Computer Program to Determine the Sine Wave Modulation Transfer Function (MTF) of Imaging Devices

MTR 96B0000025

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Approved for public release; distribution unlimited.

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ABSTRACT

This document describes a computer program which computes the spatial frequency response, also known as the Modulation Transfer Function (MTF), of imaging devices from a sine wave target. The computer program also measures an imaging devices' gray scale linearity and detects aliasing. MITRE developed this software for performance assessment of image scanners and printers for the Federal Bureau of Investigations' Integrated Automated Fingerprint Identification System (IAFIS), in which it is used for image quality requirements verification, product certification, and production quality assurance.

KEYWORDS: Digitizer, Printer, FBI, IAFIS, Image Quality, MTF, Scanner, Sine Wave

PREFACE

The authors would like to thank Tom Hopper of the FBI for originally pointing out the potential for image quality degradation due to decimation rescaling, which was one of the motives for including an aliasing detection algorithm in the code; also, for his sustained interest in the program's development/features, and suggestions for ensuring that the C-language coding style employed is 'standard' and understandable.

This report documents version 3.1 of the computer program.

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SECTION 1

INTRODUCTION

1.1 BACKGROUND AND PURPOSE

The FBI's Criminal Justice Information Services (CJIS) Division is acquiring an Integrated Automated Fingerprint Identification System (IAFIS) that will greatly enhance the FBI's identification services to local, state, and federal law enforcement agencies. The IAFIS is a large, complex information system that will use both off-the-shelf and advanced technologies to provide these enhanced services.

Among other components, IAFIS will incorporate image digitizing scanners, softcopy displays, and hardcopy printers, each of which can affect the image quality of fingerprint images as they traverse the system. The FBI has, therefore, established an IAFIS Image Quality Specification (FBI, August 1995) which defines the quantitative image quality requirements for the fingerprint scanners, printers, and displays that are to be used in IAFIS. One of the scanner performance requirements is specified in terms of the Modulation Transfer Function (MTF), i.e., the spatial frequency response of the scanner. The MTF is a measure of the contrast reduction imposed by an imaging device as a function of spatial frequency, i.e., as a function of image detail size. Since contrast reduction is closely related to image quality, it follows that the MTF also directly relates to image quality. A high MTF curve implies better image quality than a low MTF curve. The suitability of the MTF to quantitatively characterize the image quality performance of a linear imaging device has been well-established over the years (Higgins, 1977; Snyder, 1985).

This document describes a computer program which computes the spatial frequency response, also known as the Modulation Transfer Function (MTF), of imaging devices from a sine wave target. The computer program also measures an imaging devices' gray scale linearity, which characterizes the input/output relation of gray levels, and it detects aliasing caused by improper sampling. MITRE developed this computer program for performance assessment of image scanners and printers for the Federal Bureau of Investigations' Integrated Automated Fingerprint Identification System (IAFIS). It is used as a test tool for verification of the MTF and gray scale linearity requirements that have been established for scanners in the IAFIS image quality specification, as delineated in the associated test procedures document (FBI, March 1995). It is also used to support FBI certification testing for fingerprint scanner products, and can be part of the quality assurance supporting production scanning of fingerprint cards.

Documentation of an earlier version of the sine MTF program was produced in 1994 (Nill and Paine, 1994). The detailed parameters and performance characteristics of image scanners and printers that determines their MTFs were also developed on this project, culminating in a computer simulation model (Nill, Forkert, Fridman, and Topiwala, 1993; Forkert, 1994).

1.2 Computer Program Availability and Overview

1.2.1 Program Availability

The sine wave MTF computer program, together with this document, an example input data file, and a test case, can be obtained by contacting[1]:

Federal Bureau of Investigation
Systems Engineering Unit, CJIS Division
(Attn: Tom Hopper, Room 9360)
10th Street and Pennsylvania Avenue, NW
Washington, DC 20537-9700

Telephone: (202) 324-3506

The program was developed on a SUN computer running under SUN's UNIX-based OS 4.1.3 operating system and using SUN's ANSI C compiler, version SC1.0. The code was also compiled on a SUN computer under SUN's UNIX-based Solaris 2.4 operating system and using SUN's SC3.0.1 ANSI C compiler. The completed program was ported, via use of Watcom C, to run on IBM PC compatible computers that use the Microsoft DOS operating system. The source code is common to both the UNIX and PC-DOS versions, only the "makefile" is different. The source code can be compiled without the modules needed for acceptance of Tag Image File Format (TIFF) images, which reduces the amount of source code by 60%, simply by changing the makefile (see compilation instructions in Appendix A).

This report documents version 3.1 of the computer program. Brief instructions for running the program are given in Appendix A.

1.2.2 Program Overview

The program determines the MTF of an imaging device by performing computations on the digital image of a sine wave target input to the device. For a scanner, the input sine wave target is in hardcopy form (paper or film) and the scanner produces a digital output image. For a printer, the input sine wave target is in digital form and the printer produces a hardcopy output image. In this latter case the print must be scanned to create the digital image necessary for input to the program. The content of the commercially available sine wave target that the program expects to 'see' is shown in Figure 2-1. It consists of individual sine wave frequency patterns surrounded on two sides by reflectance gray patches covering a range of gray levels. The basic steps in the computer program are illustrated in Figure 1-1 and are described in the following:

The program first re-orients the image into a standard orientation, and then computes the image pixels per inch (ppi) and skew angle in each of two perpendicular directions. These computations use three target image corner coordinates located beforehand by the user, together with target dimensions taken from a separate input data file.

[1] Internal to MITRE, contact Norman Nill.

The gray patches and sine patterns in the image are then individually located, using ppi, skew angle, and target dimensions data. The skew angle is the angle between the length or width direction of the target and the scanner's detector rows or columns.

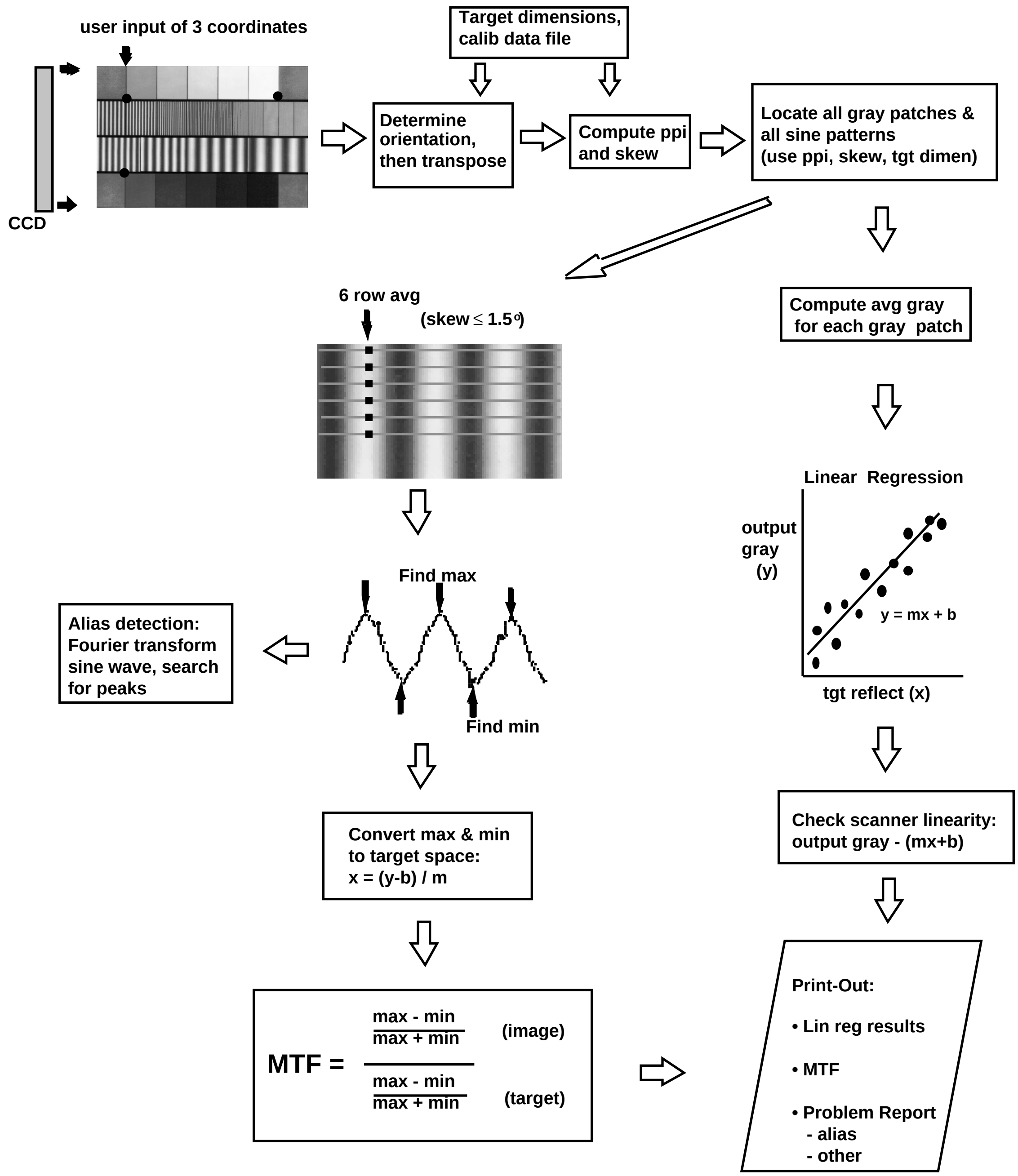


Figure 1-1. Basic Steps in Sine Wave MTF Computer Program

The average gray level of each image gray patch is computed and compared to the corresponding, known target reflectance value of each patch. A linear least squares regression computation is then performed on the data for two purposes: (1) to measure the linearity of the imaging device by comparing the deviation of the device's output gray level values from the best linear fit line; and (2) to use the best linear fit line to convert the image sine wave gray levels to their equivalent values in 'target space', where the modulation values are computed. If the MTF of a printer is being evaluated and the regression does not yield a sufficiently linear result, then sine wave gray levels are instead converted to 'target space' via a straight line fit to the gray values of the two density patches that bracket the given sine wave gray value.

The computed ppi and skew angle is used to establish the imaging device's Nyquist frequency, which is the highest spatial frequency sine wave for which modulation computations are performed. Appendix B gives a brief technical discussion of the Nyquist frequency and its ramifications. If the magnitude of the skew angle is small, then the gray levels of individual pixels are averaged across a limited number of rows in each sine wave frequency pattern to decrease noise. That is, the gray levels are averaged in a direction perpendicular to the sinusoidal variation direction.

The next step is to determine the locations of the sine wave peaks and valleys, which correspond to the maximum and minimum gray level values that are one-half period apart. Each sine wave frequency pattern contains multiple sine periods. The location of the first peak along a single row (or along a row average if $|\text{skew}| \leq 3°$) is determined via a semi-correlation technique applied across the entire length of the row. This allows successive peaks/valleys along the row to be accurately located. A successive peak is an integer multiple of periods away from the first peak and a successive valley is an integer multiple of one-half period away from the immediately preceding peak. In order to compensate for possible initial inaccuracies in the length of the period or an inaccuracy in the location of the first peak, the candidate location of each succeeding peak along the row is varied slightly to determine the best peak-valley pairing within each period.

Once each period's peak and valley gray levels are determined, they are converted to 'target space' values by using the previously calculated output image-to-input target conversion curve (for scanners, a linear regression curve). This conversion normalizes out gray level measurement differences between the target and scanner-produced image. The scanner MTF is then computed by dividing the image modulation at a given frequency by the corresponding target modulation, where modulation is defined as
(peak – valley) / (peak + valley).

One-dimensional discrete Fourier transforms along selected rows (or row averages) are also computed to detect any significant aliasing that may occur below the calculated Nyquist frequency. Significant aliasing may be caused by the upscaling required to achieve a desired higher ppi resolution than was actually scanned, or by nonuniform decimation downscaling that may be employed to achieve a desired lower ppi resolution than was actually scanned. In either case, significant aliasing results in spurious, false imagery. Aliasing can be more precisely and accurately detected in the Fourier domain than in the spatial domain.

The program output lists:

- image corner coordinates input by the user
- computed ppi and skew angle in two orthogonal directions
- linear regression and scanner linearity results for all gray patches
- MTF of the imaging device
- problem report

The program performs a number of internal tests to detect abnormal data values, such as might be indicated by aliasing, the scanner set to an extremely high contrast, contrast inversions, nonlinear behavior, or row, column corner coordinates inadvertently transposed by the user upon input. These problems are printed out, if detected.

1.3 Modulation Transfer Function (MTF) Theory

The foundation for the applicability of the MTF as a valid image quality performance measure is the concept and theory associated with linear systems. In one dimension, if $o_1(x)$ represents the gray level output of an imaging system that has input $i_1(x)$, where 'x' is a spatial location parameter, and if $ko_2(x)$ is the output to the input $ki_2(x)$, where k is an arbitrary constant, then the imaging system is said to be linear if its response to $i_1(x) + ki_2(x)$ is $o_1(x) + ko_2(x)$. If, in addition, the output to $i(x-\Delta)$ is $o(x-\Delta)$, for all values of the spatial shift parameter Δ, then the linear system is also spatially invariant.

A linear, spatially invariant imaging system has the useful property that it can be characterized in the spatial domain by its response to an impulse function, i.e., its response to a point source of light (in two dimensions) or thin line source of light (in one dimension). The system can be equivalently characterized in the spatial frequency domain by the Fourier transform of the impulse response. For example, if an infinitesimally thin line in light intensity is input to a linear imaging system such as an image scanner, then the line image output by the scanner, denoted as o(x), has a non-zero, finite, measurable width, where o(x) represents the spatial response to a line impulse and is called the line spread function. The normalized magnitude of the Fourier transform of o(x), which is the MTF, is a measure of the spatial frequency response of the scanner. The derivation of the MTF from a one-dimensional line impulse input to a linear system is given in Equations 1-1 and 1-2, where O(f) = Fourier transform of the line spread function o(x).

$$O(f) = \int_{-\infty}^{\infty} o(x) e^{-2\pi jfx} dx = |O(f)| e^{j\phi(f)} = O(f)_{real} - jO(f)_{imaginary} \qquad (1\text{-}1)$$

$$MTF = \frac{|O(f)|}{\int_{-\infty}^{\infty} o(x) dx} = \frac{\sqrt{O^2(f)_{real} + O^2(f)_{imaginary}}}{\int_{-\infty}^{\infty} o(x) dx} \qquad (1\text{-}2)$$

where

$O(f)_{real}$ = real part of O(f)

$O(f)_{imaginary}$ = imaginary part of O(f)

x = spatial distance

f = spatial frequency

$\phi = \arctan\left[\frac{O(f)_{imaginary}}{O(f)_{real}}\right]$ = phase transfer function

$j = \sqrt{-1}$

The system MTF can be computed from an impulse function input such as a point source of light (Smith, 1966), a narrow line (Kuttner, 1968), or a sharp edge (Jones, 1967). It can also be computed from non-impulse inputs such as a sine wave (Dainty and Shaw, 1974; Lamberts, 1996), square wave (Campana, 1977), or even from a random pattern (Daniels, et al, 1995). Each target type has its own set of advantages and disadvantages in application to assessment of specific linear systems. For digital scanners, which have finite area pixel elements whose outputs represent the quantized average gray value over each pixel area, very few output data points are obtained across the profile of a scanned point, narrow line, or sharp edge input target. Subsequently, there is only a small number of sample points from which to compute the entire MTF. The resulting MTF is therefore very sensitive to the details of the exact computational approach implemented, because the effective signal-to-noise ratio is low; e.g., sensitive to the type of noise smoothing that would need to be applied. Random pattern targets are difficult to sufficiently characterize in a deterministic sense. Modulation directly computed from a square wave target's peaks and valleys is not equal to the true MTF of the linear system, although an approximate conversion between the square wave response and sine wave response is possible (Coltman).

The Fourier transform operation applied to o(x) decomposes o(x) into its fundamental sine wave components. It follows that one can obtain the MTF by directly inputting individual sine waves of different spatial frequencies into the scanner and comparing the output amplitudes to the input amplitudes. This procedure determines the MTF directly from sine waves, without having to compute a Fourier transform. It is this fundamental nature of sine waves, as well as their basic simplicity, that make them an appealing target to use. Since each sine wave represents only one frequency and the target can have multiple periods of that sine wave, the signal-to-noise ratio is very high, relative to other target types. In addition, the presence of undesirable aliasing, caused by the imaging system, can often be detected by simply viewing the sine wave image, and it can be quantified by performing computations on the sine wave image. Other frequency-dependent artifacts or anomalies of a scanner can also be observed visually, since each sine wave frequency is individually imaged. Although a sine wave target is difficult to construct and is not nearly as compact as a point, line, or edge target, the aforementioned advantages make it highly suitable for use in the current application.

Suppose o(x) is now a sinusoidal wave with mean value 'm' and amplitude variation 'a'; that is, m is a constant gray level above and below which the gray level varies sinusoidally by the amount a. The modulation of this distribution is defined as a/m. Given that the peak (maximum value) equals m + a, and the valley (minimum value) equals m - a, the more common form of modulation can be obtained:

$$\text{modulation} = a / m = \frac{\text{maximum} - \text{minimum}}{\text{maximum} + \text{minimum}} \tag{1-3}$$

Therefore, by computing the output modulations at a series of sine wave spatial frequencies and normalizing by the corresponding input modulations, the MTF curve of a scanner can be generated from Equation 1-3, which is exactly equivalent to the MTF computed via Equation 1-2 (Perrin, 1966). A pure sine wave input to a linear, spatially invariant system is output as a pure sine wave of the same frequency, generally with reduced output amplitude, and possibly with a different relative phase. This process is illustrated in Figure 1-2.

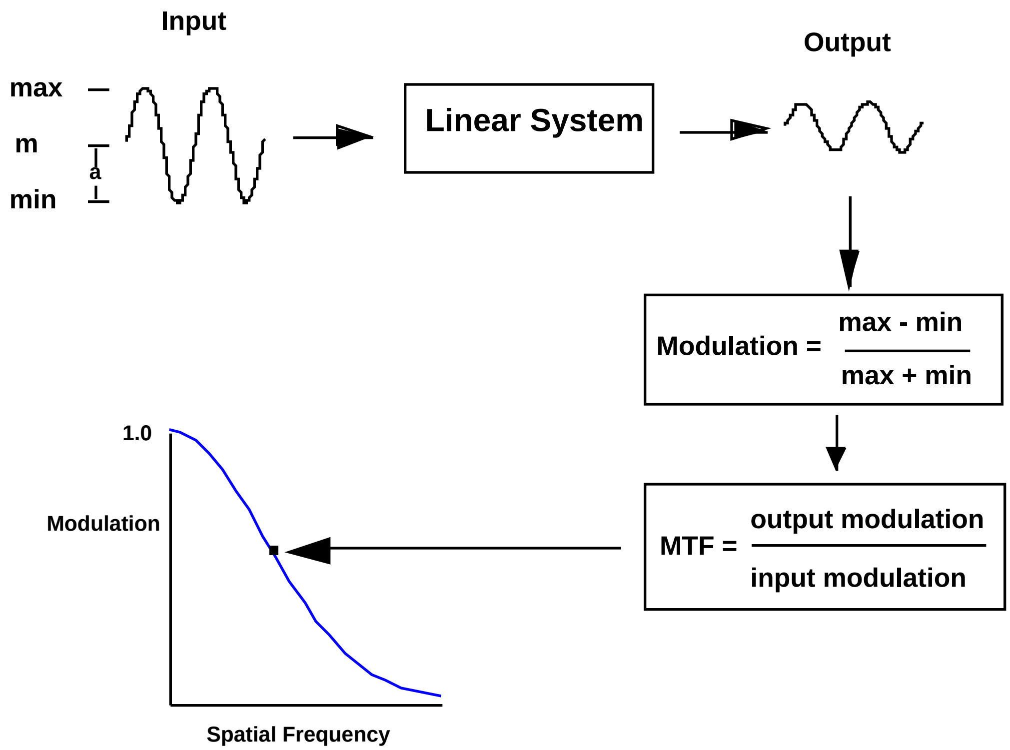


Figure 1-2. Single Sine Wave Traversing a Linear System, Generating MTF Datum

There is, however, a complication in applying the MTF concept to image scanners**.** This complication is the result of the discrete sampling nature of a scanner (Park, Schowengerdt, and Kaczynski, 1984; Feltz and Karim, 1990). Specifically, a scanner samples a continuous, analog image input at discrete locations over discrete time intervals, integrating all incident light energy over a given time interval and within a small area around each sampling point, where the small area is the individual detector element ("pixel") area. One of the consequences of this discrete sampling by finite-sized detector elements is that the scanner acts as a space variant system, which implies that the scanner MTF can be multivalued. In the context of the sine wave target, this space variance means that the phase between this target and the scanner's detector array plays a role in the actual MTF achieved. Here, the term 'phase' refers to the location of the detector pixel within a sine wave period, at the time the pixel is collecting light energy. As the target-detector phase changes, the scanner MTF can change, within limits. As a consequence of the scanner's discrete sampling nature, therefore, there is no single MTF for a given scanner.

With respect to the sine wave target layout described in Section 2.1, the relative phase between this target and the scanner detector array is constant across all periods of a scanned sine wave at the Nyquist frequency (Nyquist equals 9.84 cy/mm for a 500 pixels/inch scanner). The phase is also constant across all sine wave periods at certain multiples of the Nyquist frequency, specifically, at (2/3)Nyquist, (2/4)Nyquist, (2/5)Nyquist, and so on; although the phase still varies from frequency to frequency. For sine waves of other frequencies the target-detector phase changes, from sine period to sine period at a given frequency. A scanner MTF computed from a single scan of the target, therefore, contains a multitude of different target-detector phases.

