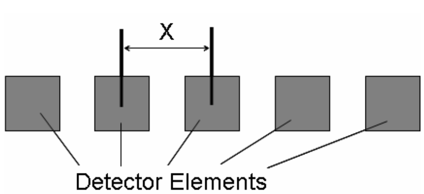


Figure 17 *Detector center-to-center spacing known as sampling period, X*

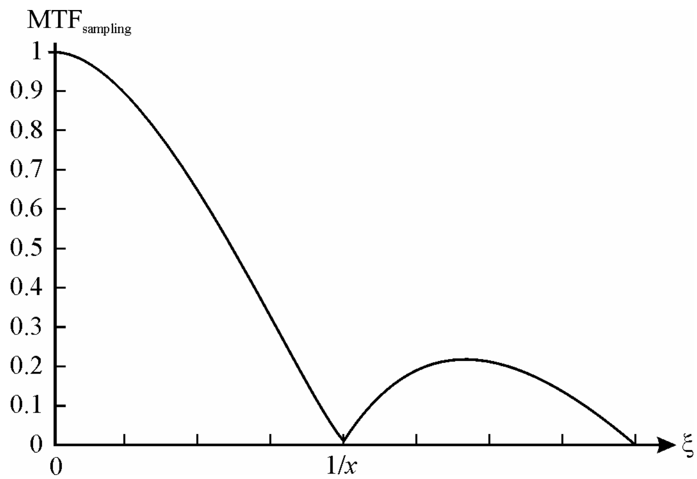


Figure 18 *Plot of the* $MTF_{sampling}$ *for a detector array with pixel width equal to x*

Another anomaly that the spacing of the detector elements can introduce is called *alising.* Each detector element represents some spatial location on the object being observed. Since the number of elements is finite, only a finite number of object locations can be represented. If the spatial frequency of the detector elements is too small, important details about the irradiance from certain object locations will not appear in the image. This "lost" detail can introduce distortion into the image.

Alising can be explained using waveforms. When a waveform is sampled, a minimum of values is needed to recreate the original waveform. As an example, consider a sinusoidal signal sampled at the peaks and troughs of the modulation as shown in Figure 19.

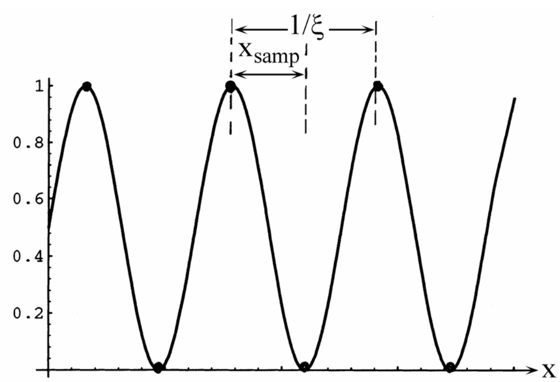


Figure 19 *Optimal sampling of sinusoidal signal. Black dots represent discrete samples*

The sampled points hold just enough information to recreate a sinusoidal signal with the same frequency, 2ξ. If the frequency of the sinusoid increases above 2ξ, the signal is not sampled frequently enough to recreate the original waveform.

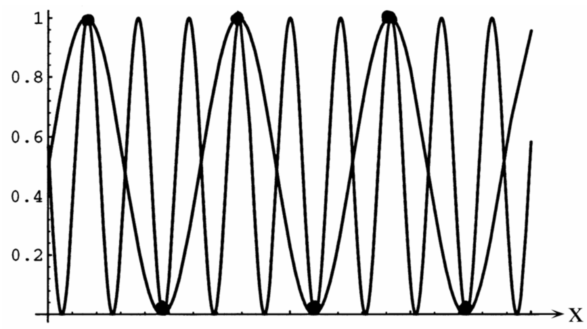


Figure 20 *Sampling of higher-frequency sinusoid using the same sampling period used in Figure 18 represented with black dots*

In Figure 20 the original waveform has a frequency three times higher than the sampling frequency. The sinusoidal signal that is recreated from the samples is the same as in Figure 19. Obviously, much detail is lost from the waveform in Figure 20 and the image will not be a good reproduction of it.

The relationship between the sampling frequency and the highest frequency that can be sampled accurately is called the *Nyquist frequency.* The Nyquist frequency is calculated with this formula:

$$\text{Nyquist} = \frac{1}{2x}$$

Cascade Property of MTFs

The most useful property of MTF theory is that MTFs for separate subsystems can be combined easily using only multiplication. The cascade property enables a technician to predict the overall system performance using separate measurements of each subsystem. An example of this property is shown in Figure 21.

