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MTR060170R5

MITRE TECHNICAL REPORT

TEST PROCEDURES FOR VERIFYING IMAGE QUALITY REQUIREMENTS FOR PERSONAL IDENTITY VERIFICATION (PIV) SINGLE FINGER CAPTURE DEVICES

December 2006

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Sponsor:	DOJ/FBI	**Contract No.:**	W15P7T-05-C-F600
Dept. No.:	G036	**Project No.:**	0706E02X

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Case number: 06-1384

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Abstract

In response to the August 2004 issuance of Homeland Security Presidential Directive-12 (HSPD-12), "Policy for a Common Identification Standard for Federal Employees and Contractors", the National Institute of Standards and Technology (NIST) developed Federal Information Processing Standard-201 (FIPS-201), "Personal Identity Verification (PIV) for Federal Employees and Contractors", issued in February 2005, whose goal is to improve the identification and authentication of Federal employees and contractors for access to Federal facilities and information systems.

The Office of Management and Budget (OMB) then designated the General Services Administration (GSA) as Executive Agent for government acquisitions for implementation of HSPD-12 and FIPS-201, and directed that all PIV component products purchased by Federal agencies must be compliant with the relevant federal policy, standards, and technical specifications.

In support of HSPD-12 and FIPS-201, the Federal Bureau of Investigation (FBI) developed a PIV Image Quality Specification, issued in July 2006. This FBI specification defines the quantitative image quality requirements for a single fingerprint capture device suitable for application in the PIV program. A single fingerprint capture device product must comply with the FBI's PIV specification (and complete other specified steps), in order for it to be placed on the FIPS-201 Approved List, at which time it is acceptable for purchase by Federal agencies.

<u>This document defines and describes the test procedures used to verify compliance of single fingerprint capture devices with the FBI's PIV Image Quality Specification.</u>

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1 Introduction

This document defines the test procedures used to verify compliance with the Federal Bureau of Investigation (FBI)'s image quality specification [**SPEC**] for Personal Identity Verification (PIV) single fingerprint capture devices. FBI certification of a PIV single fingerprint capture device is the major step in obtaining formal approval of the device for use in the federal government's PIV program [**FIPS**].

The single fingerprint capture device, with its associated image processing, must be capable of producing images which exhibit good geometric fidelity, sharpness, detail rendition, gray level uniformity, and gray level dynamic range, with low noise characteristics. The fingerprint capture device is expected to generate good quality finger images for a very high percentage of the user population, across the full range of environmental variations seen in the intended applications; a primary application is to support subject authentication via one-to-one fingerprint matching.

1.1 General Test Attributes

• Verification of compliance of a capture device to the PIV spec requirements is primarily performed by the *test method*; i.e., verification through systematic exercising of the item with sufficient instrumentation to show compliance with the specified quantitative criteria. Some requirements, as noted in the text, may be verified by the *inspection method*; i.e., verification of requirements by visual examination of the item or review of descriptive documentation [**VERIFY**].

• All required testing is the responsibility of the vendor who is seeking certification and is performed at a vendor-designated facility. The FBI neither performs the testing, nor witnesses the testing, nor receives the physical device being tested. However, the vendor must submit the digital test images to the FBI for independent analysis. These test images must be submitted in an uncompressed format[1] such as raw, TIFF, BMP, or PGM, at 8 bits per pixel (8 bpp, 256 gray levels). The vendor may also supply a technical description of the capture device and a test report of its internal test results, but neither of these documents will substitute for submission of the test images.

• It is expected that all testing will be performed on a single, representative unit of the product/model for which certification is being sought.

• The device shall be tested to meet the requirements in its normal-operating-mode, with the following possible exceptions:

[1] Uncompressed images that were previously compressed via a lossy compression, such as WSQ or JPEG, are not acceptable.

1) If the device has a strong anti-spoofing feature, of a type whereby only live fingerprints will produce an image, then this feature needs to be switched-off or bypassed in the target test mode of operation.

2) If the device's normal output is not a monochrome gray scale image, e.g., it is a binary image, minutia feature set, color image, etc., then the monochrome gray scale image (such as from an intermediate processing step) needs to be accessed and output in the test mode of operation.

3) Other normal-operating-mode features of the device similar or analogous to (1) and (2) may need to be disengaged.

• Prior to submission of test data, the vendor should open a dialogue with the FBI and describe the proposed test targets and test procedures, the goal being to obtain a consensus on suitable and acceptable targets and procedures. This is particularly important if the vendor has not previously obtained fingerprint capture device certification from the FBI utilizing the given imaging technology.

• The vendor is encouraged to analyze its test data results before submission to the FBI; test data analysis software (freeware) is available through the FBI for this purpose.

• If the test data analysis under the direction of the FBI indicates noncompliance with any of the PIV spec requirements, the vendor will be informed of the specific deficiencies and given an opportunity to correct the deficiencies and submit new test data.

1.2 FBI Point-of-Contact

Questions or concerns regarding the PIV spec, test targets, test procedures, acceptability of alternate targets/procedures, certification procedures, or availability of test analysis software, can be addressed to mtf@mitre.org, which acts on the FBI's behalf for purposes of PIV testing.

Questions and concerns may also be addressed to Eric Phillips of the FBI:

Eric M. Phillips

Telephone: 304-625-4531
Email: eric.phillips@leo.gov

2 Basic Requirements

The basic requirements for the PIV single finger capture device are given in Table 2-1.

Table 2-1. Basic PIV Device Requirements

Parameter	Requirement
Capture Size	≥ 12.8 mm wide by ≥ 16.5 mm high
True Optical or Native Resolution (Nyquist frequency)	≥ 500 ppi in sensor detector row and column directions
Resolution Scale	490 ppi to 510 ppi in sensor detector row and column directions
Image Type	Capability to output monochrome image at 8 bits per pixel, 256 gray levels (prior to any compression)

mm = millimeters ppi = pixels per inch ≥ greater than or equal to

2.1 Background

• The dimensions of the minimum capture size defined in Table 2-1 refers to a rectangle. If the capture area is some other shape, then the minimum size rectangle must fit within the boundaries of that shape, e.g., the minimum size square capture area would be 16.5 by 16.5 mm, or an elliptical capture area would need a minor axis width greater than 12.8 mm in order to fit a 12.8 mm wide rectangle within its boundary.

• The true optical or native resolution of the device must be at least 500 ppi; if the fingerprint is captured at a resolution level of, for example, 800 ppi, then that image is downsampled/rescaled to 500 ppi for output, using an appropriate rescaling technique. It is unacceptable to capture the fingerprint at any ppi level less than 500 ppi, and then upsample it to 500 ppi.

• The PIV device's aimpoint resolution scale should be 500 ppi, in which case the actual resolution scale might vary between 490 and 510 ppi, due, for example, to small directional or field angle dependent imaging perturbations. The aimpoint resolution scale could be greater than 500 ppi, up to 510 ppi, but should never be less than 500 ppi.

• All test target and test fingerprint scans are output as 8bpp, 256 gray level monochrome images, irregardless of the device's operational fingerprint image type output. Test fingerprint and operational fingerprint image polarity is expected to be: dark gray ridges with light gray valleys.

2.2 Requirements Compliance

• Verification that the device's <u>capture size</u> contains a rectangle of at least 12.8 mm wide by 16.5 mm high is performed by noting the fingerprint image width and height in pixels and dividing by the independently measured horizontal and vertical direction resolution scales, respectively, in pixels per inch.

• Verification that the device's true optical or native <u>resolution</u> is at least 500 ppi is performed by the SFR assessments in vertical and horizontal directions[2] (see section 4), and any available relevant documentation on the device, such as number of independent sensor pixels spanning the vertical and horizontal directions of the capture area.

• Verification that the device's <u>resolution scale</u> is between 490 ppi and 510 ppi, in both vertical and horizontal directions, is performed by the geometric accuracy measurements (see section 3) or, if none, from measurements on the image of the SFR target, in the vertical and horizontal directions, i.e., image pixel distance divided by corresponding target distance in inches.

• Verification that the device's <u>image type</u> output is 8 bits per pixel is performed by inspection of the test images to confirm that they are monochrome, together with results of the fingerprint gray range assessment (see section 6).

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[2] All references to vertical and horizontal directions in this document assume that the sensor detector columns and rows, respectively, align with these image directions. If such is not the case, then 'sensor dectector columns and rows' directions replaces all mention of 'vertical and horizontal' directions.

3 Geometric Accuracy

3.1 Requirements

Requirement #1 (across-bar)
A multiple, parallel bar target with a one cy/mm frequency is captured in vertical bar and horizontal bar orientations. The absolute value of the difference between the actual distance across parallel target bars, and the corresponding distance measured in the image, shall not exceed the following values, for at least 99% of the tested cases in each of the two orthogonal directions.

$$D \leq 0.0013, \qquad \text{for } 0.00 < X \leq 0.07$$

$$D \leq 0.018X, \qquad \text{for } 0.07 \leq X \leq 1.50$$

where:

$D = |Y-X|$
X = actual target distance
Y = measured image distance
D, X, Y are in inches

Requirement #2 (along-bar):
A multiple, parallel bar target with a one cy/mm frequency is captured in vertical bar and horizontal bar orientations. The maximum difference between the horizontal direction locations (for vertical bar) or vertical direction locations (for horizontal bar), of any two points separated by up to 1.5 inches along a single bar's length, shall be less than 0.027 inches for at least 99% of the tested cases in the given direction.

3.2 Background

Across-bar geometric accuracy is measured across the imaged Ronchi target bars, which must cover the total image capture area. The requirement corresponds to a positional accuracy of ± 1.8% for distances between 0.07 and 1.5 inches, and a constant ± 0.0013 inches (2/3 pixel at 500 ppi) for distances less than or equal to 0.07 inches. These across-bar measurements are also used to verify compliance with the device's resolution scale tolerance requirement given in Table 2-1.

Along-bar geometric accuracy is measured along the length of individual Ronchi bars in the image. For a given horizontal bar, for example, the maximum difference between bar center locations (in vertical direction), determined from bar locations measured at multiple points along the bar's length, is compared to the maximum allowable difference requirement (analogously for vertical bar). This requirement is to ensure that pincushion, barrel, or other types of distortion are within acceptable bounds.

3.3 Target

The *multiple, parallel bar target* refers to a Ronchi target, which consists of a series of parallel black bars with white/clear spaces between, at a spatial frequency of 1.0 cy/mm; i.e., each black bar and each white/clear space between two adjacent bars has a width of 0.50 mm, as illustrated in Figure 3-1.

Ronchi targets are commercially available on a number of substrates, e.g., transparent film, reflective mylar, and as a chrome-on-glass target. However, it is the PIV vendor's responsibility to identify a 1.0 cy/mm Ronchi target that will produce a suitable, measurable image in the vendor's PIV device; this may entail experimentation and design/fabrication of a custom Ronchi target.

The Ronchi target must cover the entire capture area with vertical bars in one image and horizontal bars in another image, each aligned to within 0.5 degrees of the relevant axis (vertical or horizontal). Acquiring a single image containing both vertical and horizontal bars, such as in a cross-hatched pattern or segmented vertical and horizontal bars, is unacceptable. If the PIV device operates under optical imaging principles then, in order to achieve more uniform contact, it is acceptable to use an index-of-refraction matching liquid between the target and the device's fingerprint platen.