The primary output of the sine wave peak/valley location method used in this MTF program maximizes the MTF from a single scan by selecting the single sine period at each frequency that exhibits the highest computed modulation. This is the desired MTF for application to performance measurement of FBI IAFIS imaging devices. There are at least four other methods for determining modulation from sine waves: (1) compute the average modulation from all peak/valley combinations; this is an optional output of the program,
(2) fit the multiple period sine wave to a model sine wave via the least squares technique, producing a single peak and single valley for the entire sine wave frequency pattern,
(3) compute the Fourier transform of the multiple period sine wave and utilize the appropriate two data points in the Fourier domain which are equivalent to the peak and valley in the spatial domain (Lamberts, 1996), or (4) compute the histogram of the entire multiple period sine pattern and identify the two peaks of the bimodal distribution, where one peak corresponds to the sine valley and the other peak corresponds to the sine peak. All four of these alternative techniques produce a quantity akin to the average peak and average valley across all sine periods measured. These four techniques do not, therefore, produce the sought after maximum, single best peak/valley combination.

SECTION 2

TECHNICAL APPROACH: ANALYSIS OF SINE WAVES TO COMPUTE MTF

2.1 SINE WAVE TARGET DESCRIPTION

The MTF program performs computations on the digital image of a sine wave target to produce the MTF of an imaging device. The program expects to 'see' a target image containing a series of multiple period sine waves of different frequencies, together with a series of gray patches whose total gray level range exceeds the gray level range of the sine waves. A data file input to the program defines the location, size, spatial frequency, and modulation of each sine pattern; and the location, size, and density value for each gray patch. With appropriate changes to the input data file, the program is flexible enough to handle a variety of sine wave target layouts, or even bar targets. Several program-compatible hardcopy sine wave targets having the layout shown in Figure 2-1 are commercially available from:

Sine Patterns, Inc.
236 Henderson Drive
Penfield, NY 14526
Telephone: (716) 248-5338

The hardcopy targets are used for testing scanners. For MTF assessment of printers, a digital sine wave target has been constructed by MITRE; see points of contact in Section 1.2.1 for obtaining this target. Table 2-1 synopsizes the basic properties of the hardcopy Sine Patterns, Inc. targets, the MITRE digital sine target, and a bar target that have been used to date to support MTF measurement of fingerprint scanners and printers for the FBI IAFIS program. Appendix C gives the input data files required to run the MTF program for each of these targets.

Table 2-1. MTF Test Targets

Model Number	Target Substrate	Frequency Range (cy/mm)	# of Gray Patches	Target Size	IAFIS Application
M-13-60-1X (Sine Patterns, Inc)	photo paper	0.1875 – 12	14	70 x 47.5 mm	500 ppi card scanners
M-13-60-0.5X (Sine Patterns, Inc)	photo paper	0.25 – 12	14	35 x 24 mm	500 ppi livescanners
M-15-60 (Sine Patterns, Inc)	photo paper	0.25 – 20	14	70 x 47.5 mm	1000 ppi card scanners
M-6 (Sine Patterns, Inc)	photo film	0.375 – 80	14	70 x 46 mm	500 ppi livescanners
A3 (MITRE)	digital	0.5 – 9.84 when printing @ 500 ppi	14	905 x 515 pixels	500 ppi printers
T90 (Applied Image, Inc)	glass	1.0 - 631 Bar Target	0	18 x 18 mm	500 ppi livescanners

All of the sine targets in Table 2-1 have the common layout that is exemplified by the M-13-60-1X target layout shown in Figure 2-1. This is the target normally used to measure the MTF of 500 ppi IAFIS fingerprint card scanners; it is printed on semi-matte photographic paper and contains four rows of patterns. The top row contains seven reflectance density patches, approximately 10 x 11.5 millimeters (mm) each; the next row contains, from left to right, sine wave patterns with spatial frequencies of 0.75, 1.0, 1.5, 2.0, 3.0, 4.0, 5.0, 6.0, 8.0, 10.0, and 12.0 cy/mm; the next row contains, from left to right, sine wave patterns with spatial frequencies of 0.5, 0.375, 0.25, and 0.1875 cy/mm; and the bottom row contains seven additional reflectance density patches. The four density patches in the four corners have nominally the same density. The manufacturer-supplied density values for each density patch are used as the target density patch values.

The manufacturer of the hardcopy targets also supplies a modulation value for each sine wave frequency pattern of the target. A scanner's MTF is computed by scanning a sine wave target and dividing the scanner's output modulation by the input target modulation. The target modulation is supplied by the target vendor, who must measure it using an instrument that itself degrades the true modulation of the target. If this degradation in target modulation is not accounted for, then the computed MTF of the scanner is incorrect – it will appear to be higher than it really is. This issue has been separately documented in detail (Nill, 1995); the basic results and solution to the problem are given in the following three items:

• As of this writing, Sine Patterns Inc. sets up their measuring instrument, which is a microdensitometer, with 0.11 numerical aperture imaging optics and a 10 micron effective scan slit width, to measure the modulations of their M-13-60-1X, M-13-60-0.5X, and M-15-60 reflection (paper) sine wave targets. Sine Patterns Inc. has measured the MTF of their microdensitometer by an independent method. The "compensated modulation", supplied with a purchased target, is the "peak-to-peak" target modulation as directly obtained from the microdensitometer scan of the target, divided by the microdensitometer MTF. "Compensated modulation" is the quantity to be entered in the MTF program's input data file. The "peak-to-peak" target modulation is the modulation determined from the amplitude of the sine wave's fundamental frequency, combined with the amplitudes of the second and third harmonic frequencies, prior to compensation for the microdensitometer effect.

• Serial numbers below 300 of the M-13-60-1X target may not be supplied with the "compensated modulation" values. In this case, the target modulation value entered into the MTF program's input data file is the supplied "peak to peak" modulation divided by the microdensitometer MTF; the latter quantity is given in the following:

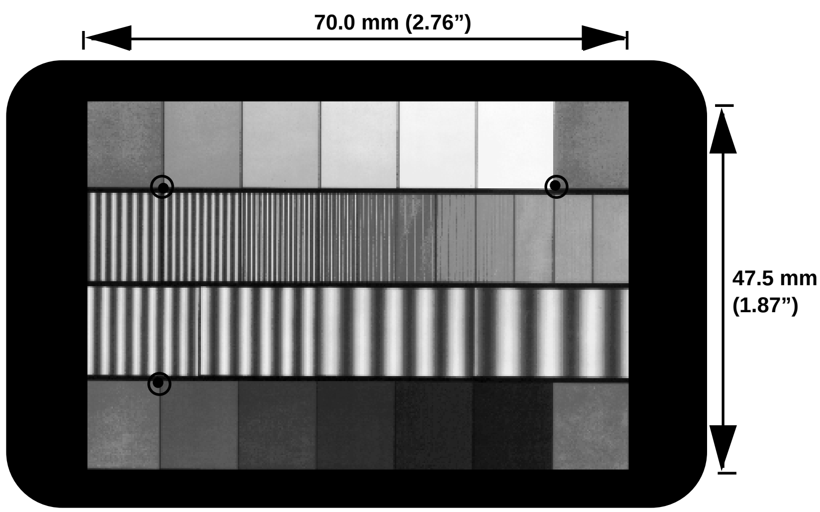
cy/mm	Microdensitometer MTF
1	1.000
2	0.998
3	0.994
4	0.990
5	0.978
6	0.960
8	0.935
10	0.890

• The transmission (film) sine wave target M-6, which has been used for IAFIS livescanner testing, is measured with a different optical and slit width setup on the microdensitometer, such that the microdensitometer MTF equals 1.0 out to the highest frequency of interest for IAFIS 500 ppi livescanners, which is 10 cy/mm. For this target the "peak to peak" target modulation may be used.

Sine Patterns Inc. gives the following tolerances for their targets in their product catalogs.

in 1995 catalog:
≤ ± 0.02 density units error on gray patches
≤ 3% sine wave harmonic distortion

in 1993 catalog:
≤ ± 0.2% spatial frequency error
≤ ± 5% sine modulation error
≤ ±0.1 degree error on sine wave pattern alignment



Circled dots on inner corners of upper left, upper right, and lower left gray patches denote locations of the three coordinates input to the MTF program by user (dots not part of target).

Figure 2-1. Sine Wave Target (M-13-60-1X) Used to Compute Scanner MTF

The MTF program can also process a bar target image. For example, the appropriate input data file to process the model "T90" target, a 15-bar, 10th-root-of-10 frequency progression target[2], is given in Appendix C. When processing a bar target, the output is what is commonly called the "contrast transfer function (CTF)" or "square wave response" of the imaging device. Although the CTF derived from a bar target is not identical to the MTF derived from a sine wave, there is a relation between the two and a formula for converting a

[2] The "T90" target is manufactured by Applied Image, Inc., 1653 East Main St., Rochester, NY, phone: (716) 482-0300.

CTF to its equivalent MTF (or vice versa) was given some years ago (Coltman). This formula conversion is less accurate when dealing with a discrete sampling system such as a scanner, so alternative conversion approaches are being investigated by MITRE (to be documented separately).

2.2 IMAGE ORIENTATION

The sine wave target described in Section 2.1 has four possible orientations. The lightest density patch (the "white patch") could be at the top, bottom, left or right when the target is scanned. The MTF program can accept a target image in any of the four possible orientations, but will internally store the image in a single orientation that simplifies location of the density patches and sine patterns for analysis. Figure 2-2(a) illustrates a vertically scanned target and Figure 2-2(b) shows the same target after transposition by the program into the common orientation internally used by the program. This common orientation is horizontal, with the "white patch" on the top right. The white patch is the single gray patch, out of the fourteen gray patches, which has the lowest density, and thus the highest reflectance (or highest transmission). It should be noted that no rotation matrices are used to change the scanned image into the common orientation, i.e., the image is not warped, rescaled, or pixel-interpolated. Rows and columns are only interchanged and/or transposed to get the common orientation, thus maintaining the original gray level values of all pixels in the image.

Given the knowledge that the original image is vertical or horizontal (a user input), the program determines the left/right or top/bottom image orientation by reading-in (from the image file) just those pixels corresponding to a segment of a candidate white patch on each side of the sine patterns. Since there is only one true white patch, which is in a known relative location, a comparison of the average gray values between the two candidate patch segments read-in identifies the orientation. Once the orientation is established, the image is transposed into the common internal orientation as it is read-in. Note, however, that with some combinations of target and scanner, the white patch may appear on the upper left side when the image is oriented in the horizontal orientation. In this case the simplest solution for correct program execution is to left/right reverse the image prior to running it through the program. Alternatively, the input data file could be changed to accommodate this reversed image, by placing the original in the upper right corner and reversing the patch lettering sequence in the data file - see Appendix C.

A scan of the sine wave target should always extend beyond the outside edges of the target, as depicted in Figure 2-2(a). The program stores the overall scanned image (target plus background) in the common orientation and the target area is then located within the overall image.

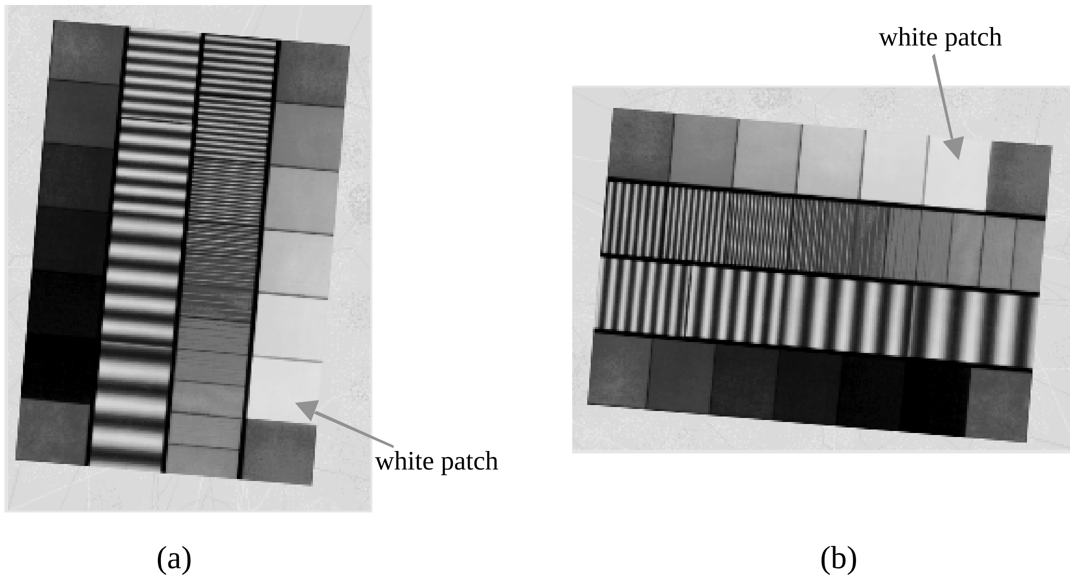


Figure 2-2. (a) Original Image of Target Scanned Vertically at +5º Skew Angle
(b) Image Transposed by Program into Common Orientation for Internal Program Use

2.3 PIXELS PER INCH AND SKEW ANGLE COMPUTATION

The user of the MTF program needs to display the scanned target image (see Section 3.1) and identify the column and row coordinates of three inner corner points of the target, specifically, the inner corner coordinates of the upper left, upper right, and lower left corner gray patches, as illustrated in Figure 2-1. These coordinates are relative to the upper left corner of the overall image (scanned target plus background) being defined as column 0 and row 0. The three inner corner points input by the user are converted to the target image's outer corner points by the program as it transposes the image into the common orientation. The fourth outer target corner is then computed by the program from the other three outer corners. User input of the inner corner points instead of the outer corner points allows the MTF program to accommodate target scans which may not capture the entire target. For example, if the target is segment-scanned (discussed in more detail in Appendix D), then there is a possibility that some rows or columns along one edge of the target may be missing, which would make it difficult for the user to identify the outer corner points.

The resolution of the scanner in pixels per inch (ppi) is determined from the three user-input inner corner coordinates of the image, together with the target dimensions taken from the program's input data file. Fractional (floating point) row, column coordinates may be input by the user, which may slightly increase the accuracy of the computed ppi in some cases (up to 1.0 ppi increase in accuracy). The ppi may legitimately differ in the horizontal and vertical directions and so both are computed. For a target scanned in the horizontal orientation, Equation 2-1a and Equation 2-1b give the formulas for computing ppi in the two directions. The denominators of H_{ppi} and V_{ppi} are interchanged for a target scanned in the vertical orientation.

$$H_{ppi} = \frac{\sqrt{(c_{ur} - c_{ul})^2 + (r_{ur} - r_{ul})^2}}{W_t - 2W_g} \qquad (2\text{-}1a)$$

$$V_{ppi} = \frac{\sqrt{(c_{ll} - c_{ul})^2 + (r_{ll} - r_{ul})^2}}{A_t - 2A_g} \qquad (2\text{-}1b)$$

where

H_{ppi} is the horizontal ppi.
V_{ppi} is the vertical ppi.
W_t is the target width in inches (e.g., 2.76").
W_g is the width of a gray patch in inches (e.g., 0.392").
A_t is the target height in inches (e.g., 1.87").
A_g is the height of a gray patch in inches (e.g., 0.451").
c_{ur}, r_{ur} is the column and row, respectively, of the lower left corner of the upper right gray patch on the target image.
c_{ul}, r_{ul} is the column and row, respectively, of the lower right corner of the upper left gray patch on the target image.
c_{ll}, r_{ll} is the column and row, respectively, of the upper right corner of the lower left gray patch on the target image.

During scanning, the sine wave target may be at a non-zero angle with respect to the scanner's detector array. This angle, denoted 'skew angle', is useful information to the user and is necessary to take into account in subsequent program computations. The scanned target skew angle is, therefore, computed in both the vertical and horizontal directions from the input corner coordinates. There will usually be some small variation between the skew angle in the two directions due in part to the discrete corner coordinates. Program computations use the average of the two directional skew angles. Equations 2-2a and 2-2b give the formulas for computing the horizontal skew angle, α_h, and the vertical skew angle, α_v, respectively. The skew angle sign convention used is positive downward, with reference to the upper right corner.

$$\alpha_h = \arcsin\left(\frac{r_{ur} - r_{ul}}{\sqrt{(c_{ur} - c_{ul})^2 + (r_{ur} - r_{ul})^2}}\right) \qquad (2\text{-}2a)$$

$$\alpha_v = \arcsin\left(\frac{c_{ul} - c_{ll}}{\sqrt{(c_{ll} - c_{ul})^2 + (r_{ll} - r_{ul})^2}}\right) \qquad (2\text{-}2b)$$

The average skew angle, α, is used by the program to support a number of computations: it aids in determining the locations of the two candidate white patches when determining the original image orientation, it aids in computing the outer corner coordinates of the image, it aids in locating the individual density patches and sine patterns, it is used to determine whether or not row averaging can be performed in the sine patterns to decrease noise, and it is used to determine the effective spatial frequency of a specific sine pattern in the image. Note that the program does not deskew the image, i.e., it does not rotate the image to zero skew angle because this would require pixel interpolation, which would change the original image's pixel values. Except for the straightforward transposition of rows and columns to place the image in the internal common orientation, the image is stored and analyzed "as is."

The outer corner coordinates of the sine target image, which are used by the program to set the boundaries of the sine target image, are computed next. The calculation applies the 'rotation of axes' formula (Foley, et al, 1990) and utilizes the three user-input inner corner coordinates, average ppi, average skew, gray patch width and height on the target, and image orientation. If the computed outer corner coordinates are more than five rows and/or five columns beyond one or more edges of the overall image, then the program notifies the user and stops execution.

Both the resolution and skew angle are essential for location of and analysis on the density patches and sine patterns. Their accuracies depend on how carefully a user determines the target corner coordinates within the overall image. Experience has shown that with typical softcopy display hardware/software and taking reasonable care, a user can routinely locate a corner coordinate to within ±1 row and ±1 column of the true corner point. To illustrate the errors that can be incurred, Table 2-2 relates errors in input corner coordinate locations to resulting errors in the computed resolution and skew angle, and to the change in the "highest mod" MTF. This data was generated by running the same sine image through the program, only changing the input coordinates for each run. The first data row in the table is for the assumed zero error case. The second, third, and fourth data rows give the results of three trials when the row and column at each coordinate are chosen by applying a uniformly distributed random variable, where each row or column can have –1, 0, or +1 pixel error. The fifth data row gives a worst case situation for one row and column offset, where the directions of the offsets were deliberately selected such that they compound rather than negate each other. The change in MTF values for each case is strictly due to the program's selection of slightly different measurement areas, as determined by the different ppi and skew angles computed in each case.

Table 2-2. Effect of Input Corner Coordinate Errors on PPI, Skew, and MTF

Error (pixels)	Horz PPI	Vert PPI	Horz Skew	Vert Skew	6 cy/mm	8 cy/mm	10 cy/mm	Case
0	500.84	500.40	.348	.945	.518	.428	.358	no error
±1	501.89	500.92	.406	1.061	.514	.429	.358	random #1
±1	500.84	499.90	.349	.945	.519	.431	.356	random #2
±1	502.89	499.90	.349	.823	.519	.431	.353	random #3
±1	502.94	501.41	.232	1.176	.521	.431	.363	worst case

2.4 LOCATING GRAY PATCHES AND SINE WAVE PATTERNS

The input data file, described in detail in Section 3.2.1, contains the relative location and size for each density patch and each sine pattern, as measured off the actual target in the common orientation. The file contains the upper left corner of each patch and pattern in terms of its horizontal and vertical distance, in millimeters (mm), from the target's upper left corner. The width (W_p) and height (A_p) of each patch and pattern is also given (in mm). These measurements represent a template of the target which is mapped onto the scanned target image.

The process of patch and pattern location on the scanned target image consists of two steps. The program first computes an interior measurement box for each density patch and sine pattern on the target, using the height, width, and upper left corner location of the patch or pattern. This box is centered in the patch or pattern but with a 10% border[3] on all sides, as defined in Equations 2-3a through 2-3d. The border offers a margin of safety for computations where discretization round-off or coordinate measurement errors, such as illustrated in Table 2-2, could otherwise place part of the box outside the image patch or sine pattern of interest. In addition, the measurement box border allows for processing of imperfectly merged segments of the total target, applicable to those scanners which do not scan and capture the entire sine wave target as a single image. Allowable limits for processing segmented/merged sine target scans through the MTF program are discussed in more detail in Appendix D.

$$x_1 = x_3 = x_{ul} + 0.1W_p \tag{2-3a}$$

$$x_2 = x_4 = x_{ul} + 0.9W_p \tag{2-3b}$$

$$y_1 = y_2 = y_{ul} + 0.1A_p \tag{2-3c}$$

$$y_3 = y_4 = y_{ul} + 0.9A_p \tag{2-3d}$$

In Equations 2-3a through 2-3d, the real numbers x_i and y_i are the coordinates, in mm, for each corner of the interior measurement box of a density patch or sine pattern on the target; subscript i=1 for upper left, i=2 for upper right, i=3 for lower left, and i=4 for the lower right box corner. The real numbers x_{ul} and y_{ul} are the coordinates of the patch or pattern's upper left corner on the target, in mm. The real numbers W_p and A_p are the width and height, respectively, of the patch or pattern on the target, in mm.

Once the interior measurement box is defined on the target, it is mapped onto the scanned target image. To accomplish this, the x, y corner coordinates are first converted from mm to columns and rows via Equations 2-4a and 2-4b. The column, row box is then rotated and translated onto the scanned target image, using the 'rotation of axes' formula given in Equations 2-5a and 2-5b (Foley, et al, 1990), which incorporates the average skew angle of the scanned target together with its offset from the upper left corner of the overall image.