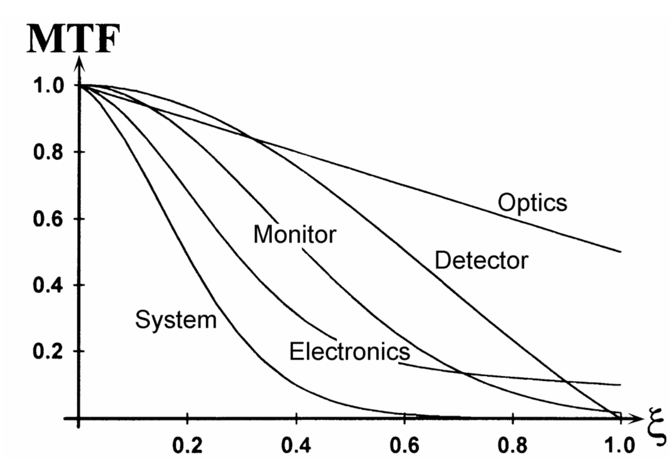


Figure 21 *Cascade property of MTFs*

In this plot, the MTFs for the optics, detector, monitor, and electronics are multiplied to yield the system MTF. Most subsystem MTF contributions are obtained from manufacturers.

MTF MEASUREMENT METHODS

In this section, several methods for measuring MTF will be discussed. Although many methods have been developed, this module will concentrate on the more common methods. The practical description of the methods described in this section will be strengthened in the laboratories.

Point Spread Function Method

The most straightforward method for measuring MTF is to use a tiny point target to measure the PSF directly. The resulting image is then processed using a computer to calculate the absolute value of the two-dimensional FFT of the image. The horizontal and vertical profiles of the processed image are the MTF of the system.

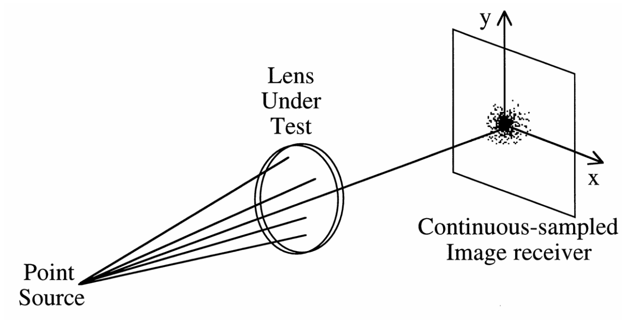


Figure 22 Measuring MTF using the PSF method

In the laboratory, this MTF measurement is performed using a visible or infrared emitting point source. The imaging system is focused on the point source, thus forming an image on a detector array and generating a digital image of the imaged source. This image of the point source is the PSF. This PSF is the equivalent blur spot produced by the imaging system and represents the smallest feature that the system can resolve. PSF information from the image is then entered into a computer program that determines the MTF of the optical system by performing an FFT. The program will then produce a report for the MTF of the system.

Knife-Edge Method

A more common method for measuring MTF is to use a sharp edge positioned in front of a uniform light source. The sharp edge is typically a sharpened piece of metal; hence the name *knife-edge method*.

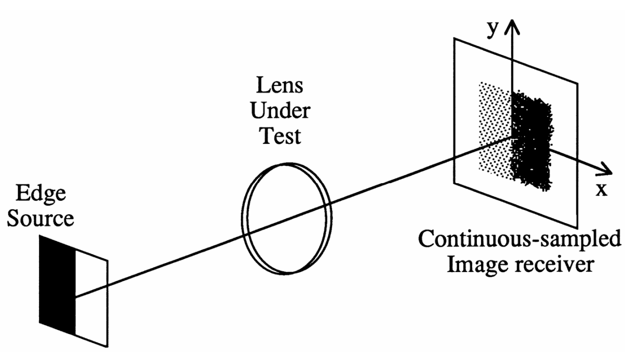


Figure 23 *Measuring MTF using the knife-edge method*

The contrast between the uniform source and the opaque metal of the knife creates a target called a *step function*. The resulting image is called the *edge spread function* (ESF). An example is shown in Figure 24.

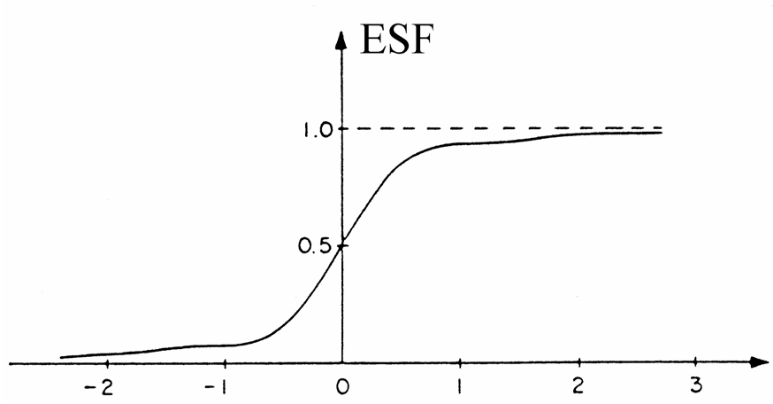


Figure 24 *Example profile of knife-edge image illustrating ESF*

The ESF profile is used to calculate the MTF of the system.