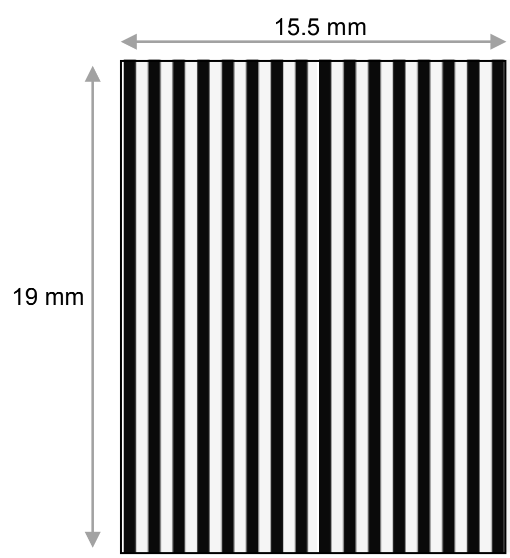

Figure 3-1 1.0 cy/mm Ronchi Target
(Covers the Example 15.5 x 19 mm Device Capture Area)

3.4 Test Procedures

The following outlines the procedures for measuring the PIV device's geometric accuracy and resolution scale; these measurements are performed by the *geo* software application, supported by *creategeofile* and *viewgeo* applications, which are on the Test Tools CD (see Appendix A). A more detailed description of the computations in *geo* is given in Appendix B.

3.4.1 Across-Bar Geometric Accuracy and Resolution Scale

The goal is to acquire measurements that comprehensively cover a Ronchi target image, in continuous, 0.25 inch wide measurement strips running the height (vertical direction measurements) or width (horizontal direction measurements) of the device capture area. If imaging artifacts caused by target blemishes, dust, target-device contact nonuniformities, etc. prevent successful measurement in some isolated areas, then measurement locations would need to be shifted.

For each measurement strip, measurements are taken across all independent 1-bar cycles (1-bar distance) and 6-bar cycles (6-bar distance). All distances for geometric accuracy are measured from bar center to bar center in pixel units, as illustrated in Figure 3-2. A bar center is located by first detecting that bar's left and right edges along a 0.25 inch edge height (for vertical bar), and then bisecting the bar's two edges, taking skew angle into account.

The device's output resolution scale is first measured over 6-bar cycles, which is used to verify compliance with the pixels per inch resolution scale requirement and establish a pixels per inch value that can be used to convert subsequent geometric accuracy measurements to inches. Next, measurements are made to test the geometric accuracy over a short distance of 1-bar cycle, and then over the longer distance of 6-bar cycles. The pixel measurements are then converted to inches using the previously computed <u>average</u> resolution for the given measurement strip.

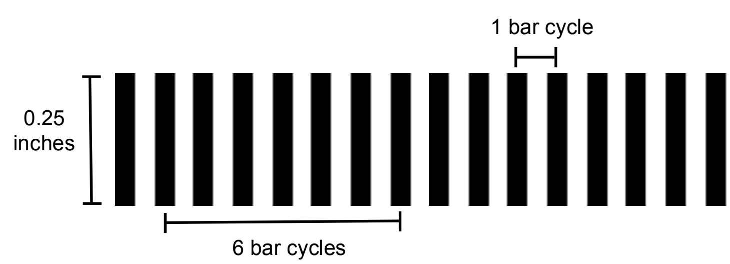

Figure 3-2. Six-Bar and One-Bar Distance Measurements

3.4.2 Along-Bar Geometric Accuracy

This test for distortion utilizes the same Ronchi target images used for across-bar geometric accuracy assessment. All distances for along-bar geometric accuracy are first measured from local bar center location to local bar center location in pixel units. The difference in fractional rows between two bar centers is converted to inches by dividing by the average ppi of the two corresponding measurement strips. Figure 3-3 illustrates a single measurement for a single horizontal bar in a device that has a 1.5 inch capture width. In this example, the maximum vertical deviation "H" occurs for the bar center in center field compared to the bar center at the edge of the field, but note that the maximum vertical deviation could occur at other bar center location pairs.

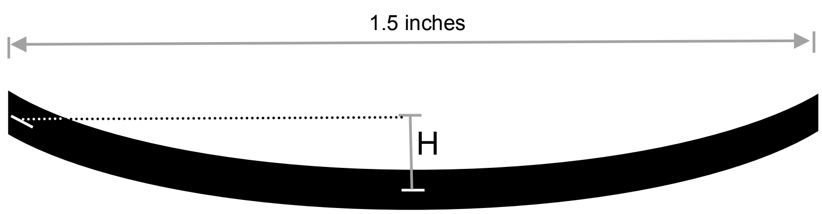

Figure 3-3. Along-Bar Geometric Accuracy Assessment (Vertical Height "H" is Test Sample Value)

3.5 Requirements Compliance

The across-bar geometric accuracy requirement is complied with if at least 99 percent of the tested cases are within the minimum and maximum distance limits given in Table 3-1, in the vertical and horizontal directions.

Table 3-1. Geometric Accuracy Requirements

Measurement	Correct Value	Directional Requirement Met if:
1-bar distance	0.03937	≥ 99% in range: 0.03807 to 0.04067
6-bar distance	0.23622	≥ 99% in range: 0.23197 to 0.24047

The along-bar geometric accuracy requirement is complied with if at least 99 percent of the test measurement values ("H" in Figure 3-3) are less than 0.027 inches, in the vertical and horizontal directions.

The resolution scale requirement is complied with if the average resolution scale is between 490 ppi and 510 ppi in the vertical and horizontal directions (see section 2).

3.6 No-Test Option

The across-bar and along-bar geometric accuracy requirements defined in section 3.1 may be verified by the *Inspection Method*[3] instead of the *Test Method*, if the fingerprint capture device has all 5 of the following characteristics, and adequate documentation for each of these characteristics is submitted to the FBI.

1) Construction of a suitable 1.0 cy/mm Ronchi target that will produce measurable images with the capture device requires extraordinary effort and resources.

2) The sensor is a two-dimensional staring array (area array) on a plane (not curved) surface.

3) There is no movement of device components, nor purposeful movement of the finger, during finger image capture.

4) There is no device hardware component (e.g., a lens or prism) between the finger and the sensor, with the possible exception of a membrane on the sensor surface which, if present, does not alter the geometry of the imaged finger.

5) Any signal processing applied to the captured finger image does not alter the geometry of the captured finger image.

A few definitive sentences or paragraph devoted to 'proof' of each of the above 5 characteristics may suffice; however, the FBI reserves the right to request additional backup information on a case-by-case basis. In the event that the *Inspection Method* is used to verify compliance with the across-bar and along-bar geometric requirements, then the resolution scale requirement is verified with the SFR target (by the *Test Method*), as described in section 2.2.

[3] *Inspection Method* - verification by review of descriptive documentation, without the use of laboratory equipment or procedures [**VERIFY**].

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4 Spatial Frequency Response (SFR)

4.1 Requirements:

The spatial frequency response shall normally be measured by either using a bi-tonal, high contrast bar target, which results in the device's Contrast Transfer Function (CTF), or by using a continuous-tone sine wave target, which results in the device's Modulation Transfer Function (MTF). If the device cannot use a bar target or sine wave target, i.e., a useable/measurable image cannot be produced with one of these targets, then an edge target can be used to measure the MTF[4].

The CTF or MTF shall meet or exceed the minimum modulation values defined in equation 4-1 (for CTF) or equation 4-2 (for MTF), over the frequency range of 1.0 to 10.0 cy/mm, in both the detector row and detector column directions, and over any region of the total capture area. Table 4-1 gives the minimum CTF and MTF modulation values at nominal test frequencies. None of the CTF or MTF modulation values in the 1.0 to 10.0 cy/mm range shall exceed 1.12, and the target image shall not exhibit any significant amount of aliasing in that range.

Equation 4-1:

$$\mathrm{CTF} = -5.71711\mathrm{E}\text{-}5 * f^4 + 1.43781\mathrm{E}\text{-}3 * f^3 - 8.94631\mathrm{E}\text{-}3 * f^2 - 8.05399\mathrm{E}\text{-}2 * f + 1.00838$$

Equation 4-2:

$$\mathrm{MTF} = -2.80874\mathrm{E}\text{-}4 * f^3 + 1.06255\mathrm{E}\text{-}2 * f^2 - 1.67473\mathrm{E}\text{-}1 * f + 1.02829$$

(equations valid for f = 1.0 to f = 10.0 cy/mm)

[4] If it is conclusively shown that neither a sine wave target, nor bar target, nor edge target can be used in a particular device, other methods for SFR measurement may be considered.

Table 4-1. Minimum CTF and MTF Requirements at Nominal Test Frequencies

Frequency (f) in cy/mm at object plane[5]	Minimum CTF Modulation when using Bar Target	Minimum MTF Modulation when using Sine Wave or Edge Target
1.0	0.920	0.871
2.0	0.822	0.734
3.0	0.720	0.614
4.0	0.620	0.510
5.0	0.526	0.421
6.0	0.440	0.345
7.0	0.362	0.280
8.0	0.293	0.225
9.0	0.232	0.177
10.0	0.174	0.135

4.2 Background

The 1.12 upper limit for modulation is to discourage image processing that produces excessive edge sharpening, which can add false detail to an image and/or excessive noise.

The target can be fabricated of any material and on any substrate that is suitable for imaging and measurement with the given device, working in reflective, transmissive, or other signal transfer mode, and in either two-dimensions or three-dimensions.

If the same imaging system were to simultaneously capture a bar target, which is a truncated square wave, and a sine wave target, then the CTF computed from the bar image will have a higher modulation value than the MTF computed from the sine wave image, at any given frequency. This difference is in accordance with the theory and is the reason why the minimum CTF spec is higher than the minimum MTF spec.

Aliasing can be investigated quantitatively and, for sine wave or bar images, from visual observation of the softcopy-displayed images. Although some amount of aliasing-due-to-decimation is often unavoidable at the higher frequencies, aliasing-due-to-upscaling[6] is

[5] The object plane is the plane of the finger surface which is being captured by the PIV device.

[6] In this document, “upscaling” is defined as capturing the image at less than 500 ppi and then performing signal processing (rescaling, resampling, interpolation, etc.) to bring the image up to a pseudo 500 ppi resolution scale.

not acceptable at any frequency up to the maximum output resolution (Nyquist frequency) of 10 cy/mm.

If the relation between the device's output gray level and input signal level is nonlinear, then this needs to be explicitly accounted for in the computations for MTF or CTF, since these metrics are strictly defined only for a linear or linearized system. Measurement of the input-output relation should therefore be considered as a derived requirement.

4.3 Target

It is not required that the CTF or MTF be obtained at the exact frequencies listed in Table 4-1; however, the CTF or MTF does need to cover the listed frequency range, and contain frequencies close to each of the listed frequencies. For any bar target used, or a custom sine wave target, the target frequency patterns must be within 0.49 cy/mm of each of the frequency increments: 1, 2, 3, 4, 5, 6, 7, 8, 9 cy/mm, and within 0.25 cy/mm of 10 cy/mm.

Also, a minimum number of sine wave cycles or bars is needed at each frequency, in order to: (1) ensure capturing the optimum phase between the device's sensor pixels and the target sine waves or bars, (2) have enough samples available for accurate measurement of aliasing, and (3) obtain an accurate measure of modulation. Table 4-2 specifies the minimum number of sine wave cycles or bars as a function of frequency.

Table 4-2. Minimum Number of Target Bars or Sine Wave Cycles (500 ppi Device)

Target Frequency (f)	Minimum Number of Bars or Sine Wave Cycles
1 cy/mm	4
> 1 to 4 cy/mm	5
> 4 to 10 cy/mm	10

Notes
Bar Target: bar length must be at least 10 times bar width; width of space between parallel bars equals bar width.
Sine Target: length of sine wave in direction perpendicular to sinusoidal variation must be at least 5/f.