[3] This safety margin can be changed by changing the number in the following line of code in the MTF.h module: #define BORDER 0.1

$$c_i = \frac{x_i}{25.4} H_{ppi} \tag{2-4a}$$

$$r_i = \frac{y_i}{25.4} V_{ppi} \tag{2-4b}$$

$$c'_i = \left[c_i \cos(\alpha) - r_i \sin(\alpha) + O_c \right] \tag{2-5a}$$

$$r'_i = \left[c_i \sin(\alpha) + r_i \cos(\alpha) + O_r \right] \tag{2-5b}$$

where

i, x_i, y_i, V_{ppi}, and H_{ppi} as defined in equations 2-1a,b and 2-3a,b,c,d.
r_i, c_i are the row and column, respectively, of the patch or pattern's ith corner on the image, assuming no skew or offset (reals).
r'_i is r_i corrected for skew and offset (integer).
c'_i is c_i corrected for skew and offset (integer).
α is the average skew angle of the image (real).
O_r is the offset in rows from the overall image's upper left corner (at 0, 0) to the target image upper left outer corner (integer).
O_c is the offset in columns from the overall image's upper left outer corner (at 0, 0) to the target image upper left corner (integer).

Figure 2-3 shows the mapping of one density patch's measurement box onto the scanned target image. The 10 percent border around each box is sufficient to tolerate errors in input coordinates of up to four rows and/or columns (i.e., errors larger than those given in Table 2-2), when analyzing the M-13-60-1X or M-15-60 target. If there is any question as to whether the program has correctly located the measurement boxes within the borders of each density patch and sine pattern in the image, the program can be run with the **-d** diagnostic option. This mode creates an overlay of the measurement boxes on the image (see Section 3.4.2 for a fuller discussion).

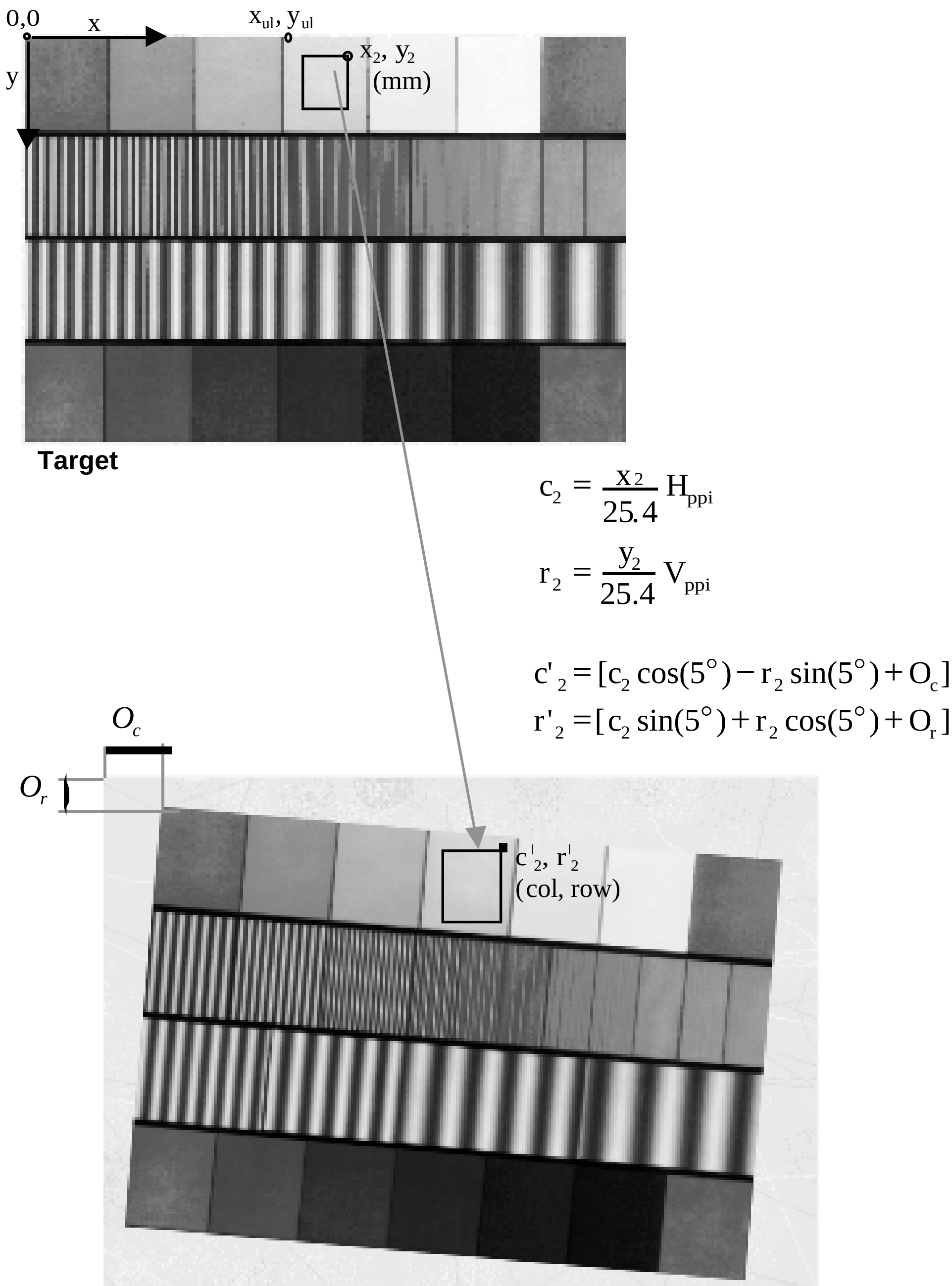


Figure 2-3. Mapping Upper Right Corner of Measurement Box from Density Patch on Target to Image (+5º Image Skew Angle)

The scanned image will usually be at least slightly tilted with respect to the scanner detector's rows and columns, which necessitates calculations of the box boundaries for each row and column. That is, as operations are performed on each row, working left to right, the column starting position (c_s) and column ending position (c_e) depends on the row (r'_c). Equation 2-6 computes the starting column for any given row, which defines the left-side boundary of a measurement box on the image, and equation 2-7 defines the ending column (right-side boundary).

$$c_s = \begin{cases} c'_1 - (r'_c - r'_1)\tan(\alpha) & \text{, for } r'_1 \le r'_c < r'_3 \text{ and } \alpha > 0 \\ c'_3 + \dfrac{r'_c - r'_3}{\tan(\alpha)} & \text{, for } r'_3 \le r'_c \le r'_4 \text{ and } \alpha > 0 \\ c'_1 - (r'_c - r'_1)\tan(\alpha) & \text{, for } r'_1 \le r'_c < r'_3 \text{ and } \alpha < 0 \\ c'_1 - \dfrac{r'_1 - r'_c}{\tan(\alpha)} & \text{, for } r'_2 \le r'_c < r'_1 \text{ and } \alpha < 0 \end{cases} \tag{2-6}$$

where

c_s is the starting column for the current row r'_c
α is the average skew angle
r'_1, c'_1, etc., are the box corner coordinates given in Equations 2-5a,b.

$$c_e = \begin{cases} c'_1 + \dfrac{r'_c - r'_1}{\tan(\alpha)} & \text{, for } r'_1 \le r'_c < r'_2 \text{ and } \alpha > 0 \\ c'_1 + W'_p\cos(\alpha) - (r'_c - r'_2)\tan(\alpha) & \text{, for } r'_2 \le r'_c < r'_4 \text{ and } \alpha < 0 \\ & \text{ or } r'_2 \le r'_c \le r'_4 \text{ and } \alpha > 0 \\ c'_1 - (r'_c - r'_1)\tan(\alpha) - \left(\dfrac{A'_p - \dfrac{(r'_c - r'_1)}{\cos(\alpha)}}{\sin(\alpha)} \right) & \text{, for } r'_4 \le r'_c < r'_3 \text{ and } \alpha < 0 \end{cases} \tag{2-7}$$

where

c_e is the ending column for the current row r'_c.
r'_1, c'_1, etc., are the box corner coordinates given in Equations 2-5a,b

$$W'_p = \frac{0.8 W_p H_{ppi}}{25.4}$$

$$A'_p = \frac{0.8 A_p V_{ppi}}{25.4}$$

W'_p, A'_p are the width and height, respectively, of the measurement box interior to the patch or pattern on the target, in mm
W_p, A_p are the width and height, respectively, for the whole patch or pattern on the target, in mm.

2.5 COMPUTING GRAY LEVELS OF DENSITY PATCHES

Once the measurement boxes for each of the 14 density patches in the image are located as described in the previous section, the average gray level of each patch is computed.

The gray values corresponding to all pixels within the measurement box of a given density patch image are used to construct a gray level histogram for that density patch. This histogram is used to identify and delete the 16 percent highest values and 16 percent lowest values. The mean of the remaining values, which is a trimmed mean (Barnett and Lewis, 1984), is computed via Equation 2-8. Using a trimmed mean for each of the 14 density patches removes outliers that may be due to dust, scratches, or other blemishes on the target. Since the box for the density patches measures approximately 8 x 9.2 mm on the M-13-60-1X and M-15-60 targets, then after deletion of the 16 percent histogram tails there are still approximately 19,000 samples left (assuming 500 ppi scanning), from which an excellent estimate of the population mean can be computed.

$$g_i = \frac{\sum_{k=0}^{255} k n_k}{\sum_{k=0}^{255} n_k} \qquad (2\text{-}8)$$

where,

g_i is the mean gray level of the ith image density patch
k is the histogram bin
n_k is the number of pixels in the kth histogram bin

Once every density patch's mean gray level has been computed, a dynamic range check is performed to ensure that all patches have a unique value (except for the four corner patches which have nominally the same reflectance on the target). A mean gray level of a given patch is considered unique if it is at least one gray level away from any other density patch mean gray level. If two or more of the mean gray levels are less than one gray level apart, a dynamic range problem is considered to have occurred in the scanner and this is reported in the program's output in a problem report (see Section 3.4.1). After the dynamic range check is complete, the program constructs a calibration curve from the density patches.

2.6 CONSTRUCTING THE CALIBRATION CURVE

The mean gray levels of the 14 density patches on the image are used together with the corresponding target reflectances of the patches to compute a linear least squares regression calibration curve, for two purposes. One purpose is to measure the linearity of the imaging device. The other purpose is to use the best linear fit line to convert image sine wave gray levels to their equivalent values in what is termed "target space", where the sine wave modulation values are actually computed. The dual purpose of the conversion of image gray levels to equivalent values in target space is to: (1) take out any differences between the lighting/detection geometry of the imaging device and the lighting/detection geometry of the microdensitometer used by the target manufacturer to measure the target sine wave modulations, and (2) to normalize-out the effects of variable contrast settings in a scanner.

Each sine wave target comes with a target data sheet containing, among other data, the manufacturer-measured density for each density patch on the target. This data is stored in the input data file to the MTF program (see Section 3.2.1). The program converts the target density (D) to target reflectance (R) using the standard photographic relation given in Equation 2-9.

$$R = 10^{-D} \tag{2-9}$$

Section 2.5 described the computation of the mean gray level for each density patch in the image. Each of these mean gray levels is paired with the corresponding target patch reflectance value. A standard least squares linear regression (Weisberg, 1980) is then performed on the set of 14 gray level, reflectance pairs, by determining the slope (m) and intercept (b), defined in Equation 2-10. Note that the target reflectance values (R) are treated as the independent variable and the computed mean gray levels in the image (g) are the dependent variable. [In the case of using a film target such as the "M-6" target given in Table 2-1, target reflectance implicitly becomes target transmission in Equations 2-9 and 2-10, with no change to the computer program itself.]

$$g = mR + b \tag{2-10}$$

where

$$m = \frac{\sum_{i=1}^{n} R_i g_i - n\left(\bar{R}\right)\left(\bar{g}\right)}{\sum_{i=1}^{n} R_i^2 - n\left(\bar{R}\right)^2}$$

$$b = \bar{g} - m\bar{R}$$

$$\bar{R} = \frac{\sum_{i=1}^{n} R_i}{n}$$

$$\bar{g} = \frac{\sum_{i=1}^{n} g_i}{n}$$

n is the number of density patches in the sine wave target
R_i is the reflectance of the ith patch on the target
g_i is the mean gray level of the ith patch on the image

As part of the procedure to compute the MTF, the gray levels of the peaks and valleys in the image sine patterns are converted to their corresponding values in target reflectance space by utilizing the inversion of Equation 2-10. Referring to Equation 2-10, letting s denote the measured gray level of the sine peak or valley (substituting for g), letting R' denote the corresponding reflectance value of the sine peak or valley in target space, and inverting, results in:

$$R' = \frac{s - b}{m} \tag{2-11}$$

As part of the linear regression computations, the coefficient of correlation of the regression, ρ, is also calculated:

$$\rho = \sqrt{\frac{b\sum_{i=1}^{n} g_i + m\sum_{i=1}^{n} x_i y_i - n(\bar{g})^2}{\sum_{i=1}^{n} y_i^2 - n(\bar{g})^2}} \qquad (2\text{-}12)$$

If the MTF of a printer is being evaluated, which is signified to the program by invoking the **-p** command line option (see section 3.3.2), then image sine wave peaks and valleys are either converted to their corresponding target space reflectance values by using the linear regression curve generated from all the density patches, or by using a piecewise linear curve. Specifically, if the linear regression does not yield a sufficiently linear result[4], i.e., if $\rho < 0.98$, then each peak or valley is converted to target space by computing the equation of the local straight line connecting the two density patches that bracket the given peak or valley and interpolating, as illustrated in Figure 2-4.

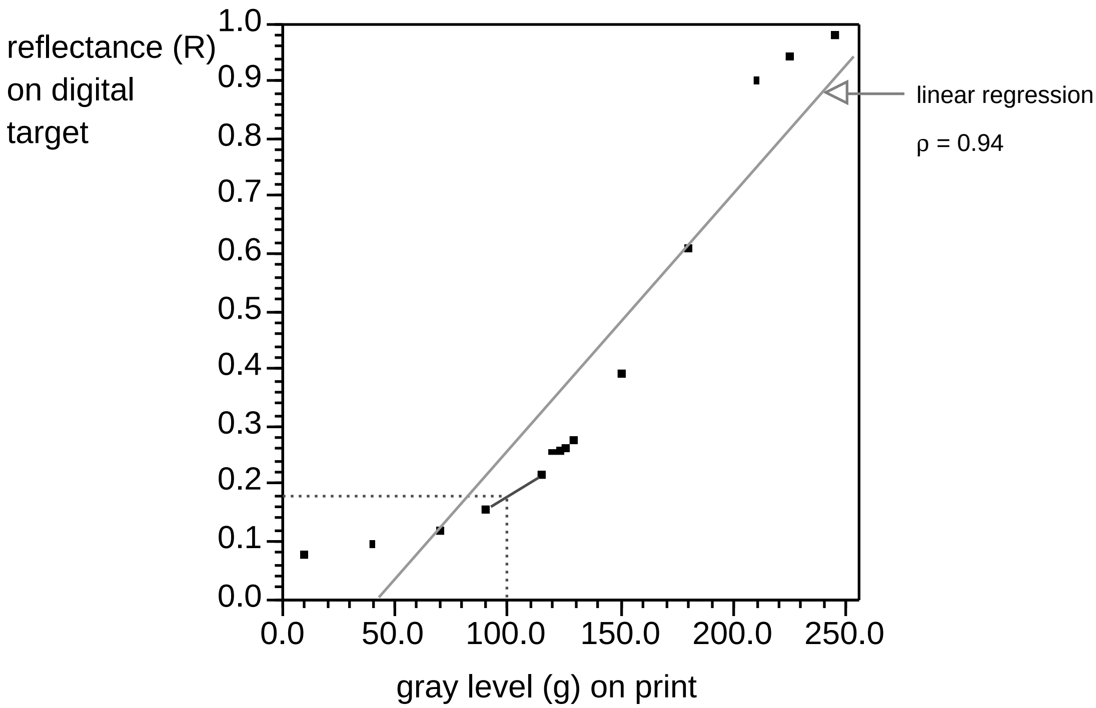


Figure 2-4. Illustration of a Nonlinear Printer Response
(print gray level 100 converted to target space reflectance 0.18 by generating local straight line)

[4] The ρ=0.98 breakpoint between use of the linear regression and use of the piecewise linear curve can be changed by changing the number in the following line of code in the MTF.h module:
#define CORR_LOWER_LIMIT 0.98

The following procedure is used to compute the reflectance on the target, R, corresponding to the sine peak or valley gray level on the image, g, by using local straight line interpolation[5]. First let g_0 and g_1 be the print gray levels of the two density patches that bracket the sine gray level g. Let R_0 and R_1 be the corresponding target density patch reflectance values. Then R, as determined from the equation of a straight line, is

$$R = \frac{(R_1 - R_0)}{(g_1 - g_0)} g + \frac{(g_1 R_0 - g_0 R_1)}{(g_1 - g_0)} \tag{2-13}$$

2.7 LOCATING SINE WAVE PEAKS, VALLEYS, AND COMPUTING MODULATION

In order to decrease the effects of noise in the sine pattern image prior to analysis, it would be advantageous to average corresponding pixels in the direction perpendicular to the sinusoidal variation. If the skew angle were known to be zero, then corresponding pixels across the entire height of the measurement box in the sine pattern could be averaged; for example, approximately 180 rows could be averaged for a scanner operating at 500 pixels/inch. As the magnitude of the skew angle increases, however, the number of rows that can be safely averaged rapidly decreases. This is so because there is an increasingly larger offset between the relative locations within the sine wave period of corresponding pixels from different rows, due to the tilt caused by the skewed image. This is illustrated in Figure 2-5, which depicts the pixels along a single scanner column and across 13 scanner rows, overlaid on a sine wave that is being scanned at a small skew angle with respect to the scanner column, row orientation. In this example, the skew angle is 3.5º and the frequency is 27 percent of the Nyquist frequency. If one were to average the pixels across all 13 rows, then it is clear that pixels representing different parts of the sine wave period would be averaged, which would falsely lower the resulting computed average modulation value.

---

[5] We first tried a second-order Lagrange interpolation polynomial over every three data points, and least squares smoothing polynomials of various orders over all data points, but these sometimes gave erratic results. Although the choice of adjacent point-to-adjacent point straight line fits ensures stability, a smoother, equally stable result from end point to end point, which is also more representative of the underlying data, could potentially be achieved. For example, we are investigating whether printer responses commonly exhibit an 'S' shape, for which closed form equations are known and a least squares curve fit could be applied.

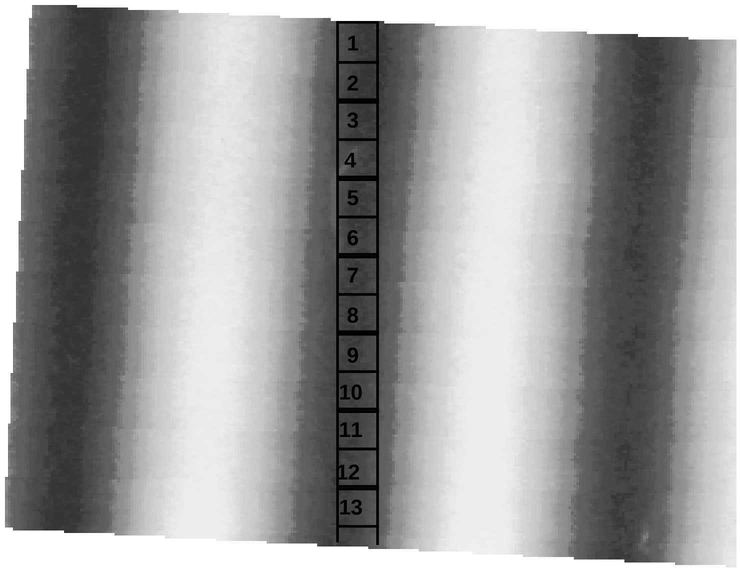


Figure 2-5. Instantaneous Location of One Column of Scanner Pixels Relative to a Skewed Sine Wave

The reduction in the MTF, due to a skew angle between a scanner detector array of pixels and a sine wave being scanned, can be derived by adapting a published formula (Jones, 1965) to the problem at hand, which results in Equation 2-14:

$$MTF_{reduction} = \frac{\sin(\pi L \alpha f)}{\pi L \alpha f} \tag{2-14}$$

where,

$L = \dfrac{25.4n}{ppi}$

n = number of pixels to be averaged

ppi = scanner pixels per inch

f = spatial frequency in cy / mm

α = skew angle in radians

Using Equation 2-14 it can be shown that errors in the scanner MTF of less than one percent occur, due to skew angle, when the following combinations of maximum parameter values are used:

n = 6 pixels, α = 0.02618 radians (skew = 1.5º), and ppi = 500, or,
n = 3 pixels, α = 0.05236 radians (skew = 3.0º), and ppi = 500.

Clearly, the effective signal to noise ratio is increased by averaging across as many rows as possible, resulting in a more stable (and more accurate) MTF. The balance between the desire to average over many rows and the desire to maintain less than a one percent error in MTF due to skew angle, is met by the skew angle - number of rows combinations given in Table 2-3, which is coded into the MTF program.