In the laboratory, a knife-edge target is placed in front of a uniform light source. The image of the edge is captured digitally using a detector array. As in the PSF method, the digital image is entered into a computer program to evaluate the MTF.

Target Method

The target method includes 3-bar, 4-bar, sinewave, and line-ruling-type test targets. The objective with all of these methods is to image a target with a known line spacing (i.e., spatial frequency) and evaluate the modulation depth in the image.

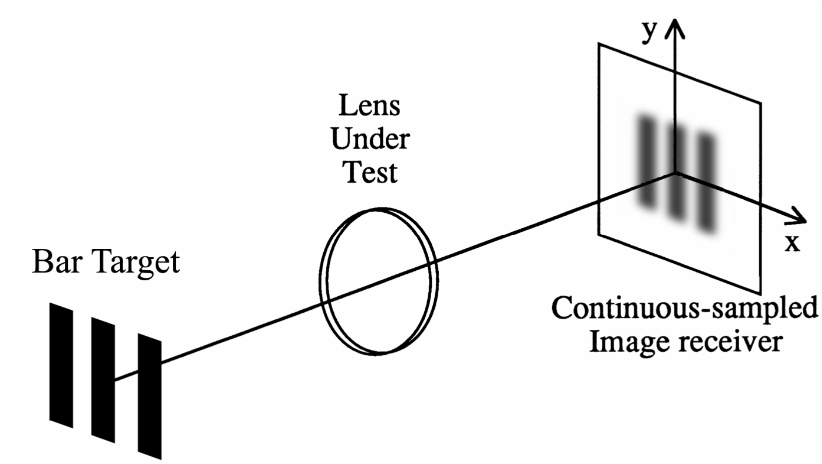


Figure 25 *Measuring MTF with a 3-bar target*

The modulation depth along a horizontal profile is then evaluated for the target. A set of targets is selected for a range of spatial frequencies of interest. This range is defined by the application for which the system is being measured. Typically, a selection of 10 targets is chosen from zero to the Nyquist frequency of the system. A graphical explanation of this process is given in Figure 26.