4.3.1 Sine Wave Target

In some PIV devices it may be possible to use a continuous gray-tone sine wave target. Sine wave targets are commercially available on reflective and transmissive substrates in variety of sizes, see Figure 4-1 for one example. These targets include a calibrated step tablet for computation of the imaging device's input-output relation. The sine wave modulation values are also supplied by the target manufacturer, which are used to normalize the device output modulation values to arrive at the device MTF.

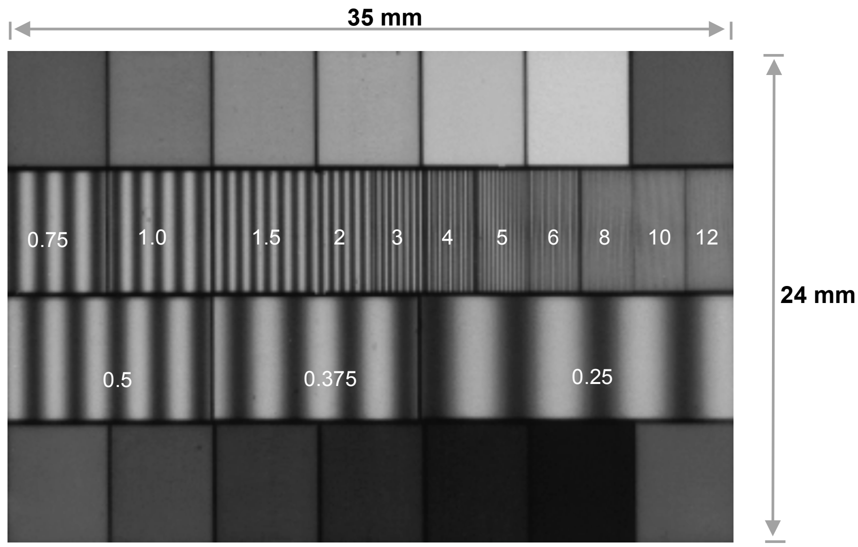

Figure 4-1. Commercial Sine Wave Target (0.25 to 12.0 cy/mm Labels Not Part of Target)

4.3.2 Bar Target

A sine wave target may be too large or may be on a substrate (photo paper or film) that is incompatible with imaging through the PIV device. Another option is to use a bi-tonal, black & white, bar target, which can be fabricated on additional substrates, such as chrome-on-glass. An example bar target is shown in Figure 4-2.

The bar target must contain at least one very low frequency component; i.e., a large square, single bar, or series of bars whose effective frequency is no greater than 3% of the Nyquist frequency. This low frequency component is used in normalizing the CTF, so it must have the same density on the target as the other target bars. The 3% of Nyquist translates into ≤ 0.3 cy/mm for a 500 ppi device, implying a bar width ≥ 1.7 mm.

Bar targets generally do not include a step tablet, so the device's input-output relation would have to be measured with other targets.

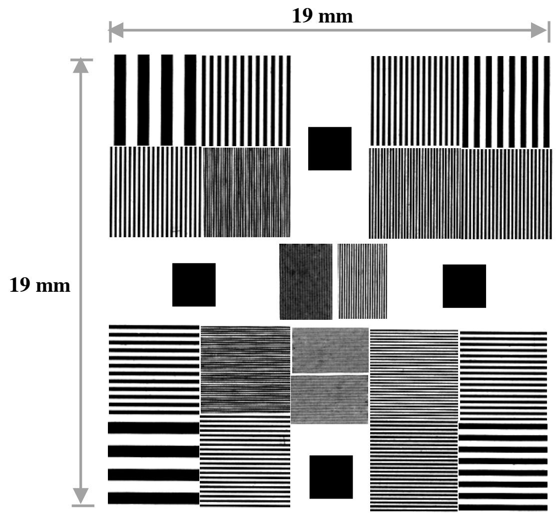

Figure 4-2. Illustration of Compact Bar Target with Vertical & Horizontal Bars (1,2,3,4,5,6,7,8,9,10 cy/mm)

4.3.3 Edge Target

If neither a sine wave nor bar target can be used, then the next choice should be an edge target. This target is geometrically simple, dimensionally compact, and can be fabricated on a wide variety of substrates. The SFR output spatial frequencies computed from an edge are a function of the selected measurement window size and the specific edge analysis application used[7].

Following are some of the desirable attributes for an edge target; Figure 4-3 illustrates an example edge target.

- Edge should be straight along its length.

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[7] For example, in the *mitre_sfr* application on the Test Tools CD:
cy/mm increment = 10 / N, where N is the number of pixels used in measurement on one side of edge, N should never be less than 20.

- Edge should be sharp enough such that its spatial frequency response has little or no impact on the device SFR measurement.

- The light and dark sides of the edge must have uniform density, with density values such that neither side of the edge is at saturation when imaging through the device. Ideally, the light side of the imaged edge would closely correspond to the average gray level of fingerprint valleys captured with the PIV device, and the dark edge side would correspond to the average gray level of imaged fingerprint ridges.

- Each side of the edge should extend at least 3 mm (width of one side of vertical edge or height of one side of horizontal edge).

- Edge length should be at least 8 mm (height of vertical edge, width of horizontal edge).

- There should be a pair of fiducial marks in the vertical and horizontal directions that correspond to known target distances; with some edge targets the edge itself could serve as fiducials, as could a frameline scribed around the edge. These fiducials would be used to measure the directional ppi, which is a necessary input to the *sfr* software application, and may also be needed for resolution scale verification. The latter would be true if the *Test* method was not used for geometric accuracy assessment, because in that case only the edge target is available to verify compliance with the resolution scale requirement.

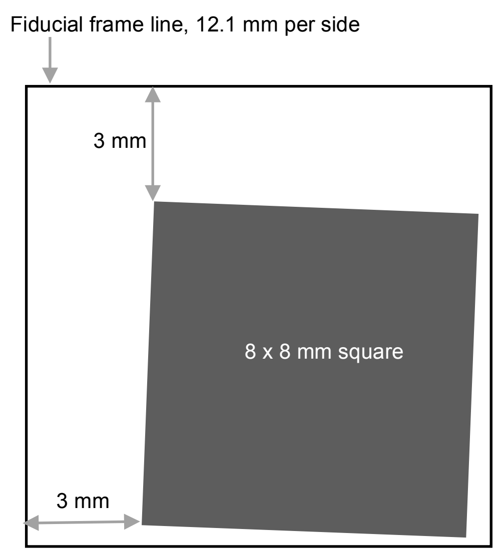

Figure 4-3. Illustration of Edge Target with 2 Usable Perpendicular Edges (Dark Square Tilted 5.2° with respect to Sensor Row, Column Directions)

4.4 Test Procedures with Sine Wave or Bar Target

The following outlines the procedures for computing the PIV device's MTF from a sine wave target, or CTF from a bar target, by using MITRE's *mtf* software application. A more detailed description of the computations in *mtf* is given in Appendix B.

1) A target data file is prepared containing information on the layout and dimensions of the target components, sine wave or bar target modulation values, and step tablet information (target step tablet data for sine wave target, or target and image step tablet data for bar target imaged through nonlinear device).

2) The target is positioned on the device's platen and aligned to within 0.5 degrees of the horizontal and vertical, i.e., with respect to the device's sensor row and column directions[8].

3) The target is captured with the PIV device, after adjusting the device parameters (such as illumination, gain settings, etc.) to ensure that the sine wave peaks and valleys, or bar and space, are not at saturation. [If bar target semi-saturation is unavoidable due to its high contrast, then it is better to semi-saturate the white spaces at gray = 255 rather than the black bars at gray = 0.]

4) The *mtf* application is run, with inputs consisting of image coordinates, target data file, digital image, and various user-selectable options displayed at runtime.

5) *Mtf* first computes the directional ppi scale and target alignment angle; this information is used together with the input data file to locate the row and column of each sine wave (or bar) frequency pattern and (for sine wave) the density patch locations, within the image. The single, representative sine wave (or bar cycle) modulation in each imaged frequency pattern is then determined from the sample modulation values collected from within that pattern. For a sine wave image, or for a bar imaged through a nonlinear device, this peak_image_ modulation is computed in target space, after converting through the output-to-input relation, as

peak_image_modulation = (maximum - minimum) / (maximum + minimum)

The PIV device's MTF or CTF is defined at each frequency as:

peak_image_modulation / M

where M is the sine wave target modulation at the given frequency for MTF, or M is the zero frequency modulation for CTF. The latter is computed from the very low frequency

[8] Note that while the sine wave or bar target is aligned to the vertical or horizontal (within 0.5 degrees), an edge target is <u>deliberately misaligned</u> to the vertical or horizontal, by 5.2 degrees.

bar pattern (≤ 0.3 cy/mm), in gray level image space if the device has a linear response, or in target space if the device has a nonlinear response.

6) Aliasing is also measured in *mtf*, because it is a potential source of unwanted image artifacts, e.g., pronounced aliasing may produce false detail in the image, such as a pseudo-ridge pattern. Aliasing can also indicate that the imaging device is operating in an unacceptable mode. Aliasing is measured by first computing a sequence of one-dimensional discrete Fourier transforms (DFT) of the row-averaged gray levels in each frequency pattern, then inspection of the relative strengths of the DFT side lobes (harmonics) indicates the degree of aliasing-from-decimation, and the location of the DFT main lobe indicates whether or not aliasing-from-upscaling is present, which would be unacceptable. More discussion of aliasing detection is given in Appendix C.

4.5 Test Procedures with Edge Target

MITRE's *sfr* software application can be used to compute the MTF from an imaged edge target. This *sfr* application follows the relevant international standard [**ISO**]; the basic processing steps are as follows:

1) The target edge is placed on the device at a tilt angle of 5.2 degrees (± 0.5 degrees), alternately with respect to the sensor row and column directions.

2) If the device has a nonlinear response then the input-output relation is independently measured and a file of the input-output data point pairs representing the nonlinearity is prepared.

3) The edge target is capture; the image is displayed and a rectangular box is defined encompassing both sides of the edge, which becomes the measurement area.

4) MITRE's *sfr* performs all its computations in target space, so it first converts the image gray levels back to target space units, using the input-output data file if nonlinear.

5) The small edge tilt angle results in a multitude of target - sensor phasings being captured with the single edge image. This allows *sfr* to left/right shift, subsample and average rows (for vertical edge) within the measurement rectangle, resulting in a single, super-sampled edge spread function (edge profile) that is independent of the target-edge phasing in any given original image row.

6) The edge spread function is noise filtered with a Hamming filter and then differentiated to obtain the line spread function.

7) The line spread function is Fourier transformed and normalized to 1.0 at zero frequency by dividing by the area under the line spread function, resulting in the MTF.

8) The MTF obtained in step 7 is the device MTF if the target edge is a very sharp "knife" edge with respect to the device's resolution capability. Alternatively, if the target edge is not a knife edge, but its spatial frequency response has been independently measured, then division of the MTF in step 7 by the target's spatial frequency response will again result in the device MTF. Lastly, if the target edge is not a knife edge and it has not been independently measured, then the measured MTF is the device MTF multiplied by the target MTF.

4.6 Measurement of Device Input-Output Relation

The input - output relation needs to be measured, either to 'prove' that the relation is linear[9], or to establish the actual nonlinear relation which would then need to be explicitly taken into account when computing the MTF or CTF.