Table 2-3. Sine Pattern Row Averaging to Decrease Noise

Skew Angle Magnitude	Number of Sine Pattern Rows Averaged
$\lvert\alpha\rvert \le 1.5^o$	6
$1.5^o < \lvert\alpha\rvert \le 3.0^o$	3
$\lvert\alpha\rvert > 3.0^o$	1

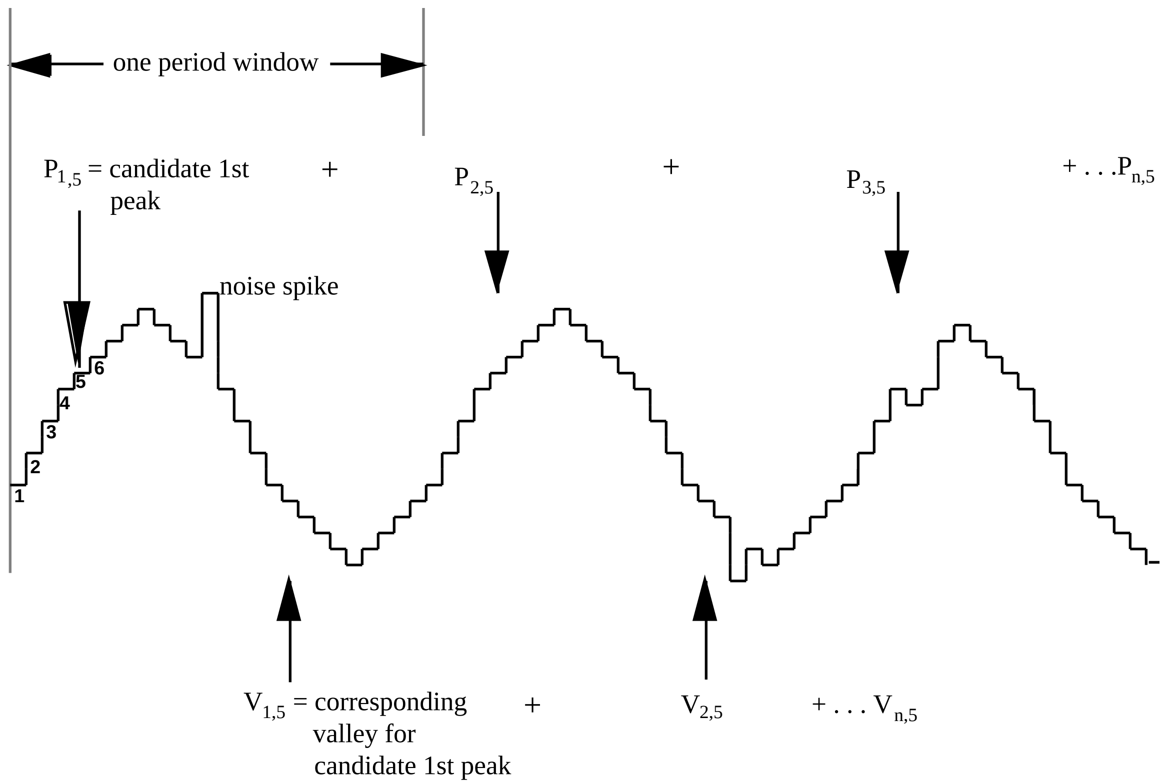
For most of the analysis in the multiple row average cases, only the integer sums of the corresponding pixels' gray levels from the rows are utilized in computations. The actual mean gray levels are only needed when the peaks and valleys are identified, whereupon the means are calculated and converted to target reflectance space for the modulation computation. Also, throughout this section, the term "scan line" refers to either the individual scanner rows within the measurement box area (when $|skew| > 3.0^o$), or to the average of multiple rows (when $|skew| \le 3.0^o$).

The modulation of an image sine pattern is based on the individual modulations computed for each sine period in each scan line in the measurement box area. The sine wave peaks and valleys, which are used to compute modulation, are found by working left to right along a scan line. Each peak (except for the end peaks) results in two modulations, one using the valley ahead of (to the right of) the peak, and one using the valley behind (to the left of) the peak.

In an unaliased target image, the sine wave peaks and valleys will ideally occur with a constant periodicity. The first step in locating a peak is to find the first (left-most) peak on a scan line. Successive peaks will be an integer multiple of periods to the right of the first peak; successive valleys will be an integer multiple of one half periods from immediately preceding peaks. The period and half period are computed as a real (i.e., non-integer) number of pixels; e.g., 15.8 and 7.9 respectively. The period computation is based on the ppi resolution of the image and the frequency of the sine pattern, taking skew angle into account.

Regardless of the initial phase between the target and the scanner detector array, the first peak will always fall within a one period window on the left end of the scan line. Because noise may obscure a peak, however, the first peak is determined using an average over the entire scan line. The aforementioned one period window is divided into bins that are one pixel in size[6]. For each bin the program determines the sum of all pixels on the scan line that are an integer number of periods from the bin (i.e., 0,1,2,... periods away). A similar sum is done for all pixels that are one-half period multiples away, which corresponds to the valleys of the trial peak. The bin with the largest average difference between the sum of peaks and the sum of valleys is determined to be the first peak. Figure 2-6 illustrates how the windowing and summing are accomplished.

[6] The program can also use sub-pixel bins, but this refinement is obscured by the error latitude built into the overall peak finding process. Although sub-pixel binning works (first peaks are returned as real number, fractional indices), its use comes at a computational time price with almost no effect on the result. Therefore, only whole pixel bins are used to determine first peaks.



The one period window lies at the left end of the sine pattern being analyzed. The $P_{1,5}$ shown is the 5th candidate location for the 1st peak. Successive P's are one period apart. $V_{1,5}$ is a half period away from $P_{1,5}$ and is the candidate valley corresponding to $P_{1,5}$. Sucessive V's are one period apart. The average peak, valley difference is computed from:

$$\frac{\sum_{i=1}^{n} P_{i,5} - \sum_{i=1}^{n} V_{i,5}}{n}$$

$P_{1,5}$ is then incremented to the next pixel to create $P_{1,6}$ and the average peak, valley difference is again computed. This process is repeated for the number of pixels covering one period. The candidate peak which results in the largest value for the average peak, valley difference is considered to be the true first peak on the scan line.

If the first peak were to be selected based solely on samples in the single (left-most) one period window, then the noise spike shown above would falsely be selected as the first peak. The technique described minimizes the effect of noise spikes by averaging over many periods.

Figure 2-6. Locating the First Peak on a Sine Pattern Scan Line

Successive peaks and valleys on a scan line are based on the first peak and the pixels per period (and half period) for the sine patch being analyzed. The peak finder traverses a scan line from peak to peak in two passes. On the first pass modulations are computed for peak-valley pairs using valleys that follow peaks. On the second pass, the modulations are computed using valleys that precede the peaks. All modulations are stored in an array for later analysis.

The number of pixels in one period of a sine pattern is determined from the manufacturer-supplied target frequency (f, in cy/mm), the calculated scanner resolution (ppi), and the calculated skew angle (α), as given in Equation 2-15.

$$\text{number of pixels in period} = \frac{\text{ppi}}{25.4(f)\cos(\alpha)} \qquad (2\text{-}15)$$

In Equation 2-15, it is seen that the number of pixels in a period is a function of the skew angle. This is so because, as the magnitude of the skew angle increases, it takes more pixels in a row to cover the period; i.e., the effective period becomes longer and therefore the effective spatial frequency, which equals (f)cos(α), becomes lower. Equation 2-15 also implies that there will almost never be an exact whole number (integer number) of pixels in a period or half-period. To accommodate this, the program uses a real index in traversing a scan line. A pixel is selected based on the closest integer value to the index. For a sine pattern with a period of say, 12.2 pixels, the program more accurately chooses peaks at n, n+12, n+24, n+37 and n+49 instead of n, n+12, n+24, n+36, n+48, where n is the integer location of the first peak.

Inaccuracies in making the target size measurements (used in calculating ppi) or in locating the image corners (used in calculating ppi and skew angle) will be reflected in the calculated number of pixels in a sine period. This error will accumulate as the peak-finder traverses a scan line. A second, smaller error will occur for the peak to valley distance (half-period calculation). In order to compensate for accumulated inaccuracies in the length of a sine wave period, the peak-finder allows “wiggle room” around the peaks to determine the best local maximum-minimum pairing. The size of the “wiggle window” varies with the frequency, but is an integer approximately equal to ten percent of the period (in pixels) for lower frequencies. For higher frequencies, the window is relatively larger, but never more than a half-period in size. A window is centered on a predicted peak in a peak-valley pairing. For low frequencies the windows are divided into one pixel bins, and into sub-pixel bins for the higher frequencies. Sub-pixel bins are rounded to the nearest whole pixel before reading a gray level. Each sub-pixel bin in the peak window is paired with a sub-pixel bin one-half period away. The sub-pixel granularity of the bins causes some repeated computation, but no ill effects. The advantage is that the ± error window remains centered on the predicted peaks and valleys (real number indices). In order to be rigorous, the program also compensates for half-period inaccuracies by allowing a small window centered at a predicted valley. This window is only one percent of the period in size, but can make a difference when a predicted valley lies close to a pixel boundary.

The image modulation for a given sine pattern is computed for each peak-valley combination found in each sine period and in each scan line in the pattern. Any peak which has a gray level greater than: (255 + gray patch F average value) / 2, or any valley which has a gray level less than: (gray patch I average value) / 2, is deleted from further consideration. Although the impetus for this is to accommodate segment scanned sine targets, as discussed in Appendix D, it is also a useful technique for pruning outliers due to noise in unsegmented sine target scans. That is, due to the density (reflectance) ranges of the target as designed and manufactured, scanner sine wave peaks and valleys should be within the range of the whitest (patch F) to blackest (patch I) gray level patches. Allowing peak and valley values slightly beyond the white and black gray patch values ensures that edge enhanced or high-pass filtered sine images are correctly processed.

Each scan line in a sine pattern contains multiple sine wave periods. For example, the measurement box in the 10 cy/mm sine pattern (Nyquist frequency) of the M-13-60-1X target contains 40 periods and the measurement box in the 4 cy/mm sine pattern contains 16 periods (assuming the box is sized using the 10% safety margin). For this case, since the height of the measurement box is approximately 9.2 mm, there are approximately 180 individual rows in the sine pattern that are used (assuming 500 ppi). Considering the number of periods, number of rows, and six row averaging for the case when $|skew| \leq 1.5^o$, then for this case there can be 2370 sample modulation values calculated for the 10 cy/mm sine pattern, and 930 sample modulation values calculated for the 4 cy/mm sine pattern.

To compute the sample image modulations, the gray levels corresponding to all peaks and valleys along each scan line are first converted to their target space values by using Equation 2-11 or Equation 2-13. Row-averaged gray levels are used if the skew angle magnitude is less than or equal to 3.0^o. The sample image modulations are then computed via Equation 2-16, pairing peaks and valleys from the <u>same</u> sine period:

$$M_{image} = \frac{R'_p - R'_v}{R'_p + R'_v} \qquad (2\text{-}16)$$

where

M_{image} is the image modulation for a peak-valley pair
R'_p is the value of the peak in target space (G'_p for printer assessment)
R'_v is the value of the valley in target space (G'_v for printer assessment)

The scanner MTF at a given spatial frequency is then computed in the program from the image modulation and target modulation, as:

$$M_{scanner} = \frac{M_{image}}{M_{target}} \qquad (2\text{-}17)$$

Note that another definition of $MTF_{scanner}$ sometimes presented in the literature is M_{image}, at any frequency, divided by M_{image} at a very low frequency. However, this definition is inexact since it would normalize-out any existing image degradation due to light flare or veiling glare caused by the scanner. If such degradations exist in the scanner, the MTF normalized by a low frequency will be higher than its true value.

The standard output MTF of the program is computed from the single largest sample image modulation at each frequency. This MTF is indicative of the best output quality of the scanner, in the sense that it closely corresponds to the result that would be obtained if the phase between the target and scanner's detector array was optimized for each sine pattern scanned. With reference to the discussion at the end of Section 1.3 regarding target-scanner phase, an even higher image modulation could be computed by independently selecting the highest peak and lowest valley in a sine pattern, regardless of which sine period or which scan line either was selected from. However, a slow drift in the average value across the scan of a given sine pattern may exist, due either to the target manufacturing process (Lamberts, 1996), or due to scanner variations. This drift anomaly invalidates the combining of a peak from one sine period on one scan line with a valley from a distant sine period on a distant scan line.

In addition to the program's standard MTF output, the program can also be instructed to output the MTF computed from the average of all sample image modulations at each frequency; this MTF is closely related to the overall average output quality of the scanner.

2.8 DETECTION OF ALIASING

Aliasing occurs when undersampling. Aliasing exhibits itself as a change in sine wave frequency and/or generates sine wave harmonics, and it can result in spurious, false imagery (Gonzales and Woods, 1992, pp.112–119). Aliasing will ordinarily occur at frequencies above the scanner's Nyquist frequency, assuming the target being scanned has high frequency spectral content. The scanner's Nyquist frequency is equal to one half of the scanner's ppi resolution. Appendix B presents a further discussion of the Nyquist frequency and its ramifications.

There are two forms of aliasing of concern when determining the MTF of an image scanner: aliasing due to upscaling and aliasing due to nonuniform decimation. Although arising from different sources, both forms of aliasing can degrade a scanned image (Braunegg, Forkert, and Nill, 1995). The concern here regards significant aliasing at frequencies below the scanner's Nyquist frequency, which should not occur.

Aliasing due to upscaling occurs when a frequency does not exceed a scanner’s output resolution but does exceed the scanner’s native resolution. For example, a scanner with a true resolution of 300 ppi which uses "pixel interpolation" to achieve a (pseudo) 500 ppi resolution, will produce aliasing down to about 6 cy/mm, well below the 500 ppi Nyquist frequency of 9.84 cy/mm. As another example, a true 500 ppi scanner that exhibits uncompensated linear image motion with a magnitude of 3 pixel widths, will produce aliasing down to about 7 cy/mm. Because of the problems low frequency aliasing can cause in imagery, and because a significant amount of aliasing should not occur below the Nyquist frequency, the program alerts the user to the problem by applying an aliasing-due-to-upscaling detection algorithm to the sine wave image and reporting the results. The algorithm is applied from 5 cy/mm up to and including the computed Nyquist frequency, as summarized in Table 2-4.

Aliasing due to nonuniform decimation occurs when: a) a scanner’s native resolution exceeds its final output resolution, but is not an even multiple of the output resolution, and b) nonuniform decimation, which is an uneven sampling method, was used to downsample the image to the final output resolution. For example, uniform decimation can be used to downsample the output of a scanner with a true resolution of 1000 ppi to obtain a 500 ppi final output resolution (because the true resolution is an even multiple of the final output resolution). The decimation in this case drops every other row and column, which is a uniform process. On the other hand, if the output of a 600 ppi (true resolution) scanner is to be decimated to obtain a 500 ppi final output resolution, nonuniform decimation must be used (i.e., every sixth row and column must be dropped). The uneven sampling of the original image due to nonuniform decimation can result in degraded imagery. Note that other methods of downsampling such an image, using smooth interpolation processes, can yield satisfactory results (Braunegg, Forkert, and Nill, 1995, Section 4). The MTF program applies an aliasing-due-to-nonuniform-decimation detection algorithm to the sine wave image and reports the results. This algorithm is also applied from 5 cy/mm up to the computed Nyquist frequency (see Table 2-4).

Table 2-4. Aliasing Detection Performed by Program

Frequency	**Aliasing due to Upscaling**	**Aliasing due to Nonuniform Decimation**
f <5 cy/mm		
5 cy/mm ≤ f < Nyquist	X	X
f ≅ Nyquist	X	
f > Nyquist		

Aliasing can sometimes be discerned visually and judged qualitatively by viewing the scanned sine wave target on a softcopy display. For a more accurate, higher level of detection and quantification, however, Fourier transformation is employed in the program. Since each sine wave pattern on the target represents a single frequency, this frequency should appear as a strong peak in a known frequency location in the Fourier frequency spectrum of any row (or row average) of the imaged sine pattern. If the peak occurs at an unexpected Fourier frequency, then there is a very high probability that the image sine pattern is aliased due to upscaling. If there is a strong secondary frequency peak in addition to the primary peak at the correct sine wave frequency, then there is a very high probability that the image sine pattern is aliased due to nonuniform decimation. The number of cases tested for aliasing at a given frequency sine pattern is as follows: every 24th row if |skew| > 3.0º, every 8th scan line if 1.5º < |skew| ≤ 3.0º (where one scan line is a three row average), or every 4th scan line if |skew| ≤ 1.5º (where one scan line is a six row average). For each test case, the sine wave is tested for aliasing due to upscaling. If aliasing due to upscaling is not detected, the sine wave is then tested for aliasing due to nonuniform decimation. Either type of aliasing is then considered to be present at the tested frequency if it is detected in at least three of the tested cases.

The program computes the magnitude, |H(f)|, of the one-dimensional frequency spectrum, H(f), of a scan line by applying a Discrete Fourier Transform (DFT) to the average-value-removed scan line data, as given in Equations 2-18 and 2-19 (Gonzales and Woods, 1992, pp.85-92).

$$H(f) = \frac{1}{n}\sum_{x=0}^{n-1}\left[h(x) - \overline{h(x)}\right]\exp[-j2\pi fx / n] \qquad (2\text{-}18)$$

$$|H(f)| = \sqrt{H^2(f)_{real} + H^2(f)_{imaginary}} \qquad (2\text{-}19)$$

where

n is the number of pixels along the scan line
h(x) is the set of pixel gray level values on the scan line
$\overline{h(x)}$ is the average value of h(x)
x is the pixel sequence, x = 0, 1, 2, ..., n-1
f is the spatial frequency bin, f = 0, 1, 2, ..., n-1
f corresponds to the real frequencies: 0, Δf, 2Δf, ..., (n-1)Δf
$\Delta f = \dfrac{1}{(n)(\text{pixel width})}$
$j = \sqrt{-1}$

The scan line is first trimmed so that it will contain a nearly integral number of periods of the sine wave represented by the pattern. Examples of this trimming process are given in Table 2-5. The average value of the scan line is then subtracted from each data value to increase the effective signal-to-noise ratio. With the spatial increment (x) and normalized spatial frequency (f) as defined in Equation 2-18, the DFT produces a bin for each whole number frequency from zero frequency up to and including the Nyquist frequency (the frequency corresponding to two pixels per period)[7].

Table 2-5. Typical Regions of Sine Wave Patterns Used for Aliasing Detection

Patch Frequency (cy/mm)	**Periods in Bordered Patch**	**Whole Periods in Bordered Patch**	**Pixels to Approximate All Whole Periods in Bordered Patch**
10	39.20	39	77
8	31.36	31	76
6	23.52	23	75
5	19.6	19	77

Assumes:
- 4.9 mm nominal patch width
- 10% border removed from patch (resulting in a 3.92 mm bordered patch width)
- 500 ppi resolution

The sine pattern image is not aliased due to upscaling if either a) the strongest peak occurs at the bin representing the number of periods of the computed scan line, or b) the peak occurs in the bin to either side of this predicted bin (because there might not be an exactly integral number of sine wave periods in the scan line). For example, suppose the scan line is 78 pixels long and the computed period is 11.99 pixels. This scan line, which has 6.51 periods in it, is trimmed to exactly 6 periods, containing 71.94 pixels, which is then approximated by 72 pixels. This is close enough to an exact integer multiple of a period (within 0.1 pixel) to avoid zero padding in this example. Because there are six periods of the sine wave in the trimmed scan line, the largest magnitude bin in the Fourier spectrum should occur at bin six, where bin zero is the zero frequency bin. If the sample contained only a single sine wave period then the peak would be at bin one, etc. Note that it is also acceptable for the largest magnitude bin in this example to occur at bin five or bin seven, to allow for the effects of not having an exactly integral number of periods in the scan line. A plot of the DFT of a scanned sine wave that exhibits detectable aliasing due to upscaling is given in Figure 2-7.

[7] Theoretically, zero padding the trimmed, average-value-subtracted scan line could also be performed to ensure that the data sample length input to the DFT is close to an exact number of periods. However, experimental results on pure sine waves indicated that zero padding can adversely affect the robustness of the alias detection logic while not adding any practical benefit. Zero padding is therefore not utilized.

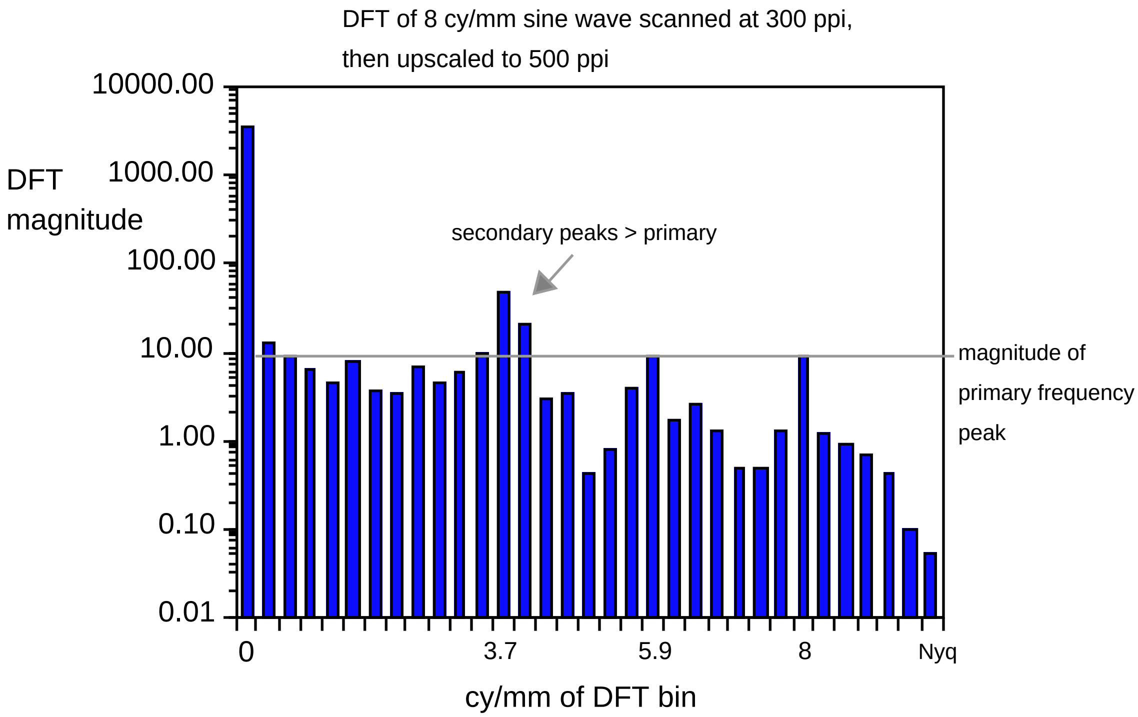


Figure 2-7. DFT of Sine Wave that Exhibits Aliasing Due to Up-Scaling

The 10 cy/mm sine pattern is treated as the Nyquist frequency for 500 ppi IAFIS scanners, even though the actual Nyquist frequency is slightly less than 10 cy/mm. That is, the actual Nyquist frequency ranges from 9.74 cy/mm @ 495 ppi, to 9.94 cy/mm @ 505 ppi for 500 ppi IAFIS scanners. Because the 10 cy/mm is beyond the Nyquist frequency, the strongest peak should occur beyond the last bin. However, bins beyond the last bin actually appear to be “folded over” into the existing bins. For example, if the last bin is number 24, but the peak for the 10 cy/mm sine wave should occur in bin 26, that peak will actually be folded over and appear in bin 22. In this case, no aliasing due to upscaling occurs if the strongest peak appears in bin 21, 22, or 23.