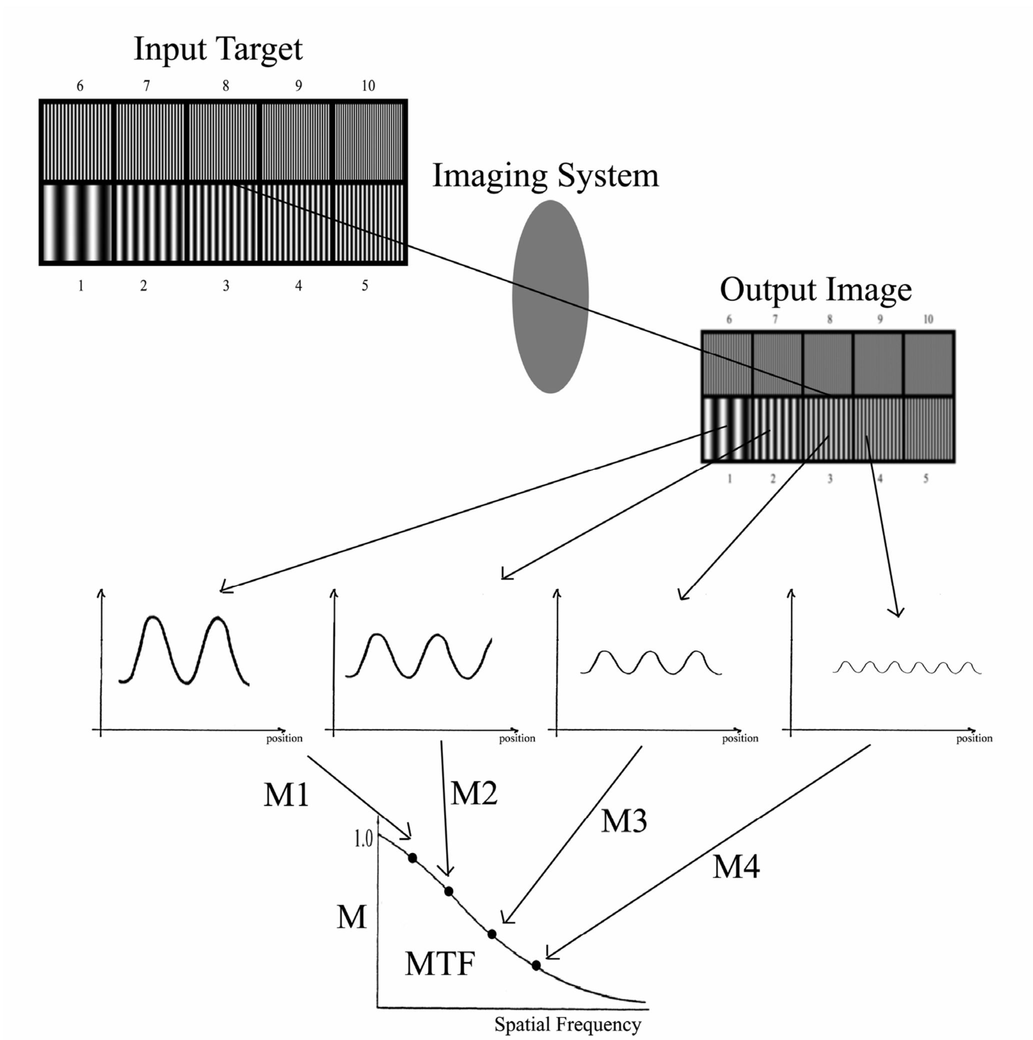


Figure 26 *Graphical explanation of sinewave target evaluation of MTF*

The target is processed by the system to produce the output image. The output image is captured digitally and stored in a computer. A profile of each cell of the sinewave target is extracted from the image using specialized image processing software. From these profiles, the modulation depth for each cell is calculated: M1, M2, M3, and M4. These points are plotted on a common curve, with *M* as the vertical axis and spatial frequency as the horizontal axis. The individual points are connected to form a curve that represents the MTF of the optical imaging system.

APPLYING MTF TO RECONNAISSANCE SYSTEMS

Now that the basic theory of MTF and some of the main measurement methods have been presented, we will discuss how MTF is used in evaluating reconnaissance systems. The general goal of MTF measurements is to predict the performance of an optical system. This prediction can then be used to select which lens system and video camera should be used for a particular application. The methodology presented in this section can be used for any wavelength range such as visible or infrared.

Video camera surveillance is used primarily for observation of distant objects. This is achieved using a lens system (typically telescopic) to image the object and a focal plane detector array to detect the image. An electronic information system is used to record the detected image and either store it or view it in real-time as a single image or a series of images called *video*. Knowledge of the MTF and resolution of the system will allow you to predict whether an object of a certain size will be resolvable in the recorded imagery.

The size of the object should be selected on the basis of what features we need to observe or analyze. As an example, suppose we want to use an optical system to identify a person. Every person has many features that make this identification possible. If the optical system can provide a sharp image of a very small feature such as an eye, many other identifying features should also be distinguishable.

So let's identify a system that will clearly resolve human eyes. Let's start by assuming that the systems we are going to evaluate have lens configurations that are telescopic and use detector arrays composed of charged coupled devices (CCD). Having defined the system, we must now determine our surveillance specifications. For instance, at what distance do we want to be able to identify a person? For purposes of this example, let's select 100 m. This specification, along with the fact that a human eye is approximately 2 cm in diameter, gives us the information necessary to start our performance evaluation.

Once the object and distance have been specified, the angular extent of the object must be calculated. At this point we need to make the assumption that the object will be repeated or periodic, enabling us to calculate a spatial frequency. For our human eye, we will assume a repeated pattern with spacing equal to twice its diameter (Figure 27).

Often in carrying out performance calculations, another form of the spatial frequency called *angular spatial frequency*, ξ_{ang}, is used. ξ_{ang} specifies how the object being observed repeats itself with respect to angular displacement measured from the observation point. This angular displacement is represented as θ in Figure 27. ξ_{ang} units are cycles/mrad. The following formula defines angular spatial frequency:

$$\xi_{ang} = \frac{R}{x}$$

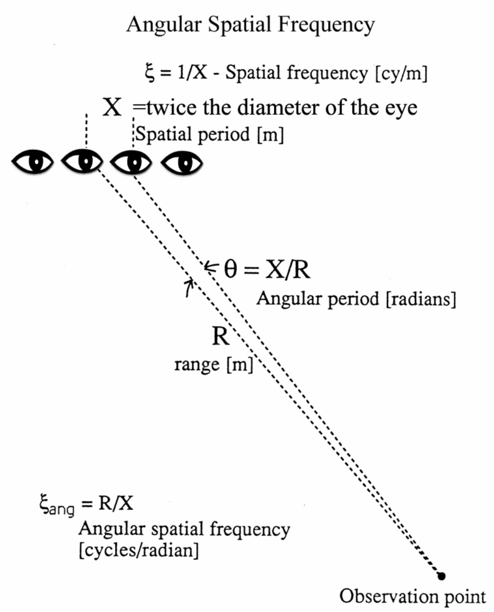


Figure 27 *Conversion of object size to spatial frequency*

For the case of observing an eye at 100 meters, ξ_{ang} is calculated in the following manner:

$$\xi_{\text{ang}} = \frac{R}{x} = \frac{100\text{ m}}{2\times(2\times10^{-2}\text{ m})1000} = 2.5\text{ cycles/mrad}$$

The factor of 1000 converts radians to milliradians.