Since a COTS sine wave target incorporates its own step tablet; the *mtf* application can compute the input-output relation directly from this step tablet and take it into account in the sine wave MTF computations (whether it is nonlinear or linear).

The input-output relation must be independently measured when using a bar target or edge target which does not contain a step tablet component. Measurement can be performed, for example, by inserting a series of neutral density filters into the imaging path, or by similarly varying the sensor exposure in discrete, known steps while imaging the blank platen, or by imaging a physical, pre-calibrated step tablet. Whatever method is used, it must produce enough steps to adequately define the input - output relation over the range of gray levels exhibited by the imaged sine wave, bar, or edge target. For example, Figure 4-4 illustrates a nonlinear input - output relation used with an edge target, where the edge image maximum gray and minimum gray levels are within the step tablet measurement range.

[9] Merely referring to a sensor manufacturer's spec sheet that might state, e.g., that their 'CMOS sensor chip has a linear response', is inadequate, because that sensor is integrated into the PIV vendor's device, which is a System, with its own set of hardware, firmware, and software signal processing. It is the linearity or nonlinearity of this total system that needs to be established, not the standalone linearity of the single component sensor chip.

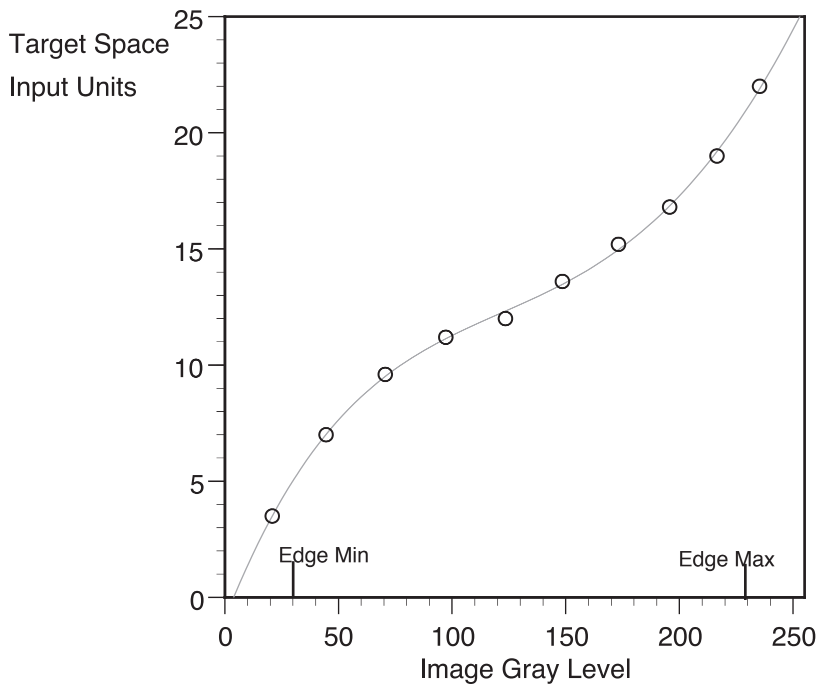

Figure 4-4 Example Nonlinear Input-Output Relation

4.7 Requirements Compliance

The SFR requirement for a 500 ppi PIV device is complied with if, in both the detector (sensor) row and column directions, and over any region of the total capture area:

(1) the measured CTF is no less than that defined by equation 4-1, or the measured MTF is no less than that defined by equation 4-2 (whichever applies), at each measured frequency in the range of 1.0 to 10.0 cy/mm
and,
(2) the measured CTF or MTF (whichever applies) is no greater than 1.12 at any frequency in the range of 1.0 to 10.0 cy/mm
and,
(3) any detected aliasing-due-to-decimation is within acceptable limits, where the acceptable amount decreases with decreasing frequency, reaching zero acceptable amount for frequencies less than 7cy/mm
and,
(4) no aliasing-due-to-upscaling is detected at any frequency in the range of 0.0 to 10.0 cy/mm.

5 Gray Level Uniformity

5.1 Requirements

#1 - Adjacent Row, Column Uniformity
At least 99% of the average gray levels between every two adjacent quarter-inch long rows and 99% between every two adjacent quarter-inch long columns, within the capture area, shall not differ by more than 1.5 gray levels when scanning a uniform dark gray target, and shall not differ by more than 3.0 gray levels when scanning a uniform light gray target.

#2 - Pixel-to-Pixel Uniformity
For at least 99.0% of all pixels within every independent 0.25 by 0.25 inch area located within the capture area, no individual pixel's gray level shall vary from the average by more than 8.0 gray levels when scanning a uniform dark gray target, and no individual pixel's gray level shall vary from the average by more than 22.0 gray levels when scanning a uniform light gray target.

#3 - Small Area Uniformity
For every two independent 0.25 by 0.25 inch areas located within the capture area, the average gray levels of the two areas shall not differ by more than 3.0 gray levels when scanning a uniform dark gray target, and shall not differ by more than 12.0 gray levels when scanning a uniform light gray target.

#4 - Noise
The noise level, measured as the standard deviation of gray levels, shall be less than 3.5 in every independent 0.25 by 0.25 inch area located within the capture area, when scanning a uniform dark gray target and a uniform light gray target[10].

5.2 Target

A uniform light gray target and a uniform dark gray target are produced on any substrate that is compatible with imaging in the given PIV device. For example, reflective and transmissive uniform gray targets are commercially available; see Appendix A for sources. Alternatively, pseudo-targets may be substituted for physical targets. The pseudo-target concept images the blank capture area with the sensor exposure turned up or down (but not off!), by varying exposure time or illumination/excitation. Each target or pseudo-target must cover the entire capture area of the PIV device.

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[10] Note that no attempt is made to isolate different sources of noise or separately measure different types of noise; the computed noise represents all noise types and sources taken together.

5.3 Test Procedures and Requirements Compliance

The following gives the procedures for measuring the PIV device's uniformity, with respect to requirements 1, 2, 3, and 4. These measurements are performed by MITRE's *snr* software application, which is on the Test Tools CD (see Appendix A); *snr* requires that the light gray image and dark gray image have the same size (width and height).

The PIV device is adjusted so that the average image gray level from the light gray target is at least 4.0 gray levels below the maximum image gray level attainable with the device, and the average image gray level from the dark gray target is at least 4.0 gray levels above the minimum image gray level attainable with the device. For a full 8 bpp range image (0 to 255 gray levels), this implies that the light gray image is less than or equal to 251.0 and the dark gray image is greater than or equal to 4.0. However, if the device is setup such that some gray levels cannot occur, e.g., due to saturation or clipping, then the maximum or minimum value must be adjusted accordingly. For example, if gray levels 253, 254, 255 can never occur, then the maximum gray level would be 252 and the light gray image would need to be less than or equal to 248.0. Ideally, the average light gray image would be near the gray level of imaged fingerprint valleys and the average dark gray image would be near the gray level of imaged fingerprint ridges, that are typically acquired with the device (but still holding to the 4 gray level delta from maximum and minimum attainable gray levels). In all cases the polarity of the light and dark gray images are expected to be the same as for fingerprint scans, i.e., light uniform gray image corresponds to fingerprint valleys and dark uniform gray image corresponds to fingerprint ridges.

Since these uniformity tests involve pixel-to-pixel and small-area difference measurements, foreign artifacts such as dust, target scratches, bubbles, or pinholes can adversely affect the results. Care in testing needs to be taken, e.g., use quality, uniform targets and clean the device's platen. If a small quantity of measurement samples still contain residual foreign artifacts, for which it can be ascertained (such as by visual inspection of the image) that they are not part of the device, then these samples may be discounted from the final results.

Due to the fact that single finger device capture areas are relatively small and are generally not a multiple of 0.25 inches in width or height, adhering to strict independence of all 0.25 inch measurement windows, row or column segments, could result in a substantial percentage of the capture area not being measured. To overcome this problem, it may be necessary to slightly overlap some of the adjacent 0.25 inch windows, row or column segments that are used in the various measurements. For example, if the width of the capture area is 375 pixels, then exactly 3 independent quarter-inch windows (each 125 pixels wide at 500 ppi) will fit across the width. However, if the capture area width is 350 pixels, then the leftmost and center windows can still be independent of each other, but the center and rightmost windows would have to overlap by 25 pixels in order to cover the capture width; with no overlap, only 2 windows across could be measured in this case and 29% of the width (100 columns) would not be measured. [The *snr* application automatically computes the overlap when necessary.]

5.3.1 Adjacent Row, Column Uniformity (Requirement #1)

The average pixel gray levels of all 0.25 inch long horizontal row segments and all 0.25 inch long vertical column segments are computed over the entire capture area, for the light gray and dark gray images.

The magnitude of the difference between the average gray levels of every two adjacent row segments and every two adjacent column segments are computed for each image. Figure 5-1 illustrates the measurements for row segments.

Compliance with the requirement is achieved when at least 99.0% of the differences between adjacent row segment averages, and at least 99.0% of the differences between adjacent column segment averages, are less than or equal to 1.5 gray levels in the dark gray image, and are less than or equal to 3.0 gray levels in the light gray image.

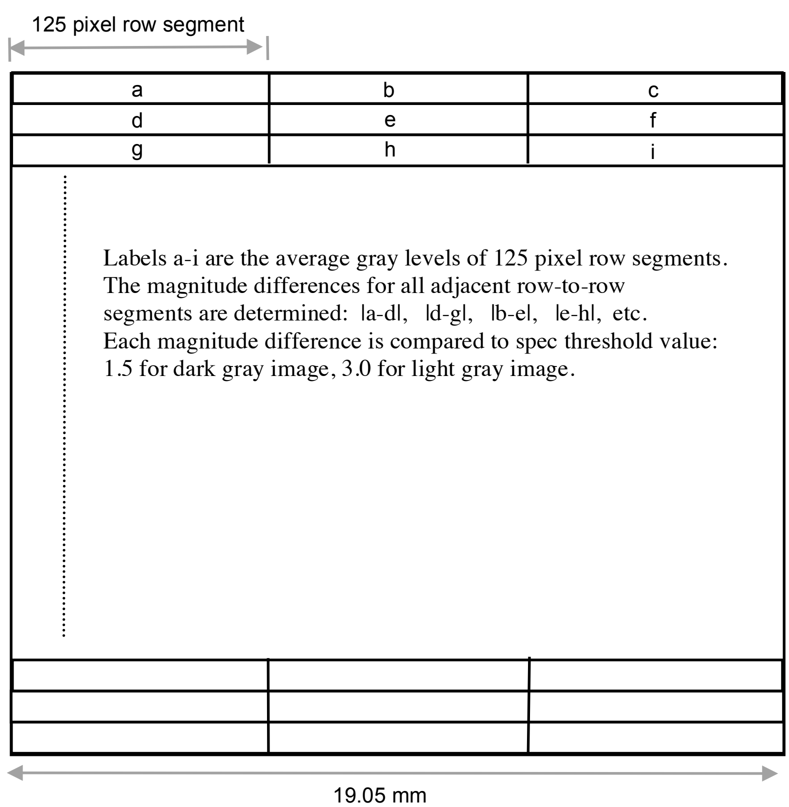

Figure 5-1. Row-to-Row Segment Uniformity Measurements (375 Pixel Wide Capture Area)

5.3.2 Pixel-to-Pixel Uniformity (Requirement #2)

The locations of the minimum number of quarter-inch windows that cover the capture area are identified for the light gray and dark gray images.