If the strongest peak occurs in the correct location, the bins are then examined to determine if aliasing due to nonuniform decimation is present. The second strongest peak is found and the magnitude of this peak is compared to the strongest peak. If the magnitude of the secondary peak is greater than 0.27 times the magnitude of the primary peak, aliasing due to nonuniform decimation is detected (e.g., see Figure 2-8). This test is not performed if the sine wave frequency is beyond the Nyquist frequency because the folded frequencies make it difficult to determine the true magnitude of the bins. Also, the search for a secondary peak ignores bin zero and bin one, because bin zero corresponds to the DC component of the signal and bin one may contain “leakage” from bin zero or may reflect a low-frequency component due to effects such as lighting variation. The 0.27 threshold value has been empirically determined, based on test results of 40 sine images obtained from 12 different brands/models of scanners, 10 of which were known to be decimated images, to be the best compromise value for detecting nonuniform decimation when it actually occurs, while not detecting it when it does not occur[8].

[8] If indicated by further empirical evidence, the decimation detection threshold value can be adjusted by changing the number in the following line of code in the MTF.h module:
#define MAX_SECONDARY_TO_PRIMARY_RATIO 0.27

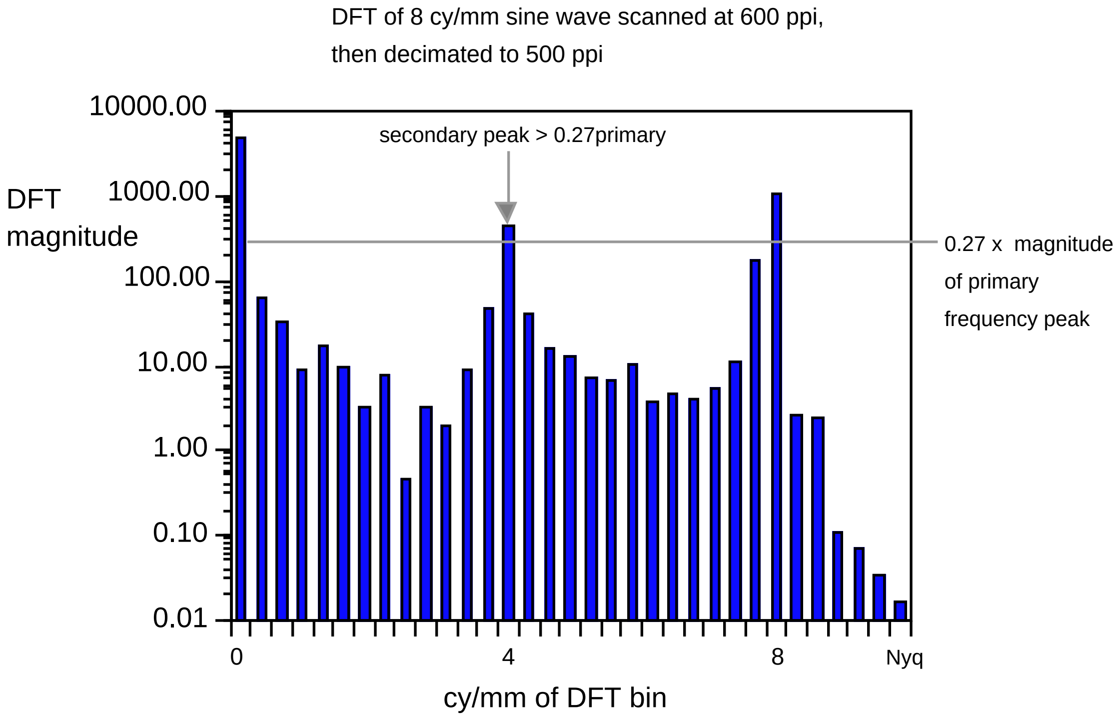


Figure 2-8. DFT of Sine Wave that Exhibits Aliasing Due to Non-Uniform Decimation

In general, all of the bins in the spectrum will be non-zero due to noise from target blemishes, scanner electronics, quantization error, etc. However, the largest magnitude bin will be where predicted, i.e., within plus or minus one bin of the bin corresponding to the sine wave's fundamental frequency, unless the image exhibits significant aliasing of the type usually associated with upscaling. We use the term "usually associated" here because other scanner problems may also produce strong secondary peaks in the DFT which the program will report as "aliasing due to upscaling". For example, significant image jitter due to an imperfect mechanical scanning mechanism can produce large secondary peaks in the DFT much like those due to upscaling, with similar degrading effects on the image quality. As for downsampling, uniform downsampling by decimation will not produce secondary peaks in the DFT and will produce good image quality; nonuniform downsampling by any of a number of different good interpolation techniques will produce some secondary peaks, but they are not pronounced enough to cause significant image degradation (Braunegg, Forkert, and Nill, 1995); and, finally, nonuniform downsampling via decimation will produce strong secondary peaks which affect the image quality and are
detected by the program. The program's aliasing detection logic is summarized in Table 2-6.

Table 2-6. Aliasing Detection Logic for a Sine Pattern

For each scan line to be tested in the sine pattern
    Perform DFT
    Find primary peak
    Find secondary peak (ignoring bin 0 and bin 1)

    If the fundamental frequency is less than the Nyquist frequency
        If the primary peak is not within ±1 of the fundamental frequency bin
            Record aliasing due to upscaling
            Proceed to next scan line
    Else If the primary peak is not within ±1 of the folded fundamental frequency bin
            Record aliasing due to upscaling
            Proceed to next scan line

    If the fundamental frequency is less than the Nyquist frequency **and** the magnitude of the secondary peak is greater than 0.27 times the magnitude of the primary peak
        Record aliasing due to nonuniform decimation
        Proceed to next scan line
    Else
        Proceed to next scan line
End For Loop

If more than three records of aliasing due to upscaling
    Aliasing due to upscaling occurred
If more than three records of aliasing due to nonuniform decimation
    Aliasing due to nonuniform decimation occurred

If aliasing due to upscaling occurred and aliasing due to nonuniform decimation occurred
    Report "aliasing" for this sine pattern
Else If aliasing due to upscaling occurred
        Report "aliasing due to upscaling" for this sine pattern
Else If aliasing due to nonuniform decimation occurred
        Report "aliasing due to nonuniform decimation" for this sine pattern
Else
    No aliasing detected for this sine pattern

SECTION 3

PROGRAM OPERATION

3.1 IMAGE DISPLAY

After obtaining the output digital image from the scanner and prior to running the MTF program, the user must display the unrotated image. Certain information needed to run the program is obtained from the displayed image in conjunction with a display column/row indicator control; namely, whether the image is vertical or horizontal, and the inner corner column, row coordinates of the upper left, upper right, and lower left gray patches, as illustrated in Figure 2-1. The program assumes that the coordinates of the upper left corner of the overall image (i.e., the target plus background) is at column 0, row 0. That is, the display cursor placed at the upper left corner of the overall image should read 0,0, not 1,1. The program allows input of fractional (floating point) row and column coordinates for the displayed patch corner locations. In some cases this may increase the accuracy of the ppi computation by up to 1.0 ppi along the target length direction, and up to 0.5 ppi along target width direction (for M-13-60-1X and M-15-60 targets).

Many softcopy displays will not have sufficient resolution to display the entire image all at once, at full image resolution, e.g., an image of 1200 x 1500 pixel size cannot be fully displayed at 1:1 scale on a 1024 x 1280 pixel display. In this case, the user must either have the enabling software to roam through the full resolution image to locate the three corners, or if a scaled-down version is presented to fit the entire image onto the display, the corner coordinate column, row values must be appropriately scaled up to their true values on the full resolution image. Concerning the latter option, note that accurate column, row corner location is more difficult with an image displayed at reduced scale and is not recommended. Finally, simply viewing the displayed image can indicate any obvious problems that would suggest a need to re-scan the target (e.g., significant artifacts, gray level saturation, large skew angle, obvious aliasing, image streaking, etc.).

3.2 INPUT FILES

3.2.1 Target Data Input File

Each hardcopy sine wave target will have different density patch values and sine wave modulations, and may also differ slightly in dimensions, all due to manufacturing variations (exception: A3 target properties are invariant because it is a digital target). In order to accommodate these differences, the program reads dimensional and calibration data associated with the target from an input data file. <u>This input data file must contain the manufacturer-supplied gray patch density values and sine modulation values associated with the specific serial-numbered target in use.</u> On the other hand, the dimensional data that MITRE has measured[9] for the targets listed in Table 2-1, which is also a part of the input data file, has been found to be stable (i.e., sufficiently invariant) for any one target model, across all serial numbers of that target model. The dimensional data for the targets listed in Table 2-1 may therefore be considered to be invariant from serial number to serial number of a given target model. One caveat, however: the target manufacturer may at any time, without notice, change the target dimensions. If there is any question about the correctness

[9] To give an indication of the dimensional measurement accuracy required, distances greater than one inch were determined with a magnifier and ruler having 1 mm increments; shorter distances were determined with a 10X magnifier having a measuring reticle eyepiece with 0.1 mm increments.

of a particular set of dimensional data, the scanned sine image should be run through the MTF program with the **-d** option, and the subsequent diagnostic output image should be inspected. Appendix C contains the data files for all of the sine wave targets, and for the 15-bar target listed in Table 2-1. Figure C-1 illustrates the target dimensional data that is utilized in the data files.

The target data file is human readable and provides for comments as well as data. Comments can appear throughout the file, are delimited by a leading '#' character, and can occupy a single line or follow a data entry on the same line. Data entries must appear in a specific order in the file; there are no "keywords" to distinguish data items. Additionally, the target dimensions must be measured with the target positioned in the program's standard orientation as shown in Figure C-1. Following here, is a line-by-line description of the data components of the input data file.

Although the target data file can begin with comment lines, the first data entry must be the target serial number. This can be a string of up to 80 printable characters, <u>with no blanks</u>.

The second data entry is the total number of density patches plus sine patterns on the target and must be an integer.

The third data entry is the target width in millimeters. This, and the fourth data entry, the target height in mm, are real numbers. Referring to Figure B-1, it is important that these measurements are for the width and height of the target only, i.e., <u>not</u> including any of the black or white border that surrounds the target.

The remaining data entries in the file are for the density patches and sine patterns. The entries for a given patch or pattern are grouped together. The data must be in order and consists of seven entries for each density patch and eight entries for each sine pattern. Most of the entries for a density patch are of the same kind as for a sine pattern.

The first entry for a patch or pattern is the label. This is a string of up to eight characters. The density patches are labeled "A" to "G" along the top row, from left to right; and are labeled "H" to "N" along the bottom row, from right to left. <u>Note that this labeling sequence may differ from the density patch labeling supplied with the target by the manufacturer; the program expects the labeling sequence described here</u>. Sine patterns are labeled "1" to "4", from right to left in the third row from the top; and are labeled "5" to "15", from left to right in the second row from the top. See Figure B-1 for visualization of these locations.

The next entry is either a "d" or an "s" indicating, respectively, a density patch or sine pattern.

The next two entries locate the upper left corner of the density patch or sine pattern. The first of these two entries is the distance in millimeters from the left edge of the target to the left edge of the patch or pattern. The second of these two entries is the distance in millimeters from the top edge of the target to the top of the patch or pattern.

The next two entries are the width and height of the patch or pattern, in millimeters.

For density patches, the last entry is the patch density, which is supplied by the manufacturer with the target. However, note again that the labeling sequence for the density patches provided by the manufacturer may not be the same as that required by the MTF program.

For sine patterns the last two entries are the modulation and the frequency in cy/mm, which are supplied by the manufacturer with the target. The modulation used is the manufacturer's "compensated modulation" value. If the manufacturer only supplies "peak to peak" modulations, then divide these modulations by the microdensitometer MTF as discussed in Section 2.1, and enter the result in the data file**.**

3.2.2 Image Input File

The digital image of the sine wave target that is input to the MTF program can be formatted as either a headerless or fixed-size header "raw" file, or as a Tag Image File Format (TIFF) file. For either format, the digital image must be quantized to eight bits per pixel (256 gray levels per pixel). The user inputs the name of the image file and the program 'discovers' the type of image file.

Raw, Headerless or Raw, Fixed-Size Header Image Format:

This file contains the eight bit per pixel (one byte per pixel) image data, possibly including a fixed-size header at the beginning of the file, and/or including non-pixel trailer bytes at the end of the file. This file must be in raster format, i.e., following the optional header, the first N bytes of the file are the first row of the image, the next N bytes are the second row, etc. The bytes (pixels) of each row must be in display order, i.e., the first byte of the file is the byte of the image that would be in the upper left corner on a display screen (with no rotation of the displayed image), the next byte is the one that would be to the immediate right of the first on the display, etc.

If the program determines that it has a raw file (i.e., the file is not a TIFF file), the user is asked to input the number of columns and number of rows in the image, as integers, e.g., 1350, 965. The user is then asked to input the size of the header, which may be 0. If the program determines that it has a TIFF file, no user inputs are asked for at this stage.

TIFF Image Format:

TIFF files adhere to a standard (TIFF, 1992), although some TIFF reader software can only interpret part of the standard. The MTF program utilizes a set of freeware TIFF reader modules[10], which reads and correctly interprets most of the TIFF standard's "Required

[10] These TIFF software modules are copyrighted, as follows:

"Copyright (c) 1988, 1989, 1990, 1991, 1992 Sam Leffler

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Most recent TIFF code and documentation is available at the Internet site:
http://www.sgi.com/Fun/tiff/tiffv3.4beta018/html/index.html

Fields for Grayscale Images", such as image width, image length, and photometric interpretation (image polarity). Even though the TIFF's grayscale image fields also allow for several types of compression, several bits per pixel options, and more than one sample per pixel, the image read into the MTF program must be uncompressed, have eight bits per pixel, and have one sample per pixel. Other non-required TIFF fields, such as the “Gray Response Curve”, are ignored by the MTF program.

It is possible for the MTF program to seemingly successfully read a TIFF file, while it is in fact misreading the file. For example, if there is a data entry under the TIFF field for "Gray Response Curve", the MTF program will not utilize this information and will therefore incorrectly interpret the image gray level values. In most cases of this type of occurrence, one or more facets of the program output will have abnormal values, such as a low linear regression correlation coefficient, or highly erratic MTF results. If program output results appear to be abnormal and a TIFF image was input, it is suggested that the image be reformatted to "raw" format and re-run. Display of the TIFF image may be helpful but not conclusive in this situation, because the user's display software for TIFF images will most likely not be identical to the TIFF software used in the MTF program.

3.3 USER INTERFACE: PROGRAM OPERATING INSTRUCTIONS

The MTF program is invoked by typing: mtf

Direction for some special case processing can be given to the program by entering additional commands on the same "command line" that **mtf** is typed on, as discussed in Section 3.3.2. The normal operation of the program, however, follows the single typing of **mtf** with program queries and user responses, as discussed in the next section.

3.3.1 Running the Program: Program Queries and User Responses

Once the program is invoked by typing **mtf**, it will display a MITRE logo for a few seconds and then begin to prompt the user for input. Table 3-1 gives the program query as presented to the user on the softcopy display, and examples of valid user responses, both in **bold** type; comments and descriptive information not part of the display are given in *italics*.

Table 3-1. Program Displayed Queries and User Responses

PROGRAM QUERY:	USER RESPONSE (examples):
Enter image filename:	**EXAMPLE.TIF**
Please enter the overall image width and height in pixels:	**959, 1429** *A comma, space or carriage return can separate the integer numbers.*
Please enter the number of image header bytes: *For raw format images only, user inputs number of columns (width) and number of rows (height) in the image and the number of header bytes in the image file.*	**0**
Are these values correct [y/n]?	**y** *(program continues)* **n** *(width, height, and header prompt is repeated)*
For either TIFF or raw image format, the user enters the target data filename and the inner corner coordinate for 3 of the corner gray patches on the image.	
Enter target data filename:	**TGTDATA**
Enter Col, Row for each of 3 gray patch corners: **lower right corner of the UPPER LEFT PATCH:** **lower left corner of UPPER RIGHT PATCH:** **upper right corner of LOWER LEFT PATCH:**	*These may be integer or floating-point:* **240, 222** **722, 227** **238, 1214**
Enter the orientation - Vertical or Horizontal [V/H]: *Orientation of the target is obtained by viewing the displayed image (without rotation). Vertical ("portrait") orientation shows the density patches on the left and right sides, Horizontal ("landscape") orientation shows the density patches along the top and bottom.*	**V**
The program now displays the 3 corner coordinates that were entered and the orientation. The user will be asked to verify these values: **Are these values correct [y/n]?**	**n** *(Program asks for 3 corner coordinates and orientation again.)* **y** *(target image analysis begins)*
From this point on there is no further interaction with the user until the analysis is finished. At that time the user will be queried about continuing: **Process another image [y/n]?**	**n** *(Program terminates.)* **y** *(Program goes back to beginning.)*

3.3.2 Command Line Execution

The MTF program uses a default name, **MTFOUT**, for the standard output file name and the standard output itself is concise. It is possible to create additional output by invoking some command line parameters during program initialization. These command line parameters are presented in Table 3-2 and are described in more detail in Section 3.4.2.

Table 3-2. Command Line Parameters for Additional Output

Command Line Parameter	Explanation
-h	Prints a "help" message about program usage.
-a	Outputs an additional MTF computed from the average sine modulation values, and outputs corresponding standard deviations.
-d	Generates an output image file which is used to verify that the density patches and sine patterns were correctly located by the program. The output image file will be named ***filename*.box**, where *filename* is the first eight characters of the input image file name.
-e	Generates extended data output, including histograms of the high and low values for each density patch and sine pattern.
-p	Computes the MTF of a printer. User will be asked to input the print pixels per inch, which equals the digital target width (or height) in pixels divided by the printed target width (or height) in inches.
-r	Displays data rights notice.
mtf -a -d -e	Except for **-h** and **-r**, the parameters can be used in combination. In the example on the left, the program would output the average modulation MTF, output the ***filename*.box** image file, and output extended data (histogram) results.

3.4 OUTPUT DATA FILES

3.4.1 Standard Output

The program outputs results to both the softcopy display and to a fixed name file called **MTFOUT**. The output filename can only be changed by changing the source code and recompiling[11]. <u>Note that results are always appended to this output file</u>; it will continue to grow each time the program is run. The user will, therefore, need to periodically perform 'housekeeping' on an existing **MTFOUT** file.

On some systems (DOS, UNIX), results written to the softcopy display can be redirected to a disk file or to a printer. On some UNIX systems, error messages and normal output can be redirected to separate places. The MTF program source code has been constructed to utilize this last feature on systems that permit it, i.e., normal output and error messages are written to separate data streams.

Figure 3-1 shows a sample printout of the standard program output. The program output begins with a line having the date and time of the computer run, as well as the version number of the MTF program. The next line has the target serial number, taken from the input data file.

The user-entered image input file name is output on the next line. If the user adheres to a naming convention for image input file names, this line can help identify the scanner and specific scan that was analyzed.

The target data input file name is output on the next line.

Input coordinates ...
The next four lines give the inner corner coordinates that were input by the user. These are for the lower right corner of the upper left gray patch, lower left corner of the upper right gray patch, and upper right corner of the lower left gray patch.

Input image columns ...
The input image size and scan orientation (vertical or horizontal) is shown on the two next lines.

Scanner resolution ...
The pixels per inch shown on the next line relate to the input image in its scanned orientation. The pixels per inch calculations are based on the target dimensions from the input data file and the inner corner coordinates of the input image.

Target Skew Angle ...
The target skew angles on the next line are computed from the three input inner corner coordinates. Skew in the horizontal and vertical directions are with respect to the orientation of the input image. The line immediately following the computed skew angles indicates if row averaging of the sine pattern gray levels was used to arrive at the modulation values. Row averaging is used if the average skew angle magnitude is less than or equal to 3.0 degrees.