Since the optical system we are using is telescopic, it has magnification. This magnification will cause the image spatial frequency to be different from that of the object. The image spatial frequency resulting from an optical system with magnification can be determined using

$$\xi_{\text{image}} = \frac{\xi_{\text{ang}}\cdot 1000}{f},$$

where f is the focal length of the lens system.

For our example, the calculated angular spatial frequency is 2.5 cycles/mrad. If the focal length of the lens system is 35.7 mm, the spatial frequency at the image plane for the eye will be 70 cycles/mm.

In our example, we have now determined that our system must be able to resolve objects with spatial frequencies in the 70 cycles/mm range. Next, we must set a limit for the attenuation of the signal at this frequency. A good rule of thumb is to use 20 percent as a lower limit for image attenuation.

To make a performance prediction for this system, we will need the MTF of the overall system. As mentioned earlier, overall MTF values are found by multiplying together the MTF values of various parts of the system, such as the optics, detector, and electronics. So we will assume that manufacturers have provided specifications and MTF values for two different lens systems with a focal length of 35.7 mm and for a specific CCD system.

The MTF of the overall system is determined by selecting a spatial frequency and identifying from the plots at the left in Figure 28 the MTF values for the different lens systems and the MTF value of the CCD. Then each lens MTF value is multiplied by the MTF value for the CCD. The resulting products are the MTF values for the two systems at the selected spatial frequency. This process is repeated for several other values of spatial frequency and the results are plotted. The results of this process for our example are shown at the right in Figure 28.

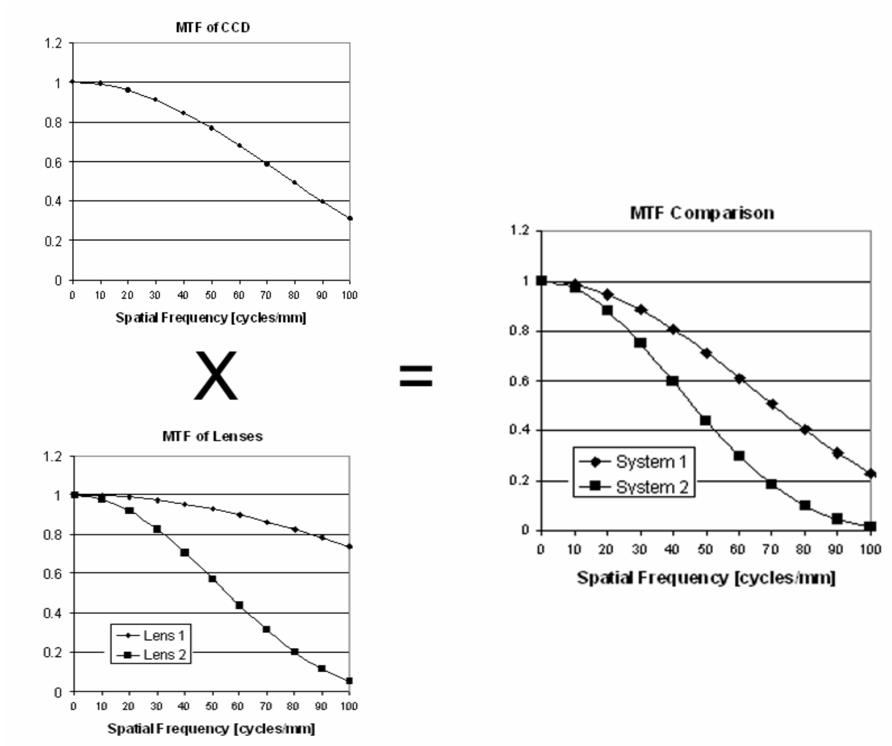


Figure 28 *Calculation of overall MTF to compare two different lenses*

Since both systems use the same CCD system, the MTF comparison plot in Figure 28 can be used to determine the best lens configuration for our system. As seen in the MTF comparison plot, System 2 has attenuation slightly lower than 20 percent at the optimal object size of the eye occurring at 70 cycles/mm. This is below the specification we set. Also, the vertical axis values, which provide attenuation information, are consistently higher for System 1, indicating superior performance. Overall, System 1 performs far better than System 2. Thus, we would recommend the use of System 1 in our reconnaissance system.