The average gray level for each quarter-inch window, rounded to the nearest whole number (nearest integer value), is computed for each image.

The absolute value of the difference between the average of a given quarter-inch window and each of the individual pixel gray levels within that window is computed. Figure 5-2 illustrates the procedure (a 500 ppi device has 125 x 125 = 15,625 test values in each quarter-inch window).

Compliance with the requirement is achieved when no more than 1.0% of the pixels in each dark gray image window are more than 8 gray levels away from the window average, and no more than 1.0% of the pixels in each light gray image window are more than 22 gray levels away from the window average.

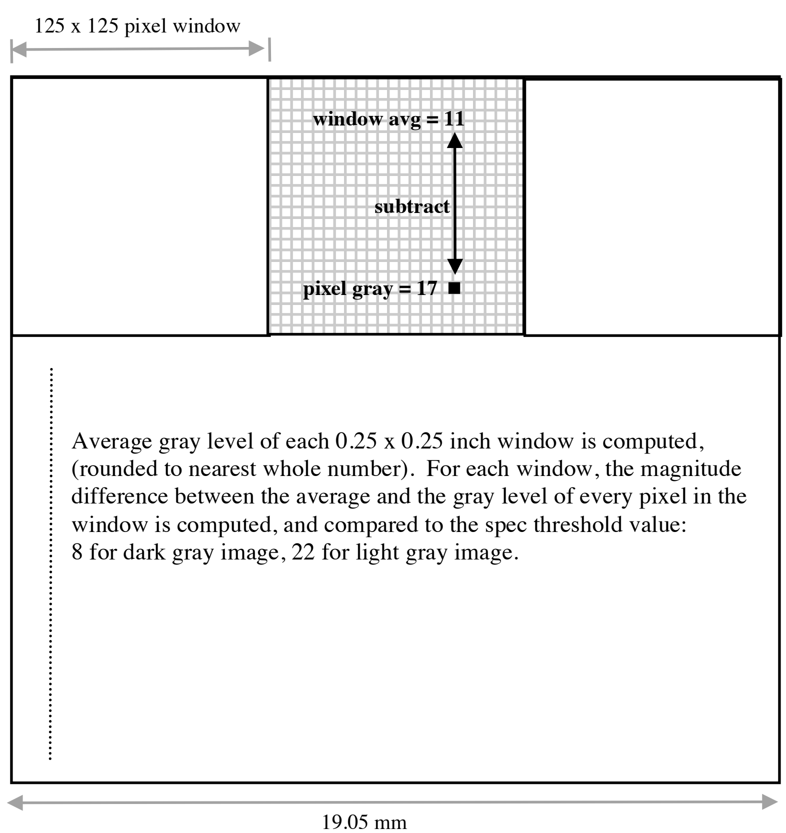

Figure 5-2. Pixel-to-Pixel Uniformity Measurements (375 Pixel Wide Capture Area)

5.3.3 Small Area Uniformity (Requirement #3)

The locations of the minimum number of quarter-inch windows that cover the capture area are identified, for the light gray and dark gray images.

The average gray level for each quarter-inch window is computed for each image (without rounding to whole number) as illustrated in Figure 5-3.

The absolute value of the difference between the gray level averages for every possible pairing of quarter-inch windows is computed. Compliance with the requirement is achieved when the largest difference for the dark gray image is less than or equal to 3.0 gray levels, and the largest difference for the light gray images is less than or equal to 12.0 gray levels.

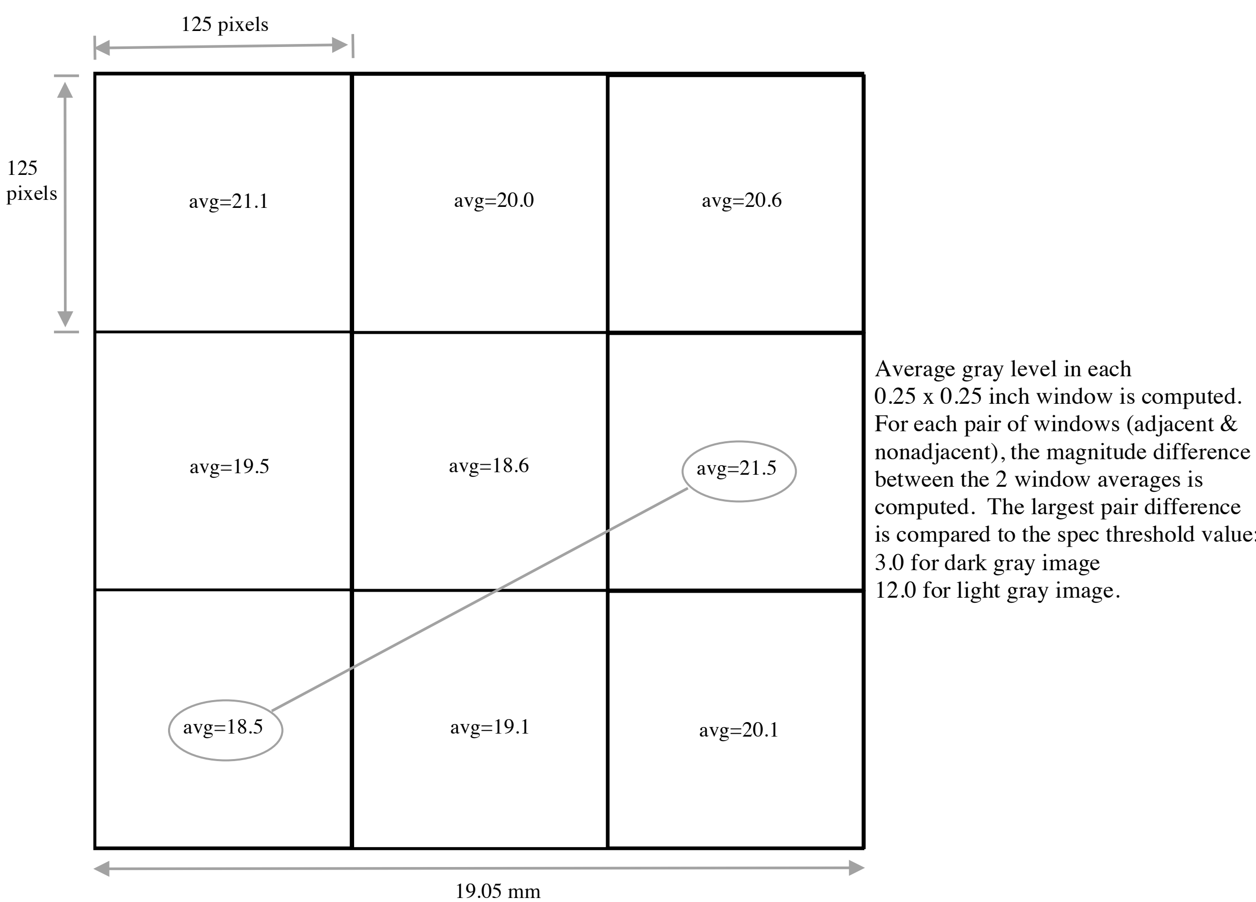

Figure 5-3. Area-to-Area Uniformity Measurements (375 x 375 Pixel Capture Area)

5.3.4 Noise (Requirement #4)

The locations of the minimum number of quarter-inch windows that cover the capture area are identified, for the light gray and dark gray images.

The standard deviation of pixel gray levels (σ) is computed within each quarter-inch window in the light gray and dark gray images, where,

$$\sigma = \sqrt{\frac{\Sigma\left(G_i - \overline{G}\right)^2}{n-1}}$$

$\overline{G}$ = average gray level in given window
G_i = gray level of ith pixel in given window
n = number of pixels in given window

Compliance with the requirement is achieved when the standard deviation of pixel gray levels (σ) is less than 3.5 in every 0.25 by 0.25 inch window located within the capture area, when scanning a uniform dark gray target and a uniform light gray target.

6 Fingerprint Image Quality

6.1 Requirements

Requirement #1 - Fingerprint Gray Range:
At least 80.0 % of the captured individual fingerprint images shall have a gray-scale dynamic range of at least 150 gray levels.

Requirement #2 - Fingerprint Abnormalities
The images must be true representations of the input fingerprints. Artifacts, anomalies, false detail, or cosmetic image restoration effects detected on the fingerprint images, which are due to the device or image processing, shall not significantly adversely impact supporting the intended applications.

Requirement #3 - Fingerprint Sharpness and Detail Rendition:
The sharpness and detail rendition of the fingerprint images, due to the device or image processing, shall be high enough to support the intended applications.

6.2 Target

The vendor submits a set of 20 finger images captured with the PIV device, nominally acquired from 10 different subjects, with 2 fingers per subject (preferably left and right index fingers)
and,
the vendor submits a set of 5 index finger repeat images captured with the PIV device, from a single finger of a single subject. It is expected that this finger will be completely lifted off of the device and then re-presented to the device for each succeeding scan, i.e., do not simply lay the finger on the device and capture it 5 times in succession.

These images shall be submitted for assessment in 8 bpp, monochrome (grayscale) uncompressed form, with polarity such that ridges are dark and valleys are light, in some common format such as TIFF, PGM, BMP, or raw. The images shall not have been previously compressed/decompressed from any lossy compression, such as JPEG or WSQ. If raw format images are supplied, the width and height in pixels, and number of header bytes (if any) must also be supplied. Although BMP format images may be submitted, note that the analysis software on the Test Tools CD (see Appendix A) is not compatible with BMP format.

6.3 Test Procedures

6.3.1 Fingerprint Gray Range

A single subimage is defined within the image capture area. This subimage is sized and positioned such that it includes most or all of the fingerprint. Specifically, if the background has a constant gray level, then the subimage can be sized to include the entire fingerprint together with an arbitrary amount of background. However, if the background has substantially varying gray levels, then the subimage needs to be sized to avoid the background and only include all, or a substantial portion of the fingerprint. Figure 6-1 illustrates these rules for two cases using a subimage width, height proportional to the image width, height.

The gray range is computed within the subimage in each of the 20 finger capture images. This gray range is equal to the total number of gray levels in the subimage which contain signal, where a gray level bin is counted as containing signal if it contains at least a minimum number of pixels.

Background:
- Since a subimage contains tens of thousands of pixels, the expectation is that if a given gray level bin contains signal, then it would be populated by more than just a few pixels, since all signal pixels are spread out between no more than 256 gray level bins. Therefore, if a gray level bin contains very few pixels it is probably just noise; e.g., dark current, crosstalk, or amplifier noise. A threshold value of 5 pixels can be used to separate gray level bins populated only by noise, from bins populated by signal (+ noise).

- The definition of gray range in this section is not necessarily equal to the simple difference between maximum gray level and minimum gray level, e.g., if there is a break/gap in the gray level histogram the two quantities are not the same.

- This analysis is performed by the *grayfinger* software application, which is on the Test Tools CD (see Appendix A). In *grayfinger*, the user selects a subimage size based on a percent of the image width and height, and that subimage is then centered within the total image area.