---

[11] To change the output file name, change the text in quotes in the following line of code in the MTF.h module: #define MTFOUTNAME "MTFOUT"

Thu Jun 13 08:42:12 1996 v3.1
Target Serial Number is: 119

Image input file name = EXAMPLE.TIF
Data input file name = TGTDATA

Input coordinates of inner corners of target image:

Upper Left Col =	240	Upper Left Row =	222
Upper Right Col =	722	Upper Right Row =	227
Lower Left Col =	238	Lower Left Row =	1214

Input image columns = 959, rows = 1429, header = 0
Scan Orientation = Vertical
Scanner resolution (pixels per inch): HORZ = 502.198 VERT = 498.924

Target Skew Angle: HORZ = 0.207 deg. VERT = 0.430 deg.
|skew| <= 1.5 degrees, modulations are computed from 6 row averages

REFLECTANCE REGRESSION LINE: slope = 268.378283 intercept = -6.096686
coefficient of correlation = 0.998293

Density Patch	Tgt Density	Tgt Reflect	Image Gray	Image Std Dev	LinReg Img Gray	LinReg Error
A	0.612	0.244	57.878	0.963	59.480	-1.602
B	0.510	0.309	74.340	1.340	76.840	-2.501
C	0.416	0.384	93.786	1.712	96.882	-3.096
D	0.324	0.474	118.085	2.190	121.180	-3.094
E	0.253	0.558	141.601	2.447	143.785	-2.184
F	0.148	0.711	191.761	1.734	184.778	6.983
G	0.615	0.243	58.236	1.117	59.028	-0.792
H	0.627	0.236	57.256	0.921	57.253	0.003
I	1.124	0.075	17.521	0.543	14.075	3.446
J	1.041	0.091	21.342	0.547	18.323	3.019
K	0.922	0.120	27.692	0.754	26.021	1.671
L	0.809	0.155	36.024	0.785	35.566	0.458
M	0.708	0.196	45.822	1.078	46.474	-0.653
N	0.604	0.249	59.041	1.116	60.699	-1.658

Tgt Freq. cy/mm	Effective Freq.	Target Mod	MTF using Highest Mod
0.188	0.188	0.604	0.997
0.250	0.250	0.589	0.982
0.375	0.375	0.585	0.967
0.500	0.500	0.605	0.955
0.750	0.750	0.602	0.943
1.000	1.000	0.589	0.930
1.500	1.500	0.602	0.877
2.000	2.000	0.629	0.830
3.000	3.000	0.629	0.702
4.000	4.000	0.628	0.655
5.000	5.000	0.608	0.555
6.000	6.000	0.601	0.456
8.000	8.000	0.441	0.358
10.000	10.000	0.338	0.278
12.000	Sampled Beyond Nyquist Frequency		

Figure 3-1. Example of Standard Program Output

REFLECTANCE REGRESSION ...
The next line gives the computed reflectance regression line. The computed slope and intercept are reported, as well as the coefficient of correlation (see Section 2.6 for a discussion of the reflectance regression line). Following is a listing of the regression results for each of the density patches. The patch label is shown on the left followed by the patch's target density read from the input target data file. The third column shows the target density converted to reflectance via Equation 2-9. The gray levels of the fourth column (*Image Gray*) represent the computed average ("trimmed mean") gray level of each density patch in the image (see Section 2.5 for details). The standard deviation given in the fifth column (*Image Std Dev*) is computed from the trimmed mean samples. Column six of the density report (*LinReg Img Gray*) gives the target reflectance (from column three) converted to a gray level via the regression line equation. The difference between this linear regression predicted result and the actual image gray level of column four is reported in the last column (*LinReg Error*). <u>The last column, therefore, indicates the deviation of the scanner from linear operation.</u>

Tgt Freq. ...
The sine pattern section of the standard output has a row representing each sine wave frequency pattern. The first column of the report lists the pattern's frequency in cycles/mm as read from the target data file. The effective frequency in the second column takes into account the apparent change in target frequency when the target sine waves are skewed with respect to the scanning axes. Specifically, when the computed average skew angle (average between horizontal and vertical directions) is greater than 3 degrees, the target frequency is multiplied by the cosine of the average skew angle to obtain the effective frequency (see discussion surrounding Equation 2-14). The target modulation (*Target Mod*) is the target manufacturer-supplied value read from the target data file. The scanner MTF reported in column four, *MTF using Highest Mod*, is equal to the highest sample modulation found in the analysis of the image sine pattern divided by the target modulation given in column three.

<u>**Problem Report**</u>

The problem report section of the standard program output (not shown in Figure 3-1) flags computed data results which indicate abnormal data magnitudes and/or do not meet the MTF, linearity, or ppi resolution requirements for scanners set in the FBI's IAFIS Image Quality Specification-IQS (FBI, 1995). The message: "No problems encountered." is printed, if such is the case. Problems that are detected and reported are as follows:

• Target resolution problem: The IQS requires that the scanner resolution be in the range: 495 ppi to 505 ppi. If the computed resolution is outside this range it is reported. Note that if the resolution is far from 500 ppi, and it should have been 500 ppi, then the possibility exists that the wrong target orientation was input to the program by the user.

• Dynamic range problem: If the average gray levels of any two of the density patches differ by one gray level or less, it indicates a scanner dynamic range problem. [The four corner density patches are not tested since, by manufacturer design, they are supposed to have the same values.]

• Low coefficient of correlation for the regression line (< 0.98): A low value may indicate that the scanner is operating nonlinearly. If the coefficient of correlation is low <u>and</u> if a printer MTF is being calculated (i.e., the **-p** option was selected), then local (point-to-point) straight line fits will be used instead of linear regression for determining the image gray to target space reflectance mapping.

• Linearity problem: The IQS specification requires that the difference between the linear regression predicted image gray level and the actual average image gray level for a given density patch be no greater than 7.65. Differences greater than 7.65 indicate nonlinear operation of the scanner.

• MTF problem: The IQS requires that the MTF be within a specified range of modulation values at each defined frequency. The IQS test procedure (FBI, March 1995) more specifically states that the MTF computed from the highest modulation at each frequency shall be used for requirement verification; this is the "MTF using Highest Mod" in the program print-out. MTF values outside the IQS range are reported, frequency by frequency.

• Aliasing problem: Image sine patterns in which aliasing was detected are reported, frequency by frequency, in the problem report and by an asterisk appended to the reported MTF for the pattern. Both aliasing due to upscaling and aliasing due to nonuniform decimation downscaling are reported, but if both are detected, only the term “aliasing” is reported.

If problems are reported, a number of non-scanner items should be checked and eliminated as the potential problem source before trying to isolate the problem to the scanner. As mentioned previously (Section 3.2.2), a TIFF input image improperly read by the MTF program may still run and produce results, but one or more of the results will most likely be highly abnormal and will, therefore, show up in the problem report. Other possible non-scanner related sources of problems are user input related: inputting 'vertical' when the image is 'horizontal' (or vice versa); inadvertently interchanging rows and columns of the three corner coordinates that are input (or inputting inaccurate values); constructing the input data file with inaccurate or out-of-sequence measurement data; or using the wrong input data file.

In some cases the scanner may not scan or capture the entire sine target. For example, when segment-scanning the target (discussed in Appendix D), a number of rows or columns along one edge of the target may be lost. If the computed outer corner coordinates are more than five rows and/or five columns beyond one or more edges of the overall image, then the program notifies the user and stops execution. In such a case, a number of rows and/or columns that were lost need to be added back into the image, as a uniform gray. For example, if the left-most 10 columns of the target are lost during scanning, then at least 10 columns (preferably more) of gray pixels should be appended to the left side of the image before running the MTF program. Whenever pixels need to be added, the program should be run with the **-d** option and the output diagnostic image inspected to make sure the nonimage added gray pixels did not falsify the linearity or MTF computations.

The following section describes diagnostics program run modes which have outputs to further aid problem solving.

3.4.2 Diagnostic and Extended Outputs via Command Line Execution

Invoking the **-d** command line parameter mentioned in Section 3.3.2 causes the generation of the raw, binary output file: ***filename*.box**, where *filename* is the first eight characters of the input image file name. The creation and internal storage of this file causes program memory requirements, in terms of computer random access memory (RAM), to almost double. For example, an 1100 x 1500 pixel image, which requires 2.2 megabytes of computer RAM to run in the standard mode (sum of bytes for image + MTF program +

variables storage, excluding computer operating system), will require 3.8 megabytes if the **-d** command is invoked.

If **-d** is invoked, the ***filename*.box** file can be displayed by an image display program to show which parts of the image the MTF program actually analyzed. The dimensions and orientation of this file are the same as those of the original image input file.

The ***filename*.box** file, an example of which is shown in Figure 3-2, denotes the measurement box areas of each density patch and sine pattern that were sampled during analysis. Sine pattern valleys are shown in white and peaks in black, for contrast against the normally bright peaks and dark valleys. Density patch sampled areas are shown in white. If the visual display of ***filename*.box** shows any box area that is not completely contained within a density patch or sine pattern, the program's output results should not be used. In this case, the target measurement data in the input data file and the input corner coordinates should be verified.

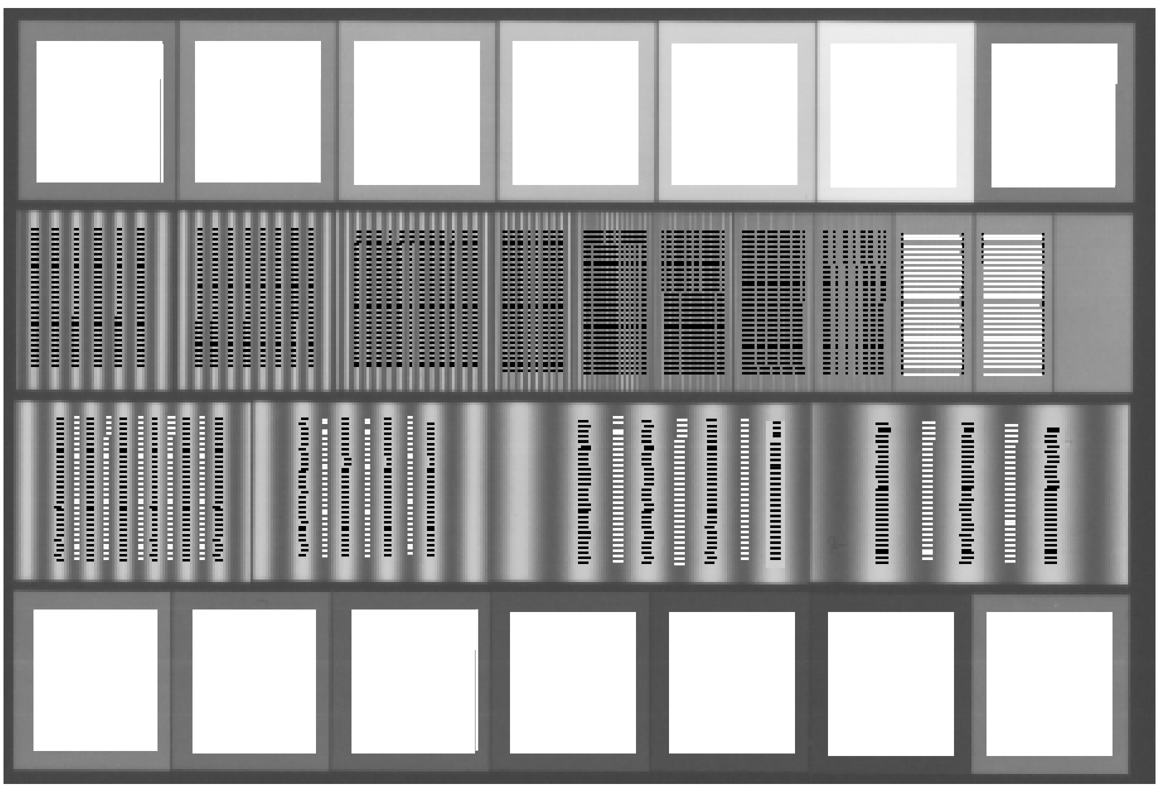

Figure 3-2. The *filename*.box Output File Which Delineates Areas Assessed by the Program (some detail is obscured in this scaled-down reproduction)

The **-a** parameter will print out an additional MTF, termed "MTF using Average Mod", which is computed from the average of all sample modulation values found at each frequency. This command will also print out the corresponding standard deviations between sample modulation values at each frequency.

The **-e** parameter will cause extended alphanumeric output to be appended to the standard output. The extensions include statistical data, including histograms, for the density patches and sine patterns, and the complete linear regression curve. The following briefly describes and illustrates the extended output.

The **-e** extended output for sine analysis contains, for each sine pattern, the mean and standard deviation for all sample modulations computed in that sine pattern. It also contains two separate histograms: the HIGH histogram shows the gray level distribution of all peak values and the LOW histogram shows the gray level distribution of all valleys. Figure 3-3 illustrates the output for one sine pattern. The histogram can reveal if an extreme outlier contributed to a higher than expected MTF, or if most values were clustered. It is possible for a peak value to be numerically lower than a distant valley value, due to phase changes or average level drift across the different periods of the sine pattern.

```
patch = 13
frequency = 8.000000 cycles/mm      effective frequency = 8.000000 cycles/mm
mean = 0.047054
sigma = 0.013601

Histogram of high/low values for target peaks/valleys:
 HIGH              LOW
 value count       value count
   162    8          141    2
   161    21         142    4
   160   101         143   32
   159   205         144   72
   158   310         145   125
   157   276         146   182
   156   278         147   252
   155   224         148   304
   154   172         149   304
   153   117         150   242
   152   53          151   139
   151   29          152   98
   150   6           153   31
                      154   12
                     155    1
```

Figure 3-3. Extended Statistical Output for Sine Patterns

The **-e** extended output for density patch analysis also contains two histograms for each patch, where the high values are greater than the mean and the low values are less than or equal to the mean. The histogram reflects the fact that the highest 16 percent and lowest 16 percent of the samples have been discarded in computing the trimmed mean. Figure 3-4 illustrates the output for one density patch. The “total+fliers”, “fliers”, “first mean”, etc. reflect the statistics before and after the trimming of the mean.

```
Patch = G   low = 122 high = 151
 total+fliers = 28332 total = 19266 fliers = 9066
 first mean = 129.933432 final mean = 129.882591
 standard deviation after flier removal = 1.160256
 factory reflectance = 0.242661 computed reflectance = 0.256223

Histogram of density patch after flier removal
(High values are above mean, lows are equal or below mean)

 HIGH            LOW
 value count     value count
   132  1661       128  2457
   131  4529       129  5199
   130  5420
```

Figure 3-4. Extended Statistical Output for Density Patches

Finally, the entire reflectance regression line is printed for all gray values between 0 and 255, when **-e** is invoked. Some target input images may yield regression lines that have negative reflectance values for the darkest gray shades. This is the result of a straight line approximating a series of data points that are not completely linear (or have a non-linearity outside of the sample set.) Any negative portion of the line will normally lie outside the range of sine pattern gray levels in the image, which is outside the range of interest. That is, the target is manufactured such that the highest peak reflectance on a sine wave is less than the highest reflectance density patch, and the lowest valley reflectance on a sine wave is greater than the lowest reflectance density patch.

3.5 PRINTER MTF

The MTF of a printer is obtained by implementing the following five steps, as illustrated in Figure 3-5:

1) Print either the entire A3 target, or pre-select the vertical and horizontal sine wave subtargets for printing. The MITRE digital target A3 has a width x height of 4000 x 2500 pixels and contains several different types of subtargets, including a vertical (515 x 905 pixels) and a horizontal (905 x 515 pixels) sine wave target, which have the general form illustrated in Figure 2-1. This application requires[12] use of the relevant value of the printer ppi. For *this* application, printer ppi is defined as print size in inches divided by number of digital target pixels, in the same dimension. For example, if the A3 target width of 4000 pixels prints to a width of 8 inches, the printer ppi = 4000 / 8 = 500.

2) Scan the print of the sine wave target with a scanner that has a substantally higher MTF than the MTF of the printer. As a useful rule of thumb, if the printer ppi (as defined in step 1) is 500, than a good quality scanner having a true ("optical") resolution in the 600 to 1000 ppi range will be needed.

3) Measure the MTF of the scanner by scanning one of the hardcopy sine targets (e.g., M-13 or M-15 listed in Table 2-1) and using the MTF program in its normal mode. Do not use the print of the A3 target for this scanner MTF measurement!

4) Using the scanned digital image of target A3 generated in step 2 and its associated data file as inputs (target A3 data file given in Appendix C), run the MTF program with the **-p** command line option. The user will be prompted to type in the printer ppi resolution.

5) The MTF of the printer equals the MTF output by the program (step 4) divided by the MTF of the scanner (step 3). The combination of the A3 sine target frequency increments and the printer ppi will usually result in the MTF obtained in step 4 being at different frequencies than the MTF obtained in step 3, so it will be necessary to interpolate one of the MTFs prior to the division.

Alternatively, if a large number of printer MTFs are to be measured, if the printer has a constant ppi, if the same print scanner is used on all prints, and if it can be verified that the scanner MTF is invariant from print scan to print scan, then the following procedure directly results in the MTF output by the program being equal to the printer MTF. For this case, the printer MTF is obtained by implementing steps 1-4 but with a change in the input data file. Specifically, generate a new MTF program input data file for use in step 4 by multiplying the modulation values in the target A3 data file by the MTF of the scanner. If the printer is operating at 500 ppi then the frequencies in the target A3 data file correspond to the frequencies associated with the scanner MTF, and one simply multiplies modulations at like frequencies. If the printer is not operating at 500 ppi, first multiply the frequencies of the scanner MTF by the quantity: 500 / (printer ppi), and then multiply the scanner modulation at each new frequency by the modulation in the target A3 data file at the same frequency. That is, modulations of the A3 target are changed, but the original frequencies in the target A3 data file are not changed.

[12] The MTF program requires the printer ppi because the target is digital and thus has no inherent physical size; the printer ppi establishes the effective spatial frequencies of the target sine waves, *as printed*.

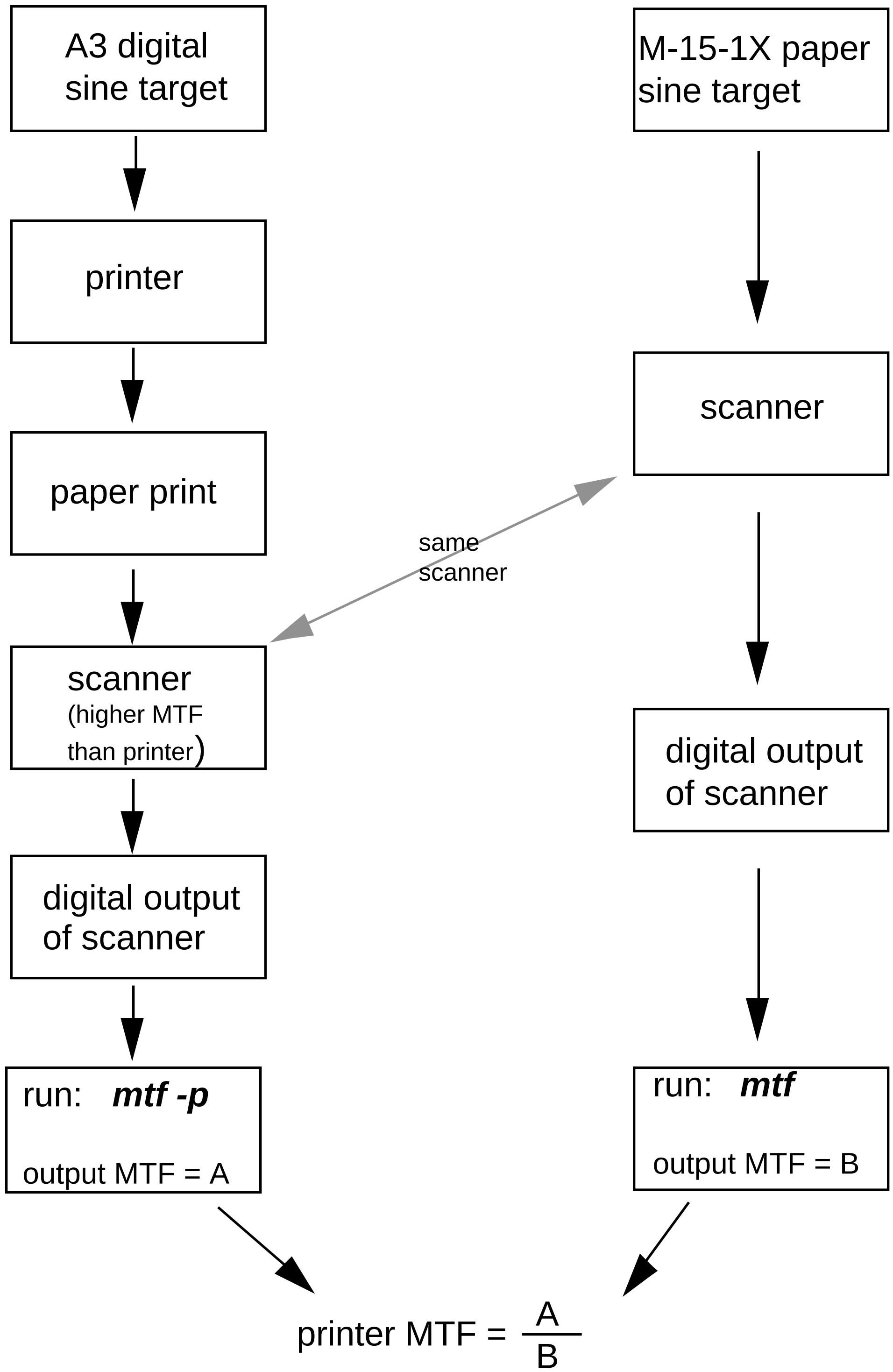

Figure 3-5. Processing Steps to Obtain Printer MTF

3.6 PROGRAM VERIFICATION

The MTF program was thoroughly tested during and at the completion of its development. Some of the major program verification tests that were performed are briefly described in the following:

- Program detection of the input image orientation and proper conversion of the image into the internal common orientation, verified by inputting the same image in the four orientations.

- Measurement boxes properly sized and located over each density patch and sine pattern, verified by outputting the program's computed measurement box corner coordinates and comparing to known patch/pattern locations, for both non-skewed and large skew images, and by inspecting the ***filename*.box** output diagnostic image.

- Trimmed mean of density patches verified by adding large noise (of several different types) to density patches whose noiseless means were independently calculated.

- Linear regression algorithm verified by running known test data.

- Locating peaks and valleys in sine patterns verified by running known, analytically fabricated sine wave test patterns, including imbedding these known patterns into real scanned images; and by comparing MTF program output for real scanned images to semi-automated measurements using commercial software.

- Discrete Fourier transform used in alias detector verified with known test data and comparison of output to commercial DFT software. The alias detection algorithm was verified by using known aliased and known non-aliased images (~ 50 images total) obtained from a dozen different brand/model scanners.

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APPENDIX A

BRIEF INSTRUCTIONS TO RUN MTF PROGRAM

<u>1) Prepare input data file.</u>
The file must contain the density patch and sine pattern locations and dimensions corresponding to the manufacturer's model number of the target (see Appendix C). The file must also contain the manufacturer-supplied gray patch density values and sine pattern modulations corresponding to the specific serial number target used.