LABORATORY

Materials

Digital camera and tri-pod mount

Computer running Microsoft Windows

ImageJ Software (freeware, downloadable from http://rsb.info.nih.gov/ij/)

Microsoft Excel

Imatest Software (free trial, $129 to purchase; http://www.imatest.com/)

Laboratory MTF target (included in module)

Procedures

The procedures consist of two different measurements of MTF for a common digital camera. In the first measurement, you will use the target method by evaluating the modulation depth in an image of the supplied target. In the second measurement, a commercially available MTF processing software program will be used to evaluate the MTF of the same digital camera. Assuming that you already have a digital camera and computer, the materials cost to complete the two laboratory procedures should be less than $200 per setup.

Initial setup—In the following procedures you will take an image of the supplied paper target and analyze it to measure the MTF of the complete digital camera system. It is vital that an original copy of the target be used in the measurement. Photocopies or similar reproductions will alter the quality of the target and degrade the accuracy of the measurement.

1. Acquire a digital camera in the 2–8 mega-pixel range (referring to the total number of CCD or CMOS detector elements). Set the camera on a solid surface or preferably a tripod. Use the manual to determine how to store images in either TIFF or BMP format. If only JPG format is available, set the image compression to the lowest setting yielding the highest-quality image. Some cameras have the ability to set the size of the picture. Use the menu to set the image resolution to the highest number of pixels possible. In addition, check the manual to determine whether there is a way to turn off the camera's sharpening filters. (Most digital cameras use a sharpening filter to enhance the edges of the captured image.)
2. Detach the "Laboratory MTF Target" (the last page of the module). Attach the target to a wall in the camera's field of view. Do not use optical or digital zoom on the camera. Move the camera so the target is in focus but as close to the camera as possible.
3. Use overhead room lights or indirect lighting to uniformly illuminate the target area. Indirect lighting is achieved using lights pointed upward so that the lights are not pointed directly at the target. Direct lighting will cause "hot-spots" of illumination on the target and should be avoided.
4. Familiarize yourself with the method required to upload the recorded images to a computer. You will be required to move the image of the target from the camera to the computer in order to analyze it.

5. Now that everything is set up, record an image of the target with the camera. It is better to use the timer feature of the camera so that the camera does not move when pressing the capture button.
6. Move the recorded image to a measurement folder in the computer.

Target method

1. Download and install the ImageJ software (http://rsb.info.nih.gov/ij/). It is available for Windows, Mac OS X, and Linux x86.
2. Open your measurement image in the ImageJ software using File→Open.
3. Now analyze the top half of the image. Use the mouse to select the cell marked "1" in the image. Choose Analyze→Plot Profile from the menu. This is a cross-sectional average of the cell you have selected.
4. Open a new worksheet in Microsoft Excel. Start two new columns called "Spatial Frequency [cycles/mm]" and "Modulation Depth." We will use this spreadsheet to record the measured values and calculate the MTF of the digital camera.
5. At this point we need additional information about the camera being tested. Specifically, we need to know the size of the pixels (sometimes called the *pitch*). There are several ways to determine this. First, look in the camera's user manual. If the information is not there, visit the manufacturer's website. A third way (and sometimes the fastest) is to visit http://www.dpreview.com. From this site you can determine the "aspect ratio," "max resolution," and "type" of sensor each camera uses. Use the table provided to determine the sensor "width." To calculate the pixel width, divide the "width" from the table by the "max resolution." Values should be between 1 and 10 um.

Type	Aspect Ratio	Width [mm]
1/3.6"	4:3	4.000
1/3.2"	4:3	4.536
1/3"	4:3	4.800
1/2.7"	4:3	5.371
1/2.5"	4:3	5.760
1/2"	4:3	6.400
1/1.8"	4:3	7.176
1/1.7"	4:3	7.600
2/3"	4:3	8.800
1"	4:3	12.800
4/3"	4:3	18.000

6. Observe the profile plot once again. Use the mouse to determine the "x" values of two adjacent peaks in the modulation. Subtract the highest value of "x" from the lowest value and record this in a laboratory notebook as "X." Use the formula shown below to determine the spatial frequency for the target cell in cycles/mm. Place this value in the first row of column one in your Excel spreadsheet.

$$\xi = \frac{1}{X \cdot \text{pixelwidth (mm)}}$$

7. Using the mouse again in the profile plot, record the maximum and minimum Gray Values. Be careful to choose these values only from the plot areas that contain modulation.