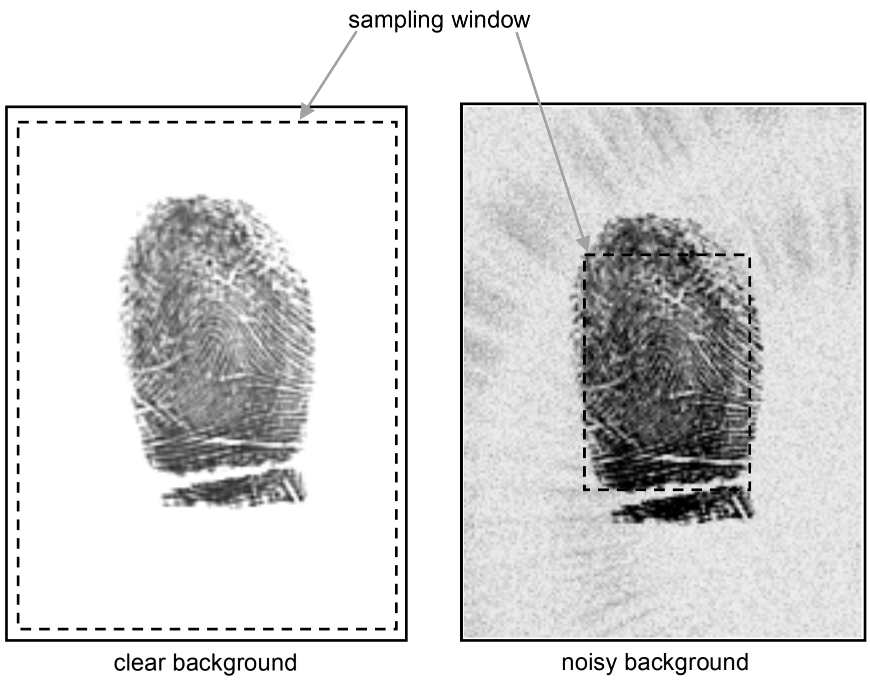

Figure 6-1. Example Subimage Definition for Fingerprint Gray Range Assessment

6.3.2 Fingerprint Abnormalities

The fingerprint images are examined to determine the presence of abnormalities which are due to the device with its associated image processing. Initial assessment is performed by close visual inspection of the displayed images. If a significant abnormality is visually detected, then the next stage is to decide whether it is on the input finger (which would be ignored), or is due to the PIV device with its associated image processing. If it is due to the PIV device or image processing, then appropriate image analysis techniques are applied to measure and quantify it[11]. In some cases, if there is cause for concern that false detail or cosmetic image restoration effects may exist in the fingerprint images, then the FBI may request comparison livescans captured from the same subjects, same fingers as with the PIV device, but using an FBI IAFIS Appendix F certified plain livescan device.

Following are some types of abnormalities which may be investigated, among others, depending on the images:

- jitter noise effects
- localized offsets of fingerprint segments

[11] Due to the varied nature of potential abnormalities, there is no single test tool or analysis method that can be applied to all cases.

- sensor segmentation / butt joints
- noise streaks, erratic pixel response
- gray level saturation
- false detail
- cosmetic image restoration effects

In addition, the 5 repeat scans of a single finger are examined for any abnormalities and the degree of reproducibility.

6.3.3 Fingerprint Sharpness and Detail Rendition

Qualitative assessment of sharpness and detail rendition is performed by close visual inspection of the displayed fingerprint images, e.g., by comparing a given image to others in the same set, or comparing a given image to other compatible sets of images.

Quantitative assessment of sharpness and detail rendition is performed by applying an objective quality metric suitable for fingerprint assessment. In applying such a metric, it is important to keep in mind that the goal is to assess PIV device quality, not input finger quality. Information on attributes, terms, and definitions of biometric image quality metrics and quality scoring is available [**IQ**]. Although no definitive fingerprint quality metric is identified here, the following lists some metrics which can be useful for fingerprint image assessment.

• The NIST Fingerprint Image Quality (NFIQ) metric described in the document: *Fingerprint Image Quality*, by E.Tabassi, C.L.Wilson, C.I.Watson, NISTIR 7151, August 2004; document and information on obtaining software available at: http://www.itl.nist.gov/iaui/vip/fing/fing.html

• The MITRE Image Quality for Fingerprints (IQF) metric.

6.4 Requirements Compliance

Requirement #1, Fingerprint Gray Range, is met if the gray-scale dynamic range is at least 150 gray levels within the measurement windows in at least 80% of the test fingerprint images.

Requirement #2, Fingerprint Abnormalities, is met if:
(a) no abnormalities are detected in the fingerprint images
or,
(b) it is concluded that none of the abnormalities that are detected in the fingerprint images are due to the PIV capture device or its associated image processing
or,
(c) it is concluded that none of the abnormalities that are detected in the fingerprint images, which are due to the PIV capture device or its associated image processing, are significant enough to adversely impact support to subject authentication via one-to-one fingerprint matching or other intended applications of the PIV device.

Requirement #3, Fingerprint Sharpness and Detail Rendition, is met if the sharpness and detail rendition is sufficient to support subject authentication via one-to-one fingerprint matching and other intended applications of the PIV device.

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List of References

IQ - *Biometric Sample Quality Standard Draft Revision 5,* INCITS Technical Committee M1-Biometrics, draft document M1/06-0181, 2006; download at:
http://m1.incits.org/m1htm/2006docs/m1docreg_2006.htm

ISO - *Photography--Electronic Still-Picture Cameras--Resolution Measurements*, International Organization for Standards (ISO) 12233:2000(E), 1 September 2000; ordering site:
http://webstore.ansi.org/ansidocstore/product.asp?sku=ISO+12233%3A2000

FIPS - *FIPS 201 Evaluation Program - Single Fingerprint Capture Device Approval Procedure*, version 4.0.0, 25 September 2006, General Services Administration; download at:
http://fips201ep.cio.gov/alldocs.php

SPEC - *Image Quality Specifications for Single Finger Capture Devices*, FBI, CJIS Division, version 071006, 10 July 2006; download at:
https://www.fbibiospecs.org/docs/pivspec.pdf
and,
http://fips201ep.cio.gov/documents/FBI_PIVspec_071006.pdf

VERIFY - *Information Technology - Biometric Performance Testing and Reporting - Part 6: Testing Methodologies for Operational Evaluation,* INCITS Technical Committee M1-Biometrics, draft document M1/06-0656, August 2006; download at:
http://m1.incits.org/m1htm/2006docs/m1docreg_2006.htm

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Appendix A

Software Test Tools and Targets

The Test Tools CD contains software applications to aid in requirements compliance verification of fingerprint devices, for both the PIV image quality specifications and the EBTS Appendix F image quality specifications. As of this writing, this CD contains the following freeware software test tools which relate to PIV specification testing; each tool includes compiled code, source code, test cases, and documentation:

mtf	- compute device's MTF from sine wave target or CTF from bar target
sfr	- compute device's MTF from edge target
geo	- compute geometric integrity of device from 1 cy/mm Ronchi target
creategeofile	- semi-automated aid in constructing input file for geo
viewgeo	- creates error map images to aid visualization of error locations and magnitudes
grayfinger	- assess gray range of fingerprints captured with the device
snr	- assess noise and uniformity characteristics of the device
pgm	- read header, width, height size of PGM format image

The Test Tools CD also contains relevant FBI image quality specifications and test procedures documents, and other test tools for EBTS Appendix F certifications (e.g., printer assessment). A request for the (free) Test Tools CD can be made to the cognizant FBI point of contact given in section 1.

The following Table A-1 presents a partial list of some of the manufacturers/vendors who sell test targets on a variety of substrates, which may be suitable for use in PIV device testing. This partial list is not intended to endorse one manufacturer/vendor over another, and it should also be noted that there are other sources for suitable targets not listed in Table A-1.

Table A-1. Commercial Target Sources

Target Relevant to PIV Testing	Vendor
Bar Ronchi Step Tablet Sine Wave	Applied Image, Inc. 1653 East Main Street Rochester, NY 14609 Telephone: (585) 482-0300 http://www.appliedimage.com
Bar Ronchi Step Tablet Sine Wave	Edmund Scientific Corp. 101 East Gloucester Pike Barrington, NJ 08007 Telephone: (800) 363-1992 http://www.edmundoptics.com
Bar Ronchi Step Tablet	Precision Optical Imaging, Inc. 62 Honeoye Falls 5 Pts Road Rush, NY 14543 Telephone: (585) 533-9133 http://www.precisionopticalimaging.com
Bar Ronchi Step Tablet Sine Wave	JML Optical Industries, Inc. 820 Linden Avenue Rochester, NY 14625-2710 Telephone: (585) 248-8900 http://www.jmloptical.com
Munsell Uniform Gray Step Tablet	X-Rite, Inc. (Munsell Color Lab) 4300 44th Street SE Grand Rapids, MI 49512 Telephone: (800) 622-2384 http://www.xrite.com
Esser/Image Engineering Test Charts: Bar Ronchi Step Tablet	Preco, Inc. 910 W. Alameda Ave. Burbank, CA 91506 Telephone: (818) 842-4632 http://www.preco.net

Appendix B

Geometric Accuracy Measurement

The following geometric accuracy assessment description is implemented in the *geo* software application. Before running *geo* the measurement areas can be defined by the *creategeofile* application. After running *geo*, error map images useful as a diagnostic aid (e.g., visualizing periodicities in error magnitudes) can be created by the *viewgeo* application. These applications are on the Test Tools CD.

Ronchi Target Accuracy:

The geometric accuracy requirements, test methodology, and compliance verification are consistent with use of a 1.0 cy/mm Ronchi bar target that has less than a 0.25 percent error in bar center-to-bar center spacing. This error tolerance is readily available from chrome-on-glass Ronchi targets, and can also be obtained from Ronchi targets on other substrates, such as reflective, flexible mylar. With this target error tolerance, it is not necessary to incorporate target calibration data into the measurement computations.

Even if the Ronchi target error is slightly larger than 0.25 percent, use of that target without calibration data is acceptable as long as the PIV device still meets the geometric accuracy requirements. The reasoning is that it is highly improbable that the target errors would be exactly in-phase with the device's geometric errors, and of opposite sign, both of which would be required for device errors to cancel target errors. If the geometric accuracy requirement is still met with this target, it simply indicates that the combination of target errors plus device errors are relatively small.

Measurement Definitions and Approach:

1) The target is scanned such that the bars are aligned parallel to one of the two axes of the device's sensor (row or column directions), to within 0.5 degrees.

2) Common terminology used in this Appendix is given in the following and is illustrated in Figure B-1.

a) A **measurement strip** is a single, continuous strip in the target image, across multiple parallel Ronchi bars, within which device resolution scale and geometric accuracy measurements are made; see Figure B-1.

b) A **bar** is an individual black stripe of the Ronchi target.

c) A **bar segment** is the portion of a bar that is contained in a measurement strip.

d) An **edge line** of a bar segment is the line at the boundary of the white background and the black bar and is calculated from image data for that bar segment. There are two edge lines for each bar segment.

d) The **center line** of a bar segment is the line running down the center of a bar, parallel to the two edge lines for that bar segment.

e) The **center point** of a bar segment is the mid-point of the bar segment's center line.

f) In the following discussion references to *row*, *top*, and *bottom* pertain to horizontal bars, with measurements in the vertical direction. The same test methodology is applied to vertical bars, with measurements in the horizontal direction, by substituting the terms *column*, *left*, and *right*, respectively.