<u>2) Obtain information to run program</u>.
• Display the image of the scanned sine target.
• Locate the column and row of the inner corner points of the top left, top right, and lower left gray patches (see Figure A-1). Reference: column 0, row 0 is upper left corner of entire scanned image.
• Note whether sine image is horizontal (width > height) or vertical (width < height).

<u>3) Run program.</u>
Type: mtf
Enter information at user prompts.

<u>4) Notes</u>
• The program always appends output to the output file: MTFOUT
• The scanned sine wave target can be in either a Horizontal (landscape) or Vertical (portrait) orientation at any skew angle.
• Typing: mtf -h will display a description of several command line options.

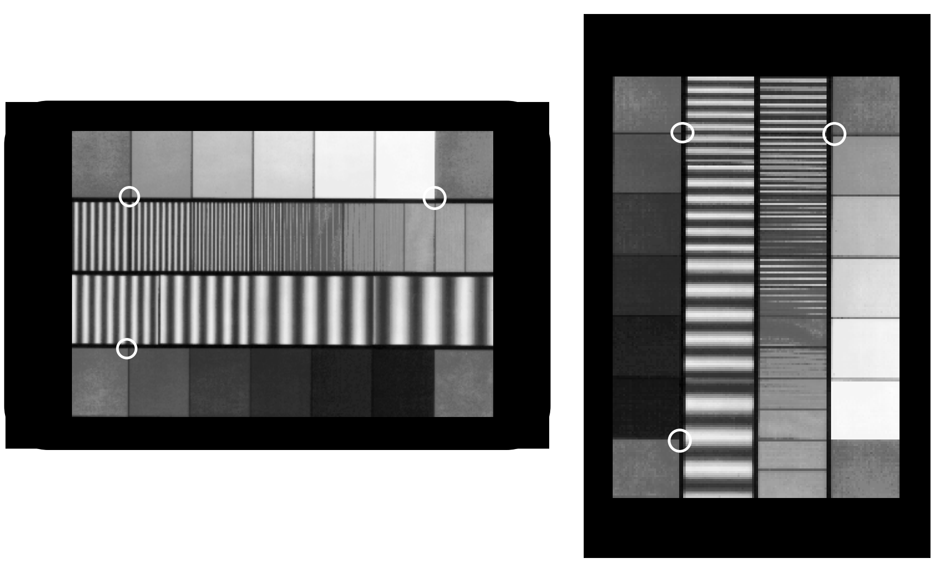


Figure A-1. Three Corner Points Whose Locations (Column, Row) are Needed to Run Program

Compiling the MTF Program With / Without TIFF Modules

Compile with TIFF Modules

	on Sun (UNIX) Computer	on PC (DOS) Computer
include:	-DUSE_TIFF in CPPFLAGS	/dUSE_TIFF in wcc_options
type:	make -f makefile.sun mtf	wmake -f makefile.dos mtf
executable:	mtf	mtf.exe

Compile without TIFF Modules

	on Sun (UNIX) Computer	on PC (DOS) Computer
remove:	-DUSE_TIFF from CPPFLAGS	/dUSE_TIFF from wcc_options
type:	make -f makefile.sun mtfraw	wmake -f makefile.dos mtfraw
executable:	mtf	mtf.exe

Note that with or without the TIFF modules, the executable file will be named "mtf" under UNIX and "mtf.exe" under DOS. The source code is reduced by 60% when removing the TIFF modules.

APPENDIX B

BACKGROUND ON NYQUIST FREQUENCY

An explanation of the term "Nyquist frequency" is given in this Appendix because it is extensively mentioned in this document and a number of calculations are based on its value.

First, a short review of the basic theory (Gonzales and Woods, 1992; Montgomery, 1975). A continuous spatial function is called "band-limited" if its spatial frequency spectrum goes to zero at some frequency, F, and stays at zero for all frequencies greater than F. The Whittaker-Shannon sampling theorem states that if a function is band-limited, then the function can be completely described from point samples of the function taken 1/2F apart. "Completely described" means that the continuous function can be exactly reconstructed, not just reconstructed at the sampling points. If the point samples are closer together then 1/2F, no harm is done (in general), but if the samples are further apart than 1/2F, it is not possible to completely reconstruct the function. The critical sampling rate, 1/2F, is called the "Nyquist sampling rate" and the corresponding frequency, F, is called the "Nyquist frequency."

In the following, the sampling theorem concept is brought into context for the case at hand. Suppose one has a 10 cy/mm sine wave input to a digital scanner which is sampling at exactly 508 pixels per inch (ppi). The period of the 10 cy/mm sine wave is 1/10 = 0.100 mm and the center-to-center pixel spacing[13] of the scanner is 25.4/508 = 0.050 mm. The input sine wave is band-limited because its Fourier transform has zero amplitude for all frequencies greater than 10 cy/mm; in fact, it only has amplitude at zero frequency, which is the average level of the sine wave, and at 10 cy/mm, which is the amplitude[14]. Since the sample spacing of the scanner is 0.050 mm and the Nyquist sampling rate for the sine wave is also 0.050 mm (1/2F = 1/(2)(10 cy/mm), the scanner is sampling the sine wave at the sine wave's Nyquist rate. Note that when sampling a sine wave at the Nyquist rate, there are exactly two samples per sine wave period.

An implication of the sampling theorem is that the Nyquist frequency is the highest frequency which contains unique and correct spectral information about the input, even though spectral information can physically be calculated for frequencies higher than Nyquist. For example, if a 15 cy/mm sine wave is input to the scanner in the example, there will be too few samples per sine period (i.e., less than 2) to meet the Nyquist condition. Specifically, the Nyquist rate for the 15 cy/mm sine wave would require samples be taken every 0.033 mm, but the scanner sampling is constant at 0.050 mm. In this case, the sampled representation of the 15 cy/mm sine wave will be flawed; it will contain an inseparable combination of the real 15 cy/mm sine wave, together with "aliases" of the 15 cy/mm sine wave. These "aliasing effects" show up in the spatial domain as a change in the apparent frequency of the sine wave, and/or add harmonics to the sine wave. In the frequency domain, the MTF of a 508 ppi scanner can physically be calculated beyond the

---

[13] It is assumed in this example that the scanner's detector pixels are adjacent, nonoverlapping, and have a constant width of 0.050 mm.

[14] Strictly speaking, the input sine wave will not have an infinite number of periods, it is chopped to some small number of periods by a window (rectangle) function when a physical target is created. This produces a band-unlimited function because the Fourier transform of a rectangle function has the form: sine(f)/f, which has non-zero amplitude values out to infinity. However, as this band-unlimited function passes through the optical component of a scanner it becomes once again band-limited, because an optical component is itself band-limited. That is, the MTF of an optical component is zero beyond a finite frequency.

10 cy/mm Nyquist frequency, but the result is an inseparable combination of real/true spectral information and false, aliased spectral information. Thus the Nyquist frequency is the highest frequency of interest.

Perfect applicability of the sampling theorem, leading to the possibility for perfect reconstruction of the input, requires that the samples taken be equi-spaced point samples, not area samples. Real scanners do not sample point-by-point; instead, light intensity incident to the scanner's detector array is integrated over individual finite areas, each defined by an individual detector element's area, or 'pixel'. Because of this sampling by non-point samples, the conditions for complete validity of the sampling theorem are not strictly adhered to, although it's implications are still approximately valid. This difference between ideal point sampling and physically realizable area sampling is illustrated in Figure B-1. In practice, one can approximate the point-sampled image corresponding to the area-sampled image actually obtained, by applying an inverse filter to the area-sampled image (Lanni and Baxter, 1992). This conversion could have use in object restoration.

The MTF program treats the 10 cy/mm sine wave target pattern as the Nyquist frequency of a scanner sampling at a nominal 500 ppi. More exactly, since the allowable sampling range for IAFIS scanners is 495 to 505 ppi, the corresponding Nyquist frequency ranges from 9.744 to 9.941 cy/mm, which means that a 10 cy/mm sine pattern is slightly into the aliasing region. However, a true Nyquist at 9.744 cy/mm is deemed to be sufficiently close to 10 cy/mm, such that measurements made off the 10 cy/mm sine wave target pattern will very closely represent the performance of the scanner at its Nyquist frequency. It is also noted that the frequency on the target itself may vary slightly from 10 cy/mm, due to small manufacturing errors or dimensional stability attributes of the photographic paper target substrate. Measurements made on one target indicate a target frequency variation of less than ± one percent, which is consistent with manufacturer specifications.

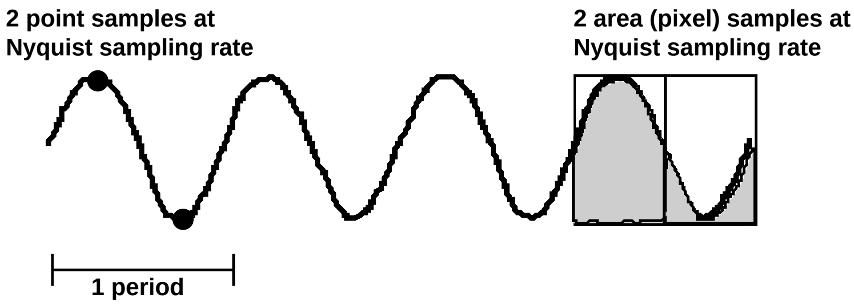


Figure B-1. Illustration of Point versus Area (Pixel) Samples at Nyquist Rate

APPENDIX C

TARGET INPUT DATA FILE

Running the MTF program requires an input data file containing dimensional data on the locations of the individual target density patches and sine patterns, requires the density values of the target density patches, and requires the modulation values of the target sine patterns. The density and modulation values are supplied by the target manufacturer and are unique to each target serial number. The modulation used is the manufacturer's "compensated modulation" value. If the manufacturer only supplies "peak to peak" modulations, then divide these modulations by the microdensitometer MTF as discussed in Section 2.1 and enter the result in the data file. The dimensional data is not routinely supplied by the target manufacturer. However, measurements MITRE has made on a number of target samples for the targets listed in Table 2-1 indicate that the dimensional data is sufficiently invariant across all serial numbers of a given target model, such that a single set of dimensional data can be used for any one target model. This is the dimensional data included in the target data files in this Appendix. For example, all serial numbers of target M-13-60-1X may utilize the dimensional data given in this Appendix. Figure C-1 illustrates the dimensional data that is needed in the data file, using the data for target M-13-60-1X as an example.

The dimensional data values given here have all been successfully used in the MTF program with real scanned images of the corresponding targets. It should be kept in mind, however, that the target manufacturer may at any time, without notice, change the target dimensions. If there is any question about the correctness of a particular set of dimensional data, the scanned sine image should be run through the MTF program with the **-d** option, and the subsequent diagnostic output image should be inspected.

The data files for the following targets, with the correct dimensional data, are given in the remainder of this Appendix, in the following order:

M-13-60-1X
M-13-60-0.5X
M-15-60
M-6
A3
T90

Note the following for the data files as printed in this Appendix:

• For the 'M-' series targets, density and modulation values are set equal to 999.999 as placeholders, since the actual values will be different for each individual target serial number.

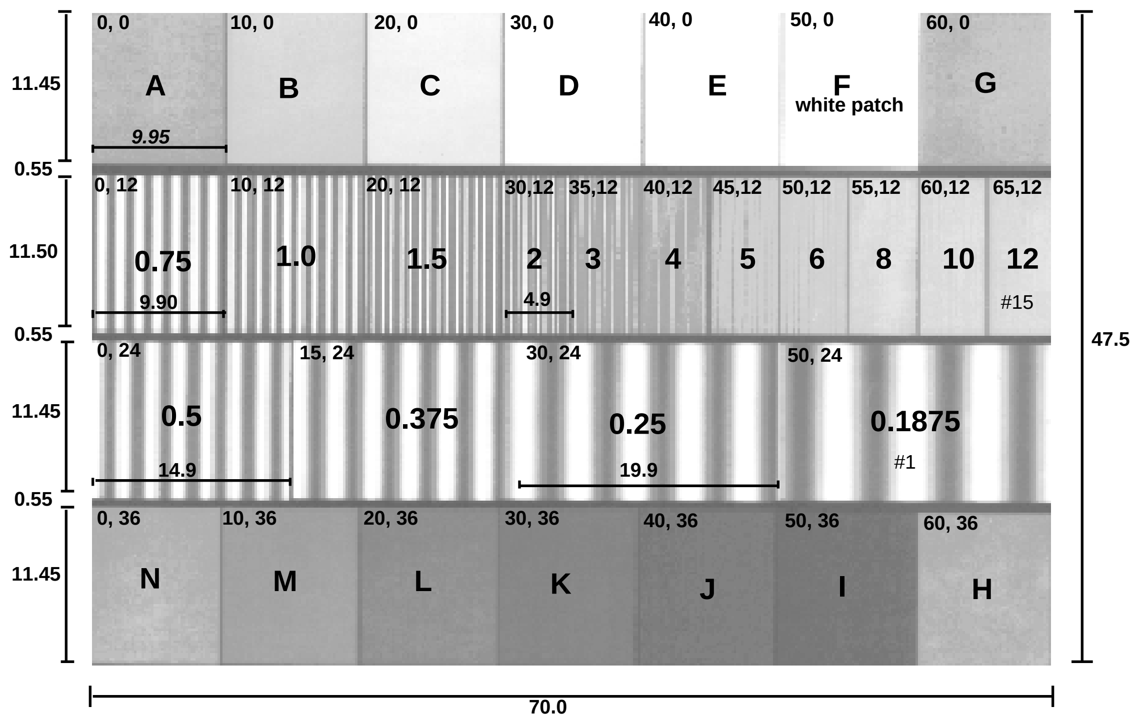
• The T90 target is a 15-bar target with no density patches. Although it requires some preparation of the image, this target has also been successfully run through the MTF program.

• The A3 target is a digital sine wave target used for testing printers.

• Each row in each data column of a table constitutes a line of data in the actual digital data file. Sequential data lines start at the top of the left-most column on the first page of a given table, go to the bottom of the the left-most column, then to the top of the middle column, then to bottom of middle column, etc.

The # symbol allows comments to be placed in the actual digital data file, which must adhere to the following rules:

- Comments can take up a whole line (standalone) or appear after a data entry on the same line.
- A standalone comment line must have the # in the leftmost column.
- A comment that follows a data entry on the same line must have a space between the end of the data and the #.
- No line can extend beyond 80 columns!
- Blank lines are ignored.
- Data entries can only appear one to a line and must start in the left-most column of a data file line.



Large-type number centered in sine pattern is spatial frequency in cy/mm.
Two numbers in upper left corner of density patch or sine pattern are horizontal and vertical mm distance, respectively, of upper left corner of the patch or pattern, from the origin at 0, 0.
Numbers with |———| are height and width of patches and patterns, in mm.

Figure C-1. Location and Size Data for Patches and Patterns in Target M-13-60-1X

Sine Target: M-13-60-1X
(page 1 of 2)

```
119        # target serial number

29         # total number of density
           # patches+sine patterns

70.0      # target width in mm
47.5      # target height in mm

# Density Patches Follow:

A         # patch label
d         # signifies density patch
0.0       # UL patch corner in mm
#            from left edge of target
0.0       # UL patch corner in mm
#            from top edge of target
9.95      # patch width in mm
11.45     # patch height in mm
999.999   # patch density

B
d
10.0
0.0
9.95
11.45
999.999

C
d
20.0
0.0
9.95
11.45
999.999

D
d
30.0
0.0
9.95
11.45
999.999
```

```
E
d
40.0
0.0
9.95
11.45
999.999

F
d
50.0
0.0
9.95
11.45
999.999    # white patch

G
d
60.0
0.0
9.95
11.40
999.999

H
d
60.0
36.0
9.95
11.45
999.999

I
d
50.0
36.0
9.95
11.45
999.999   # black patch

J
d
40.0
36.0
9.95
11.45
999.999
```

```
K
d
30.0
36.0
9.95
11.45
999.999

L
d
20.0
36.0
9.95
11.45
999.999

M
d
10.0
36.0
9.95
11.45
999.999

N
d
0.0
36.0
9.95
11.45
999.999

# Sine Patterns Follow:

1         # label
s         # signifies sine pattern
50.0      # UL pattern corner in mm
#            from left edge of target
24.0      # UL pattern corner in mm
#            from top edge of target
19.90     # pattern width in mm
11.45     # pattern height in mm
999.999 # compensated modulation
.1875     # frequency in cycles/mm
```

Sine Target: M-13-60-1X
(page 2 of 2)

2 s 30.0 24.0 19.9 11.45 999.999 .25	7 S 20.0 12.0 9.90 11.50 999.999 1.5	12 s 50.0 12.0 4.9 11.50 999.999 6.0
3 s 15.0 24.0 14.9 11.45 999.999 .375	8 s 30.0 12.0 4.9 11.50 999.999 2.0	13 s 55.0 12.0 4.9 11.50 999.999 8.0
4 s 0.0 24.0 14.9 11.45 999.999 0.5	9 s 35.0 12.0 4.9 11.50 999.999 3.0	14 s 60.0 12.0 4.9 11.50 999.999 10.0
5 s 0.0 12.0 9.90 11.50 999.999 .75	10 s 40.0 12.0 4.9 11.50 999.999 4.0	15 s 65.0 12.0 4.9 11.50 999.999 12.0
6 s 10.0 12.0 9.90 11.50 999.999 1.0	11 s 45.0 12.0 4.9 11.50 999.999 5.0	

Sine Target: M-13-60-0.5X
(page 1 of 2)

```
2         # target serial number

28        # total number of density
#           patches + sine patterns

35.       # target width in mm
24.       # target height in mm

# Density Patches Follow:

A         # patch label
d         # signifies density patch
0.0       # UL patch corner in mm
#           from left edge of target
0.0       # UL patch corner in mm
#           from top edge of target
4.9       # patch width in mm
5.86      # patch height in mm
999.999   # patch density

B
d
5.02
0.0
4.9
5.86
999.999

C
d
10.03
0.0
4.9
5.86
999.999

D
d
15.05
0.0
4.9
5.86
999.999

E
d
20.07
0.0
4.9
5.86
999.999

F         # white patch
d
25.08
0.0
4.9
5.86
999.999

G
d
30.1
0.0
4.9
5.86
999.999

H
d
30.1
18.138
4.9
5.86
999.999

I
d
25.08
18.138
4.9
5.86
999.999   # black patch

J
d
20.07
18.138
4.9
5.86
999.999

K
d
15.05
18.138
4.9
5.86
999.999

L
d
10.03
18.138
5.09
5.86
999.999

M
d
5.02
18.138
4.9
5.86
999.999

N
d
0.0
18.138
4.9
5.86
999.999

# Sine Patterns Follow:

1         # label
s         # signifies sine pattern
19.8      # UL pattern corner in mm
#           from left edge of target
12.092    # UL pattern corner in mm
#           from top edge of target
15.2      # pattern width in mm
5.86      # pattern height in mm
999.999   # compensated modulation
.25       # frequency in cycles/mm
```

Sine Target: M-13-60-0.5X
(page 2 of 2)

2 s 9.9 12.092 9.8. 5.86 999.999 .375	6 s 10. 6.046 4.9 5.86 999.999 1.5	10 s 22.7 6.046 2.31 5.86 999.999 5.
3 s 0.0 12.092 9.8. 5.86 999.999 .5	7 S 15.1 6.046 2.4 5.86 999.999 2.	11 s 25.2 6.046 2.31 5.86 999.999 6.
4 s 0.0 6.046 4.94. 5.86 999.999 .75	8 s 17.85 6.046 2.31 5.86 999.999 3.	12 s 27.7 6.046 2.31 5.86 999.999 8.
5 s 5.0 6.046 5.0 5.86 .609 1.0	9 s 20.3 6.046 2.25 5.86 999.999 4.	13 s 30.2 6.046 2.31 5.86 999.999 10.
		14 s 32.7 6.046 2.31 5.86 999.999 12.