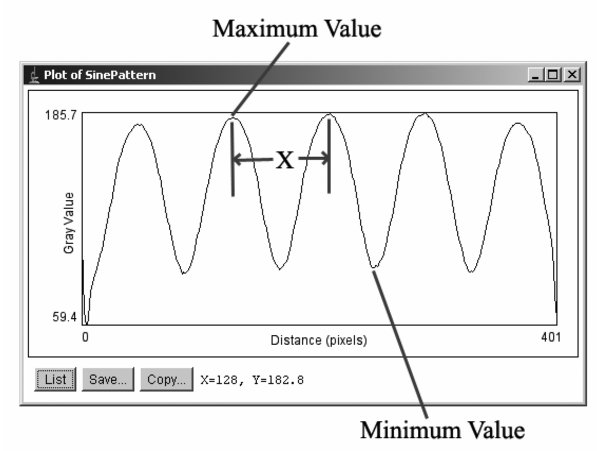


Figure 29 *Guide for choosing values in profile plot*

8. Calculate the modulation depth for the minimum and maximum Gray Values that you measured using this formula:

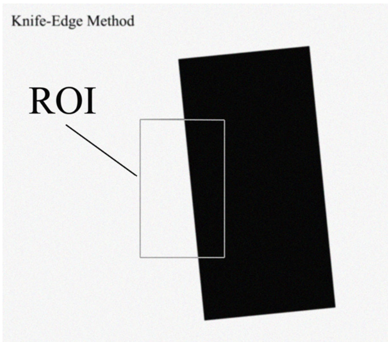
$$M = \frac{A_{\max} - A_{\min}}{A_{\max} + A_{\min}}$$

9. Record this value in row 1 of column 2 in your Excel spreadsheet.
10. Close the profile plot window.
11. Repeat the process of selecting and profiling for the remaining 9 of the 10 target cells. Calculate the spatial frequency and modulation depth for each cell and record these values in your Excel spreadsheet.
12. You are now ready to plot the MTF of the digital camera. Create a third column in your spreadsheet and call it "MTF." This column will be used to normalize the modulation depth measurements in column 2. In the first cell of this third column enter the following formula: =A1/max. The max value is the largest value in your column of modulation depth measurements. Then duplicate this formula for all 10 elements of the column. For example, if the largest value is 0.85, the formula should be =A1/0.85. The next row should have the formula =A2/0.85 and so on down the column.
13. Plot the column 1 value against the column 2 values including the name of the cells using the "XY" plot feature.
14. You have now measured the MTF of your digital camera using the Target Method.

Knife-edge method

1. Download and install the Imatest software available at http://www.imatest.com. The trial version of the software allows 20 free tests. The software is only available for Windows.
2. Run Imatest and choose "SFR: New File" from the main panel.

3. Choose a Region Of Interest (ROI) from the bottom half of the image acquired in the Target Method procedure. Your selection region should include one edge of the tilted black rectangle. The region should be approximately >60 horizontal pixels by 80–500 vertical pixels. Select "Yes – Continue" from the bottom selections if your region meets these criteria.



4. We now need to make some modifications to the "SFR data" window that appears after you have made your choice. Choose Cycles per "mm" and enter your pixel width using "microns per pixel." Select "OK."
5. The MTF of your camera is shown in the "Figure No. 1: Cycles/mm" window on the bottom plot. The black line is the MTF corresponding to the raw measurement. The red line is the MTF with an added correction for the sharpening filter used by your camera.

Discussion

Compare your MTF curves for the Target and Knife-Edge Methods. How do the measurements compare? If the measurements are drastically different, try repeating each measurement.

EXERCISES

1. Define the parameters of an optical imaging system. Draw a diagram illustrating the positions of each parameter.
2. Define the term *resolution*.
3. For a system operating at 8–10 um with a lens with an F/# of 4.4, what is the expected resolution at the image plane? Express your answer in terms of the largest resolution over the wavelength range.
4. Define the difference between the blur spot and the Airy pattern in an optical system.
5. What types of aberration are most likely due to mechanical problems and what types are most likely due to optical design problems?
6. What is the spatial frequency for each of the 3-bar elements in the USAF 1951 bar target for group number 0.
7. Describe how an optical system is like a low-pass filter.

8. Calculate the modulation depth for an irradiance profile with a maximum amplitude of 236 and a minimum amplitude of 54.
9. In words, compare the overall expected performance for two systems. The first system has a small blur spot and the second system has a large blur spot.
10. Given the following values, calculate the expected value of the MTF_{system} at 30 cycles/mm.