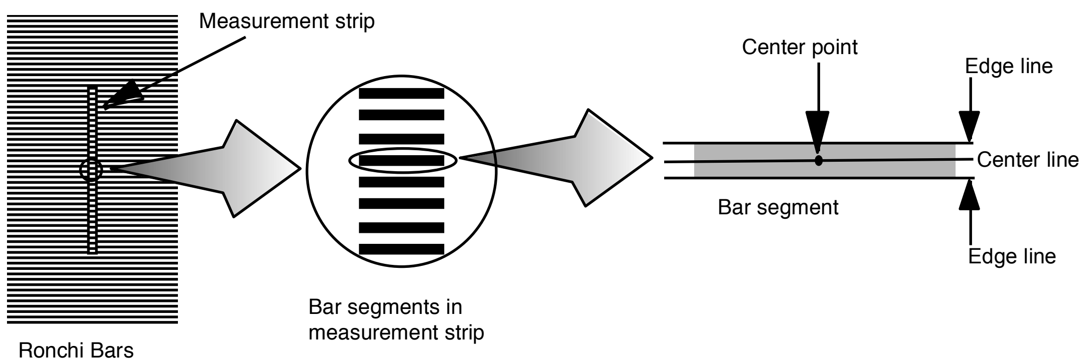

Figure B-1. Definitions Used For Ronchi Target Image Computations

3) The center line of a bar segment represents the line that is midway between the two edge lines of that bar segment. All distances are measured between the center lines of bars, because the more accurate tolerance for a Ronchi target is in terms of bar center-to-bar center distance. Center lines are not calculated directly, however, they are based on measurements of bar segment edge line locations. The steps for calculating a bar segment's edge lines are as follows:

a) The edge locations of each bar segment are calculated every fifth pixel along each bar edge, for a distance of 0.25 inches, yielding 26 points for each edge for a 500 ppi device. Edge locations are determined using the super-resolution edge

detection method presented in Seitz[12], Section 3: "Subpixel Resolution Edge Detection", to locate edges of transition from black to white and white to black. This method calculates the location of a point on an edge within 2^{2-N} of the true position, after N iterations of a bisection method. In the *geo* application, each iteration is applied to two different edge locations, x, and the process determines which of the two locations yields the maximum value of the function r(x). The inferior edge location, as indicated by a smaller r() value, is replaced by the midpoint (bisection) of the two previous locations, and this process is then repeated with these two locations. In order to overcome the possibility of artifacts such as dust or scratches altering the expected edge locations, the initial edge range is set quite large, using x values from -8 to 8. Because this range is so large, the initial search reduces the edge range by only 1/8, over 32 iterations, which avoids missing the actual edge location in this broad expanse. Once the range has been reduced in this manner, then the normal Seitz bisection proceeds. To achieve (and probably exceed) the desired 0.05 percent accuracy, N is set equal to 16.
The value of f_i is the difference between consecutive image pixel values I_i and I_{i-1}.

$$f_i = I_i - I_{i-1} \tag{B-1}$$

$$r(x) = \sum_{i=-4}^{4} |f_i| e^{-a^2(x-i)^2} \quad ,a = \frac{\pi}{4} \tag{B-2}$$

b) Once the point positions along an edge of a bar segment have been determined, the best fit line is calculated using these points in a linear, least squares regression to determine the edge line. This line fitting is done separately for each edge of each bar segment. The application of this line fitting requires that the y values correspond to the row positions for the horizontal Ronchi bars, and the y values correspond to the column positions for the vertical Ronchi bars. Figure B-2 shows an example of the 26 points along each edge of a bar, within a measurement strip, that are used to determine the center line or center point of a bar segment scanned at 500 ppi. The combination of the subpixel resolution method and linear, least squares regression allows the position of the bar segment edge line to be accurately determined to within a small fraction of a pixel, and this combination is robust in the presence of image artifacts such as dust or scratches on the target.

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[12] *Optical Superresolution using Solid-State Cameras and Digital Signal Processing, P.* Seitz, July, 1988, Optical Engineering, Vol. 27, No.7, pp. 535-540.

linear least squares regression (y = mx + b) run on each bar edge line:

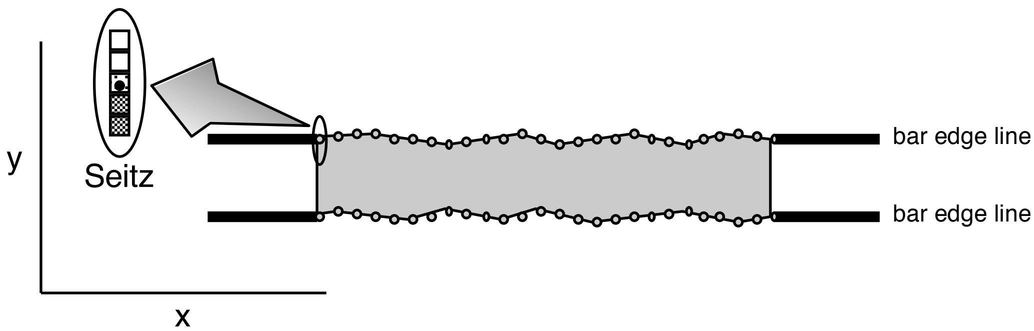


Figure B-2. Calculating the Edge Lines of a Bar Segment

4) The distance between the centers of two bar segments in the same measurement strip is effectively calculated as the perpendicular distance between the center point of one bar segment and the center line of the other bar segment. As defined in equation B-3 and illustrated in Figure B-3, the distance is actually computed from the bar edge slopes (m) and intercepts (b) of the bar edges, and the center points (x_c) of the bars.

$$D = \left|\cos(\alpha)(y_0 - y_1)\right| \tag{B-3}$$

where,

$$\alpha = \frac{\arctan(m_{10}) + \arctan(m_{11})}{2}$$

$$y_0 = \frac{(m_{00} + m_{01})x_c + (b_{00} + b_{01})}{2}$$

$$y_1 = \frac{(m_{10} + m_{11})x_c + (b_{10} + b_{11})}{2}$$

x_c is the middle row (column) of the measurement strip

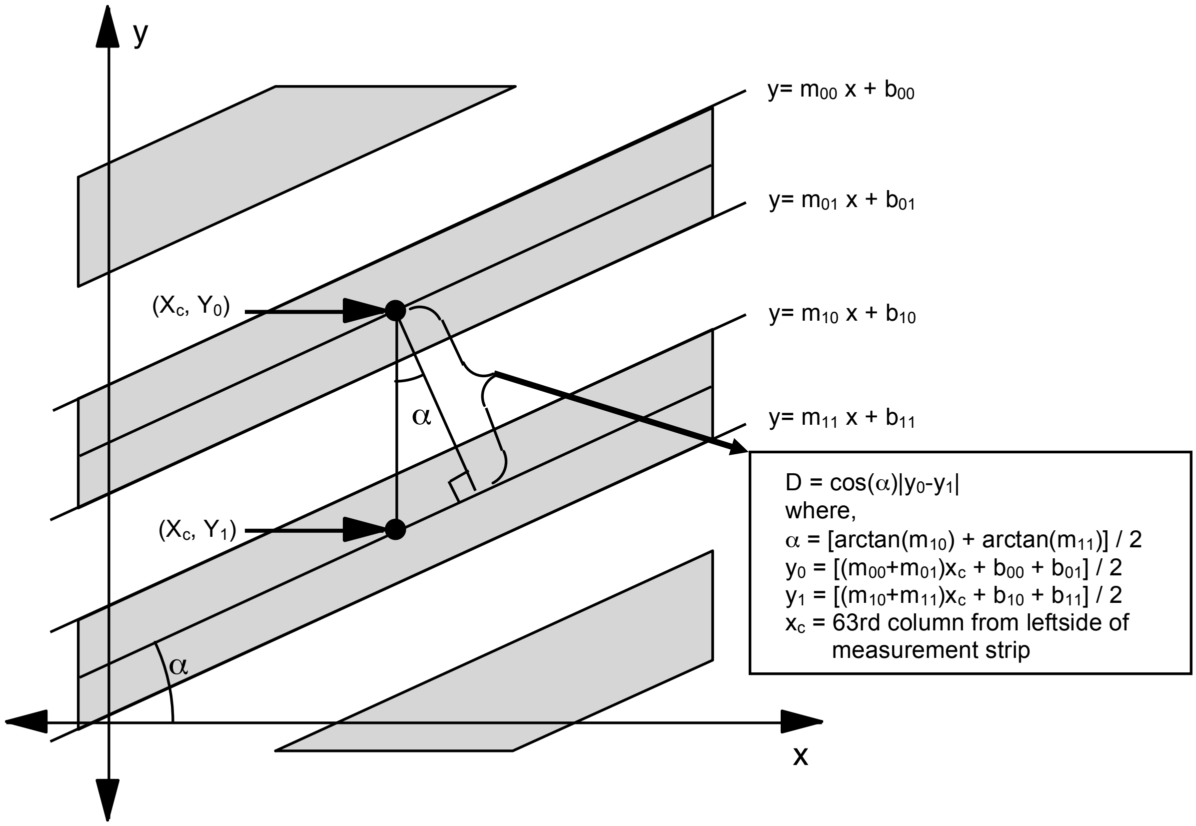


Figure B-3. Calculating Distance Between Centers of Two Bars

The center point of a bar's centerline is located X columns in from the left edge of the bar segment, where X = 63 for 500 ppi scans. Figure B-4 illustrates the distance measurement between the centers of two bar segments.

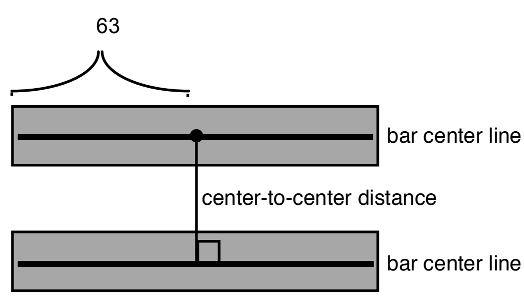


Figure B-4. Distance Between Two Bar Centers (1-Bar Distance Measurement)

5) As illustrated in Figure B-5, the first bar segment used in all measurements of a given measurement strip is the topmost full-width bar in that strip, and the last bar segment used is the bottommost full-width bar in that strip.

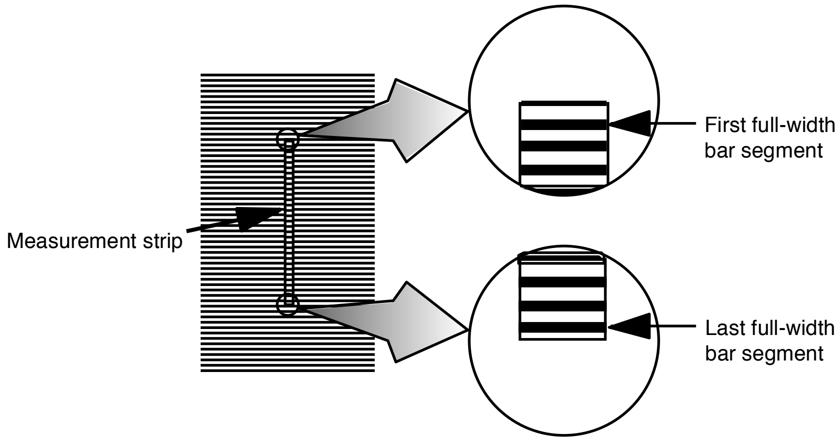


Figure B-5. First and Last Full-Width Bar Segments in a Measurement Strip

Measurements Performed:

For each measurement strip, the device resolution scale is first measured, both to verify compliance with the pixels per inch requirement and to establish a pixels per inch value that can be used to convert subsequent geometric accuracy measurements to inches. Next, measurements are made to test the across-bar geometric accuracy over a short distance of one Ronchi bar cycle; then, measurements are made to test the across-bar geometric accuracy over a longer distance of 6 Ronchi bar cycles.

The output of the *geo* application includes the across-bar results for each individual 1-bar and 6-bar sample measurement (distance error and location), the computed ppi for each 6-bar sample measurement, the along-bar distortion test results, and summary results for all 1-bar and 6-bar measurements in each measurement direction (vertical and/or horizontal).