Sine Target: M-15-60
(page 1 of 2)

```
23        # target serial number

32        # total number of density
          # patches + sine patterns

70.0      # target width in mm
47.5      # target height in mm

# Density Patches Follow:
A         # label for this patch
d         # signifies density patch
0.0       # UL patch corner in mm
#           from left edge of target
0.0       # UL patch corner in mm
#           from top edge of target
9.95      # patch width in mm
11.6      # patch height in mm
.68       # patch density

B
d
10.0
0.0
9.95
11.6
999.999

C
d
20.0
0.0
9.95
11.6
999.999

D
d
30.0
0.0
9.95
11.6
999.999

E
d
40.0
0.0
9.95
11.6
999.999

F
d
50.0
0.0
9.95
11.6
999.999     # white patch

G
d
60.0
0.0
9.95
11.6
999.999

H
d
60.0
35.9
9.95
11.6
999.999

I
d
50.0
35.9
9.95
11.6
999.999

J
d
40.0
35.9
9.95
11.6
999.999

K
d
30.0
35.9
9.95
11.6
999.999

L
d
20.0
35.9
9.95
11.6
999.999

M
d
10.0
35.9
9.95
11.6
999.999

N
d
0.0
35.9
9.95
11.6
999.999

#  Sine Patterns Follow:

1         # label
s         # signifies sine pattern
50.5      # UL pattern corner in mm
#           from left edge of target
24.0      # UL pattern corner in mm
#           from top edge of target
19.5      # pattern width in mm
11.6      # pattern height in mm
999.999   # compensated modulation
.25       # frequency in cycles/mm

2
s
35.3
24.0
15.1
11.6
999.999
.375
```

Sine Target: M-15-60
(page 2 of 2)

3 s 20.1 24.0 15.1 11.6 999.999 .5 4 s 10.0 24.0 9.9 11.6 999.999 0.75 5 s 0.0 24.0 9.90 11.6 999.999 1.0 6 s 0.0 12.0 9.9 11.6 999.999 1.5 7 S 10.0 12.0 4.9 11.6 999.999 2.0	8 s 15.0 12.0 4.9 11.6 999.999 3.0 9 s 20.0 12.0 4.9 11.6 999.999 4.0 10 s 25.0 12.0 4.9 11.6 999.999 5.0 11 s 30.0 12.0 4.9 11.6 999.999 6.0 12 s 35.0 12.0 4.9 11.6 999.999 8.0 13 s 40.0	12.0 4.9 11.6 999.999 10.0 14 s 45.0 12.0 4.9 11.6 999.999 12.0 15 s 50.0 12.0 4.9 11.6 999.999 14.0 16 s 55.0 12.0 4.9 11.6 999.999 16.0 17 s 60.0 12.0 4.9 11.6 999.999 18.0 18 s 65.0 12.0 4.9 11.6 999.999 20.0

Sine Target: M-6

(page 1 of 2)

```
# Note for M-6 Target:
# Image must be left/right reversed
# before input to MTF program if:
# whitest gray patch on displayed
# horizontal image is in Upper Left
# or Lower Right; or if whitest
# gray patch on displayed vertical
# image is in Upper Right or
# Lower Left

# M-6 sines go to 80 cy/mm but this
# file stops at 10 cy/mm

123   # target serial number

27    # total number of density
#        patches + sine patterns

70.0  # target width in mm
46.0  # target height in mm

# Density Patches Follow:

A           # patch label
d           # signifies density patch
0.0         # UL patch corner in mm
#             from left edge of target
0.0         # UL patch corner in mm
#             from top edge of target
9.7         # patch width in mm
10.         # patch height in mm
999.999     # patch density

B
d
10.0
0.0
9.7
10.
999.999

C
d
20.0
0.0
9.7
10.
999.999

D
d
30.0
0.0
9.7
10.
999.999

E
d
40.0
0.0
9.7
10.
999.999

F
d
50.0
0.0
9.7
10.
999.999    # white patch

G
d
60.0
0.0
9.7
10.
999.999

H
d
60.0
36.
9.7
10.
999.999

I
d
50.0
36.
9.7
10.
999.999    # black patch

J
d
40.0
36.
9.7
10.
999.999

K
d
30.0
36.
9.7
10.
999.999

L
d
20.0
36.
9.7
10.
999.999

M
d
10.0
36.
9.7
10.
999.999

N
d
0.0
36.
9.7
10.
999.999

# Sine Patterns Follow:

1           # label
s           # signifies sine pattern
55.0        # UL pattern corner in mm
#             from left edge of target
24.0        # UL pattern corner in mm
#             from top edge of target
9.7         # pattern width in mm
10.         # pattern height in mm
999.999     # compensated modulation
.375        # frequency in cycles/mm
```

Sine Target: M-6

(page 2 of 2)

2 s 45. 24.0 9.7 10. 999.999 .5	6 s 10.0 24.0 4.7 10. 999.999 2.	10 s 5.0 12.0 4.7 10. 999.999 5.0
3 s 35. 24.0 9.7 10. 999.999 .75	7 S 5.0 24.0 4.7 10. 999.999 2.5	11 s 10.0 12.0 4.7 10. 999.999 6.0
4 s 25. 24.0 9.7 10. 999.999 1.	8 s 0.0 24.0 4.7 10. 999.999 3.0	12 s 15.0 12.0 4.7 10. 999.999 8.0
5 s 15. 24.0 9.7 10. 999.999 1.5	9 s 0.0 12.0 4.7 10. 999.999 4.0	13 s 20.0 12.0 4.7 10. 999.999 10.0

Digital Sine Target: A3
(page 1 of 2)

```
# Patch densities and sine modulations
# are actual values for this target A3.
# mm locations are with respect to
# printing @ 500 ppi (MTF program
# accounts for difference when
#  printing @ other ppi).

A3          # target serial number

25          # total number of density
#              patches + sine patterns

45.974    # target width in mm
26.162    # target height in mm

# Density Patches Follow:

A          # patch label
D          # signifies density patch
0.0       # UL patch corner in mm
#          from left edge of target
0.0       # UL patch corner in mm
#           from top edge of target
6.35       # patch width in mm
6.35       # patch height in mm
.30103   # patch density

B
d
6.6548
0.0
6.35
6.35
.271519

C
d
13.2588
0.0
6.35
6.35
.217908

D
d
19.8628
0.0
6.35
6.35
.1676907

E
d
26.4668
0.0
6.35
6.35
.122683

F
d
33.0708
0.0
6.35
6.35
.0798604   # white patch

G
d
39.6748
0.0
6.35
6.35
.30103

H
d
39.6748
19.8628
6.35
6.35
.30103

I
d
33.0708
19.8628
6.35
6.35
.795456    # black patch

J
d
26.4668
19.8628
6.35
6.35
.622910

K
d
19.8628
19.8628
6.35
6.35
.50515

L
d
13.2588
19.8628
6.35
6.35
.412605

M
d
6.6548
19.8628
6.35
6.35
.336358

N
d
0.0
19.8628
6.35
6.35
.30103
```

Digital Sine Target: A3
(page 2 of 2)

```
1           # sine label
s           # signifies sine pattern
26.2128     # UL pattern corner in mm
#             from left edge of target
13.2588     # UL pattern corner in mm
#             from top edge of target
19.812      # pattern width in mm
6.35        # pattern height in mm
.559055     # modulation
.50474      # frequency in cycles/mm

2
s
13.2588
13.2588
12.7
6.35
.560784
.984252

3
s
6.6548
13.2588
6.35
6.35
.559055
1.514234

4
s
0.0
13.2588
6.35
6.35
.560784
1.968504

5
s
0.0
6.6548
6.35
6.35
.560784
2.46063

6
s
6.6548
6.6548
6.35
6.35
.545098
2.812149

7
S
13.2588
6.6548
6.35
6.35
.560784
3.28084

8
s
19.8628
6.6548
6.35
6.35
.535433
3.937008

9
s
26.4668
6.6548
6.35
6.35
.560784
4.92126

10
s
33.0708
6.6548
6.35
6.35
.488189
6.56168

11
s
39.6748
6.6548
6.35
6.35
.560784
9.84252
```

15-Bar Target (T90)

A bar target can also be processed through the MTF computer program, with no changes to the program. For example, the bar target model number T90, manufactured by Applied Image, Inc., Rochester, NY, has been successfully processed. This target, illustrated in Figure C-2, consists of 15 bars at each frequency, starting at 1.0 cy/mm and incrementing in frequency in a 10th root of 10 progression. For the MTF program to process the target image, the three gray patches shown in Figure C-2 must first be added to the digital image of the T90 target (which has no gray patches). These three gray patches must have the following properties:

• Each gray patch must be at least 40 x 40 pixels in size for a target scanned at 500 ppi (corresponds to size on target of 2 x 2 mm).

• The three gray patches must have the following gray level values: 128 for top left patch, 245 for top right patch, and 1 for bottom left patch.

• The inner corners of the gray patches must be coincident with the corners of the specific bars shown in Figure C-2.

• The orientation shown in Figure C-2 is considered to be the horizontal orientation; a vertical image may need to be rotated 90 degrees to horizontal, prior to processing.

If the gray patches have the correct gray values and are properly situated on the 15-bar target image, and if the correct input data file is used in running the MTF program, then the section of the MTF program output related to the linear regression will have the following values:

REFLECTANCE REGRESSION LINE: slope = 254.999997 intercept = 0.000000
coefficient of correlation = 1.000000

Density Patch	Tgt Density	Tgt Reflect	Image Gray	Image Std Dev	LinReg Img Gray	LinReg Error
A	0.299	0.502	128.000	0.000	128.000	0.000
F	0.017	0.961	245.000	0.000	245.000	0.000
I	2.407	0.004	1.000	0.000	1.000	0.000

Note that when a bar target image is input to the MTF program instead of a sine wave target image, the printout MTF is actually the "square wave response", also known as the "contrast transfer function (CTF)". When both a square wave target and sine wave target are imaged by the same imaging system, the CTF does not have the same values as the MTF, although they are related. Conversion from MTF to CTF, and CTF to MTF, is possible for a continuous, analog linear imaging system (Coltman, 1954), but the process is more complicated when dealing with a discrete-sampling linear imaging system such as a scanner (the latter case is under investigation at MITRE).

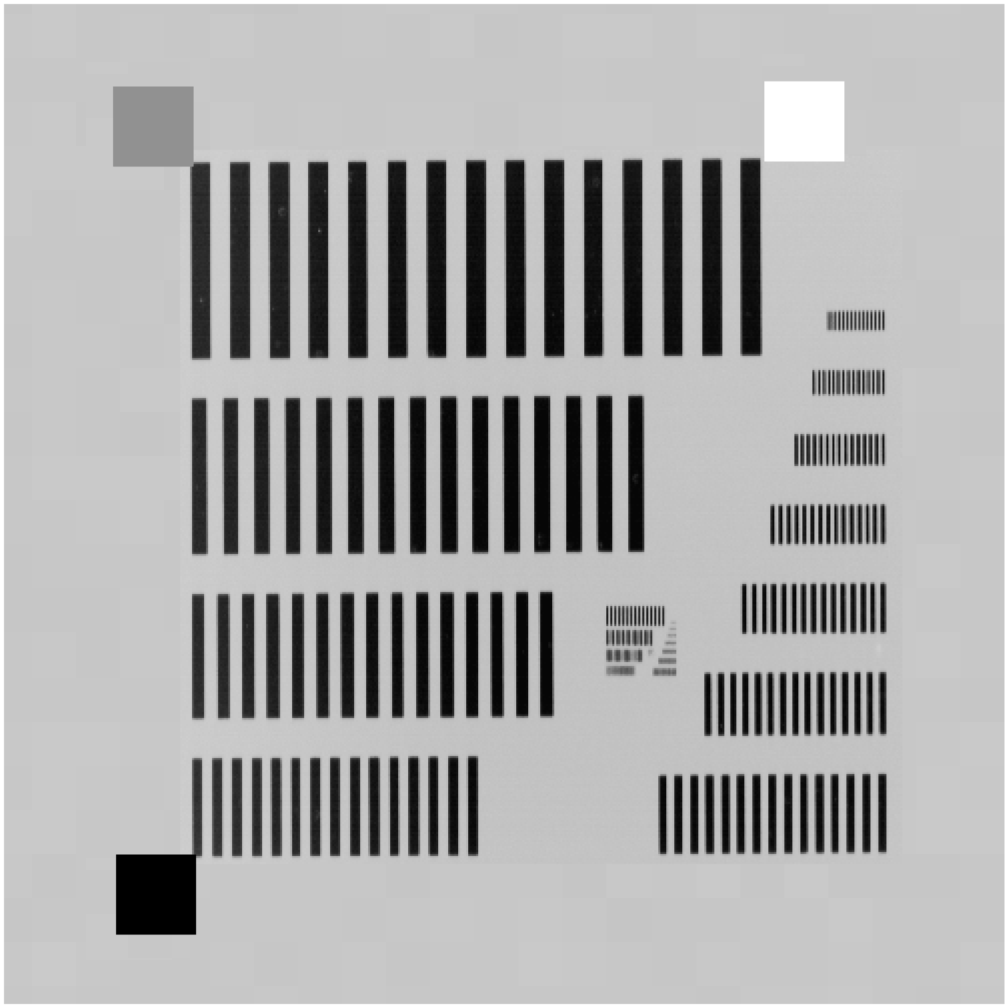


Figure C-2. Image of 15-Bar Target ("T90") with Three Added Gray Patches

Bar Target: T90
(page 1 of 2)

```
# T90 target modulation assumed to equal 1.0
# Target contains two 10 cy/mm patterns.
# Target frequencies above 10 cy/mm not in this data file.

T90-15bar   # target serial number

15    # total number of density patches + sine patterns

18.5       # target width in mm
21.633    # target height in mm

# Density Patches Follow:

A             # patch label
d             # signifies density patch
0.0           # UL patch corner in mm from left edge of target
0.0           # UL patch corner in mm from top edge of target
2.            # patch width in mm
2.            # patch height in mm
.2993302    # patch density

F
d
16.5
0.0
2.
2.
.01737409

I
d
0.0
19.633
2.
2.
2.4065402

# Sine Patterns Follow:

1         # label
s         # signifies sine pattern
2.       # UL pattern corner in mm from left edge of target
2.       # UL pattern corner in mm from top edge of target
14.5   # pattern width in mm
5.       # pattern height in mm
1.       # target modulation
1.       # frequency in cycles/mm
```

```
2
s
2.
8.
11.518
3.972
1.
1.25893

3
s
2.
12.972
9.149
3.155
1.
1.58489

4
s
2.
17.127
7.267
2.506
1.
1.99526

5
s
13.86
17.7435
5.773
1.9905
1.
2.51189

6
s
15.048
15.2134
4.585
1.5811
1.
3.16228

7
s
15.991
12.9575
```

Bar Target: T90
(page 2 of 2)

3.642
1.2559
1.
3.98107

8
s
16.74
10.96
2.893
.9976
1.
5.01187

9
s
17.335
9.1675
2.298
.7924
1.
6.30957

10
s
17.8076
7.538
1.8254
.6295
1.
7.94328

11
s
18.183
6.038
1.45
.5
1.
10.

12
s
12.55
13.478
1.45
.5
1.
10.

APPENDIX D

SEGMENT SCANNING THE TARGET

With some scanners, due to their design or operational modes, it may not be possible to scan and capture the entire M-13-60-1X or M-15-60 sine wave target as a single image (target size is 1.87 x 2.76 inches). The MTF program is reasonably accommodating to a scanner which captures the target in segments, as long as the segments are properly merged back together, by some other software, prior to input to the MTF program. For example, a ten-print fingerprint card scanner may capture each of the 1.5 x 1.6 inch rolled impression fingerprint blocks as separate images. In this case, it is recommended that the sine wave target be segmented as illustrated in Figure D-1, where the vertical and horizontal white bisector lines denote the recommended boundary locations between print blocks. Specifically, it is recommended that the white horizontal bisector line separate the 2 and 3 cy/mm sine patterns, which ensures that the entire sine target can be captured in just four adjacent print blocks. Although this separates the 0.25 cy/mm sine pattern into two parts, this particular frequency is usually not vital. Alternatively, the horizontal bisector could be placed at the boundary between the third and fourth gray patches from the top in Figure D-1. With this bisection, no individual gray patches or sine patterns are separated into two parts. However, with this bisection it requires more than four adjacent print blocks to capture the entire sine target.

If the segment images are merged back together (by other software) with an error of no more than two rows and/or two columns, then the MTF program can produce accurate results. For the MTF program to work properly with merged segment images, however, any rows or columns missing from the target scan must be 'filled in' with at least an equal number of rows and/or columns of pure black (0 gray level) or pure white (255 gray level) pixels. Figure D-2 illustrates the proper reconstruction of an M-13-60-1X sine target image when the four segments have gaps between them, and some columns along the left side and some rows along the bottom edge have been lost. In this example, the four segments have been merged back together with their correct vertical and horizontal spacings. The missing columns and rows have been filled with pure black, which makes these gaps evident. A determination that part of the left side and bottom side were also missing from the scans indicated a further need to fill in the missing rows and columns with pure black. This particular example was processed through the MTF program both in its original, complete, unsegmented form, and in its reconstructed form as shown in Figure D-2. Comparing the two MTF outputs, a difference in computed modulation (printed out to 3 decimal places) occurred at only two of the 14 sine frequencies, where the difference values were 0.001 and 0.013 modulation units. This is within the bounds of acceptability for many applications of the MTF program.

If there is any question as to the accuracy of the segment merging operation and the effect on the MTF program, the program should be run with the "**-d**" option to produce the ***filename*.box** diagnostic output image file (see Section 3.4.2). Display of the ***filename*.box** image will show whether or not the measurement box areas used by the program are within the boundaries of all density patches and sine patterns. If one edge of a measurement box does stray across a gray patch or sine pattern boundary, the MTF results may still be valid, due to the internal checks and pruning of 'outliers' that is performed by the program. If need be, the measurement box size can be decreased by increasing the magnitude of the "% safety margin," as discussed in Section 2.4. Increasing the box safety margin effectively minimizes the possibility of the box straying across a patch or pattern boundary, but it also decreases the sample size for modulation computations. Valid results on segment-scanned, merged sine target images also assumes that the scale (ppi), skew angle, and combination of scanner illumination level and detector sensitivity setting are all constant from segment to segment. The segment-to-segment scale and skew angle can be checked by viewing the merged image, and the constancy of illumination/detector sensitivity can be checked by verifying that the four corner gray patches have nearly the same average gray level.

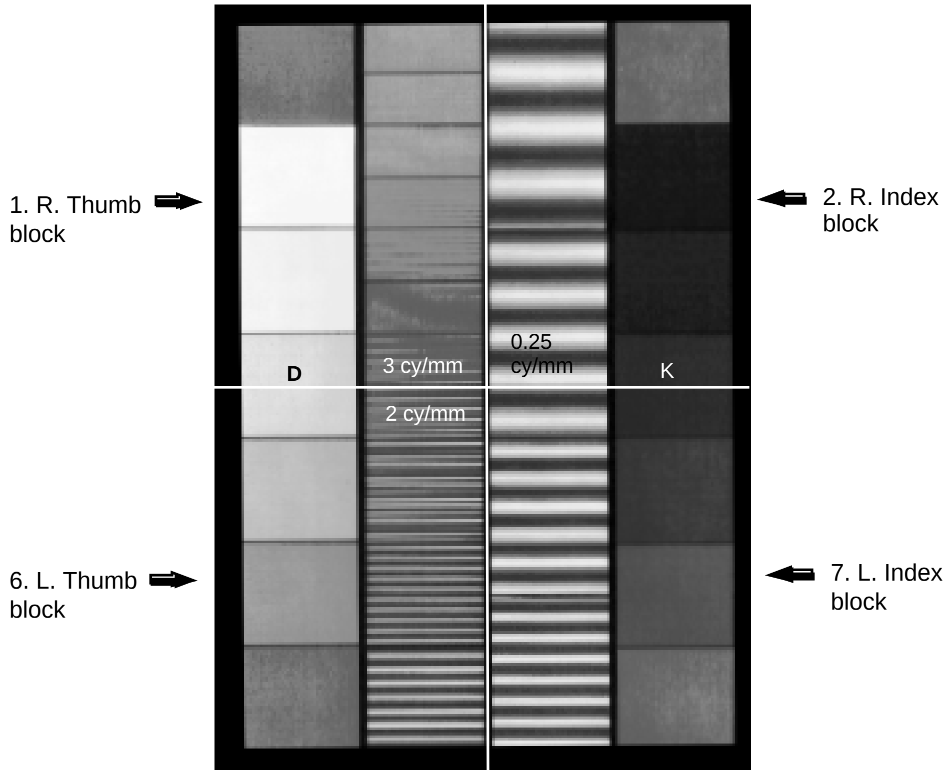


Figure D-1. Recommended Segmentation of Sine Target on Ten Print Fingerprint Card (print blocks are examples for vertical target orientation)

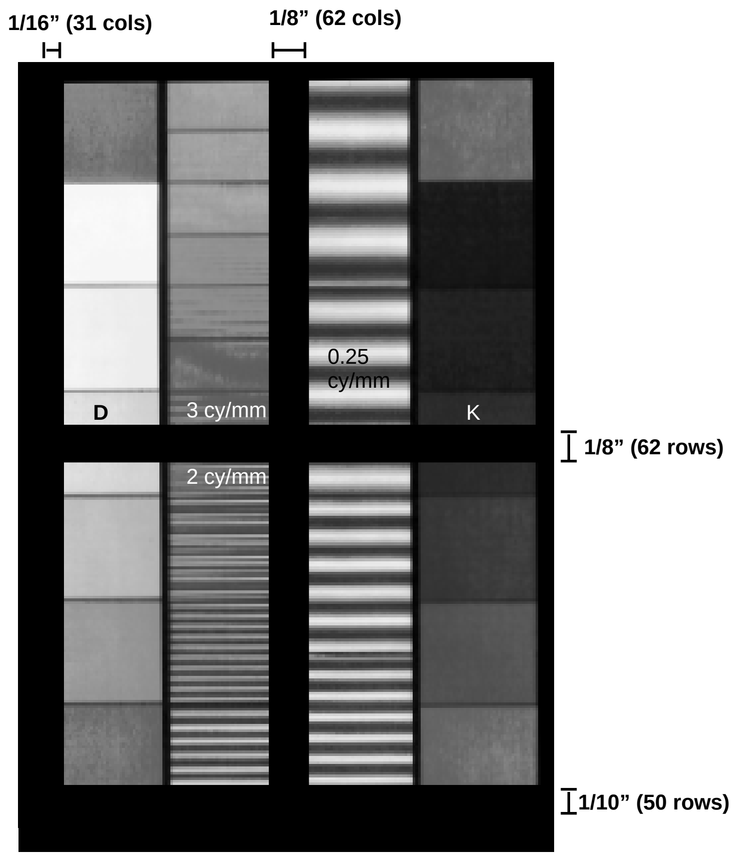


Figure D-2. Illustration of Missing Rows and Columns on Scanned Target, Which MTF Program Will Handle (assumes 500 ppi)

GLOSSARY

ANSI	American National Standards Institute
CJIS	Criminal Justice Information Services
CTF	Contrast Transfer Function
cy/mm	cycles per millimeter
DC	zero frequency component of DFT
DFT	Discrete Fourier Transform
DOS	Disk Operating System
dpi	dots per inch
IAFIS	Integrated Automated Fingerprint Identification System
IQS	Image Quality Specification
FBI	Federal Bureau of Investigation
mm	millimeter
MTF	Modulation Transfer Function
ppi	pixels per inch
OS	Operating System
PC	IBM-compatible Personal Computer
RAM	Random Access Memory
TIFF	Tag Image File Format