    $MTF_{footprint}$(30 cycles/mm) = 0.5
    $MTF_{sampling}$(30 cycles/mm) = 0.42
    MTF_{lens}(30 cycles/mm) = 0.7
    $MTF_{electronics}$(30 cycles/mm) = 0.66

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APPENDIX—FOURIER TRANSFORMS

The translation of the blur spot from the space to the time domain is accomplished using mathematical operators called *Fourier transforms.* Mathematical derivations using Fourier transforms are beyond the scope of this module but an understanding of their use is required. They will be explained here in general terms so that you can better understand the relationship between blur spot and MTF.

A Fourier transform is a mathematical tool that engineers use to translate a function from one domain to another. Engineers routinely use Fourier transforms in their design processes because it is sometimes easier to manipulate signals and information in the frequency domain. A spectrum analyzer is an electronic test instrument that performs a Fourier transform of input signals so that they can be displayed on a screen in real-time.

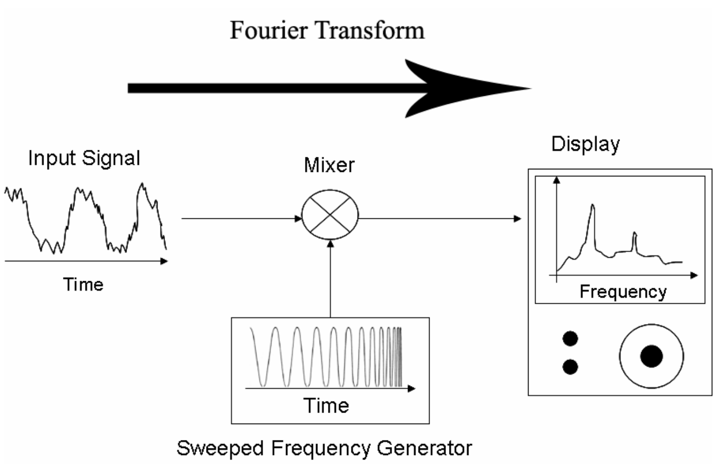


Figure 30 *Diagram of the operation of an electronic spectrum analyzer*

A spectrum analyzer uses an electronic device called a “Mixer” to compare two signals. The output of a mixer is a value proportional to the similarity of the two signals. A “Sweeped Frequency Generator” is an oscillator (generates sinusoidal signals) that has an increasing frequency output. The speed of the frequency sweep is matched to the scanning speed of the analyzer display. The mixing of the sweeping sinusoidal output of the reference generator with the “Input Signal” yields a plot of the frequency spectrum. This spectrum display shows the amount of power at each frequency contained in the input signal. In Figure 30 the input signal contains two primary sinusoidal waveforms: low- and high-frequency components. On the “Display” these components are displayed as spikes in the plot.

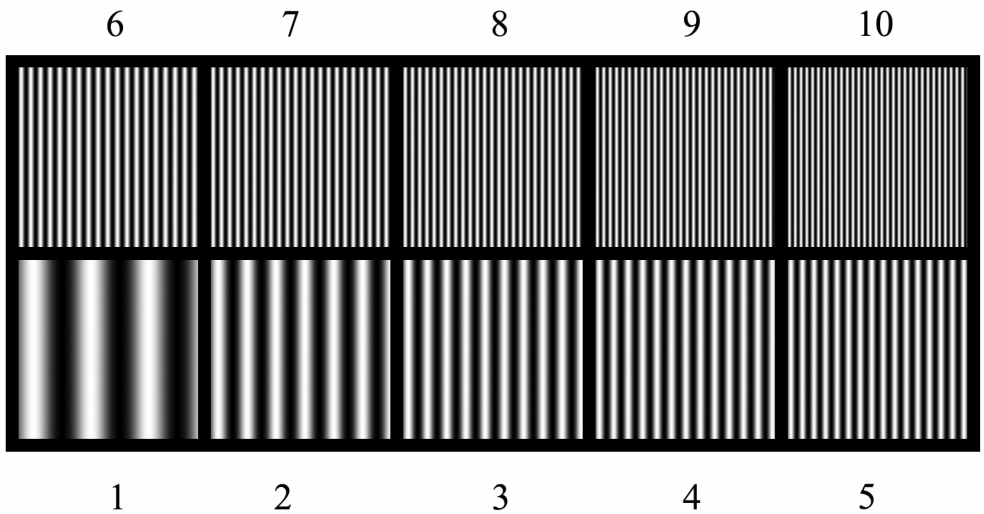
The operation of the spectrum analyzer is equivalent to the mathematical evaluation of the Fourier Transform of the input signal. Engineers use the Fourier transform to determine the expected spectrum of a signal. A spectrum analyzer is used to transform real signals to the frequency domain.

LABORATORY MTF TARGET

Note on printing: The target should be printed at 300 dpi with dimensions of 6.5″ × 9″ (as provided on the following page).

Laboratory MTF Target

Target Method



Knife-Edge Method