<u>Resolution Scale Measurements</u>

The first set of measurements establishes the device resolution scale in the row and column directions. Individual device resolution scale measurements are taken over every six-bar distance. Device resolution scale in pixels per inch (ppi) is calculated as the number of pixels between the specified bar centers in a given measurement strip, multiplied by a conversion factor, as given in equation B-4. The average resolution is then calculated for each measurement strip.

$$\text{ppi} = K \times (\text{width of 6 cycles in pixels}) \tag{B-4}$$

where,

$$K = \frac{\text{mm/inch}}{\text{number of cycles}} = \frac{25.4}{6} = 4.233$$

Across-Bars Geometric Accuracy Measurements

The first set of measurements for geometric accuracy tests the short distance accuracy, i.e., less than 0.07 inch distance. For each measurement strip, distance measurements are made between the centers of each pair of adjacent bars, starting with the topmost complete bar segment. Each distance measurement is converted from pixels to inches by dividing the distance measurement (in pixels) by the previously computed average resolution for the given directional measurement strip.

The second set of measurements tests the geometric accuracy for distances in the 0.07 to 1.5 inch range, by measuring the distance between six bars (6 bar cycles), which is a target distance of 0.23622 inches. For every sixth bar in each measurement strip, distance measurements are made between the centers of bar pairs having five bars between them, starting with the topmost complete bar segment. Each distance measurement is converted from pixels to inches by dividing the distance measurement (in pixels) by the previously computed average resolution for the given directional measurement strip.

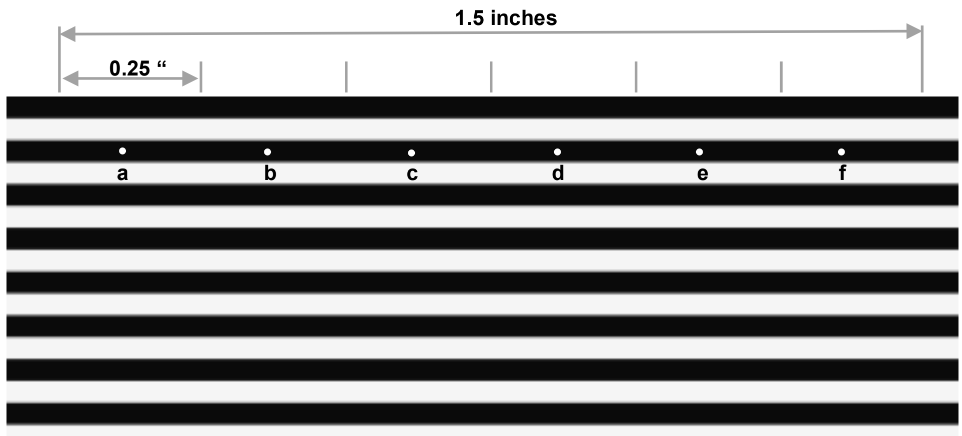
Along-Bar Geometric Accuracy Measurement (Distortion Measurement)

The bar center locations established for across-bar geometric accuracy assessment form the basis of assessments for along-bar geometric accuracy assessments, i.e., distortion assessments. As illustrated in Figure B-6, since the bar center locations at a, b, c, d, e, f are known from the previously computed across-bar measurements, then it only remains to determine the largest difference in center locations over a bar length of up to 1.5 inches, and then compare it to the allowable maximum. Some additional aspects of the distortion measurement:

- All comparable along-bar measurements are made within the image area corresponding to a single, continuous Ronchi target.

- The along-bar measurements are applied to every bar.

- The difference in fractional rows between two bar centers is converted to inches by dividing by the average ppi of the two corresponding measurement strips.



meas. strip	avg. ppi	bar center location	at row
1	501.3	a	10.0
2	500.2	b	11.3
3	498.5	c	14.2
4	500.8	d	16.2
5	502.2	e	15.3
6	504.1	f	14.5

largest vertical difference over 1.5" horizontal distance:

[(d @ row=16.2) - (a @ row=10.0)] / 501.05 = 0.01237"

0.01237" meets PIV spec, since it is less than 0.027"

Figure B-6. Example Along-Bar Distortion Measurement

Appendix C

MTF and CTF Measurement

The following procedures correspond to input requirements and computations performed by MITRE's *mtf* software application, for MTF assessment using a sine wave target or for CTF assessment using a bar target[13]. This application, together with detailed documentation, is on the Test Tools CD; the most recent version of *mtf* is always posted to the internet for downloading at:

http://www.mitre.org/tech/mtf

Figure C-1 illustrates the basic steps in *mtf*, which are described in the following.

1) A target data file is prepared for each target model, which includes the relative locations within the target of each frequency pattern, the modulation value of each target frequency pattern, and, for a sine wave target, the gray patch densities/locations. If a bar target is used and the device has a nonlinear input-output relation, then the data point pairs representing that relation are included in this input file.

For a sine wave target, the target manufacturer supplies the target modulations and gray patch densities for the specific target serial number purchased. The supplied "compensated modulation" values are used for target modulation, because these values have been corrected for the instrument (microdensitometer) used by the manufacturer to calibrate the target. [The supplied "peak-to-peak" modulation is not used, because these values have not been corrected.] The constructed target data file is submitted along with the target scans. As verification that "compensated modulation" has been used, at least a portion of the target manufacturer's data sheet for the specific serial-numbered sine wave target should also be submitted; e.g., the portion which includes target modulation data at 6 cy/mm.

2) The target is positioned on the device's platen and aligned to within 0.5 degrees of the horizontal and vertical, i.e., with respect to the device's sensor row and column directions.

Sine wave targets have medium contrast so it is relatively easy to avoid saturation upon imaging; i.e., easy to avoid the sine wave peaks in the image being pinned at gray = 255 or the sine wave valleys being pinned at gray = 0. On the other hand, a bar target is very high contrast and is more prone to producing a saturated image. Adjustments in device parameters (illumination, gain settings, etc.) should be made, as necessary, to avoid

[13] Original *mtf* version is described in: "Computer Program to Determine the Sine Wave MTF of Imaging Devices", N.B.Nill, D.J.Braunegg, B.R.Paine, MITRE Corp. Technical Report, MTR-96B0000025, June 1996

saturation. [If bar target semi-saturation is unavoidable, it is better to semi-saturate the white spaces at gray = 255 rather than the black bars at gray = 0.]

3) The digital image of the scanned target is displayed and the upper left, upper right, and lower left corners are located (row and column in pixel units). *Mtf* is then run, with inputs consisting of the 3 image reference corners, target data file, digital image, and various user-selectable options displayed at runtime. *Mtf* first computes the pixels per inch scale and alignment angle ("skew angle") in both vertical and horizontal directions for the given target image. This data, together with the relative locations of each target pattern (from input data file), is then used to establish the row and column location of each sine wave (or bar) frequency pattern and (for sine wave) the density patch locations, within the image.

4) The single, representative sine wave (or bar cycle) modulation in each imaged frequency pattern is determined from the multiple sample modulation values collected from within that pattern. The sample modulation values are computed from the maximum and minimum levels corresponding to the peak and adjacent valley in each sine wave period (or bar cycle). These maximum and minimum levels represent the image gray levels that have been locally averaged in a direction perpendicular to the sinusoidal (or bar cycle) variation[14]. Using the linear or nonlinear input-output relation, the maximum and minimum gray levels are mapped back to target space, where the image modulation is computed as,

peak_image_modulation = (maximum - minimum) / (maximum + minimum)

The PIV device's sine wave MTF is then defined at each frequency as:

MTF = peak_image_modulation / target_modulation

The PIV device's CTF from a bar target is then defined at each frequency as:

CTF = peak_image_modulation / zero frequency modulation

The CTF zero frequency modulation is normally computed from the ≤ 0.3 cy/mm bar pattern, which could be calculated in gray level image space if the device has a linear response. If, in the uncommon case, the CTF of the bar target itself is known (from independent measurements), then it would be appropriate to normalize by these target CTF values, analogous to how the sine wave image is normalized.

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[14] "Enhanced Noise Suppression in MITRE's Sinemtf Algorithm", N.B.Nill, MITRE Corp. Technical Report, MTR-00B0000017, June 2000.

5) Aliasing is measured in *mtf* by computing a sequence of one-dimensional discrete Fourier transforms (DFT) of the row-averaged gray levels in each frequency pattern. If the relative strengths of side lobes (harmonics) compared to the main lobe are too large, then aliasing due to decimation is called out. If the location of the main lobe is not at the correct frequency, for a given pattern with known fundamental frequency, then aliasing due to upscaling is called out. Aliasing statistics are printed-out when *mtf*'s verbose output mode is selected, this includes the aliasing magnitude for each test case, the percent of cases that exceed threshold, and the average magnitude for those cases that exceed threshold.

Aliasing due to decimation is usually not entirely avoidable when the device's true/native resolution is greater than the required 500 ppi, because of the rescaling algorithm (resampling and interpolation) that must be applied in order to reduce that resolution to the required final output resolution. Decimation aliasing near the Nyquist frequency can be substantially avoided, however, by applying a suitable rescaling algorithm that maintains sharpness and detail rendition[15]. On the other hand, aliasing due to upscaling is not acceptable at any frequency up to and including the Nyquist frequency, because it implies that the true/native resolution is lower than the required 500 ppi.

It is useful to apply other alias detection techniques, in order to obtain as complete a picture of aliasing as is possible. As it happens, one of the benefits of a sine wave or bar target is that it readily lends itself to showing the effects of aliasing at specific frequencies, e.g., visible banding is one tell-tale sign of aliasing. A more comprehensive assessment of the magnitude and potential impact of aliasing is therefore achieved by the synergistic combination of the quantitative, DFT approach and the qualitative, visual assessment approach. [A special case is at 80% of Nyquist frequency: visual assessment of aliasing at 80% Nyquist cannot be relied upon because all sine and bar patterns at that frequency look like they are aliased, in a discrete sampling imaging system. However, the aliasing algorithm in *mtf* does differentiate between true aliasing and the "appearance" of aliasing at 80% Nyquist, which is 8 cy/mm.]

Judgment as to the significance of aliasing in a particular imaging system depends on a complex combination of intertwined parameters, such as the following:

- the specific frequency patterns that the target has, e.g., it is more difficult to assess the impact of aliasing for a target that only has a few higher frequencies, …6, 8, 10 cy/mm, as opposed to a more complete …6, 7, 8, 9, 10 cy/mm set of patterns

- the actual frequencies at which aliasing is detected, and whether or not the qualitative (visual) and quantitative assessments agree

[15] "Rescaling Digital Fingerprints: Techniques and Image Quality Effects", D.J.Braunegg, R.D.Forkert, N.B.Nill, MITRE Corp. Technical Report, MTR-95B0000061, June 1995.

- the aliasing threshold level for quantitative measurement detection

- the % of quantitative measurement test cases at a given frequency that exhibit aliasing and by how much the detected aliasing exceeds the detection threshold

- how variable the aliasing results are with a small shift in measurement location.

In a 500 ppi system, with a good pixel rescaling/resampling/interpolation algorithm, no aliasing-due-to-decimation should occur at frequencies less than 7 cy/mm; the maximum amount of (acceptable) aliasing-due-to-decimation could be expected at 10 cy/mm. The occurrence of aliasing-due-to-upscaling at any frequency from 0 to 10 cy/mm indicates a severe problem and is unacceptable.

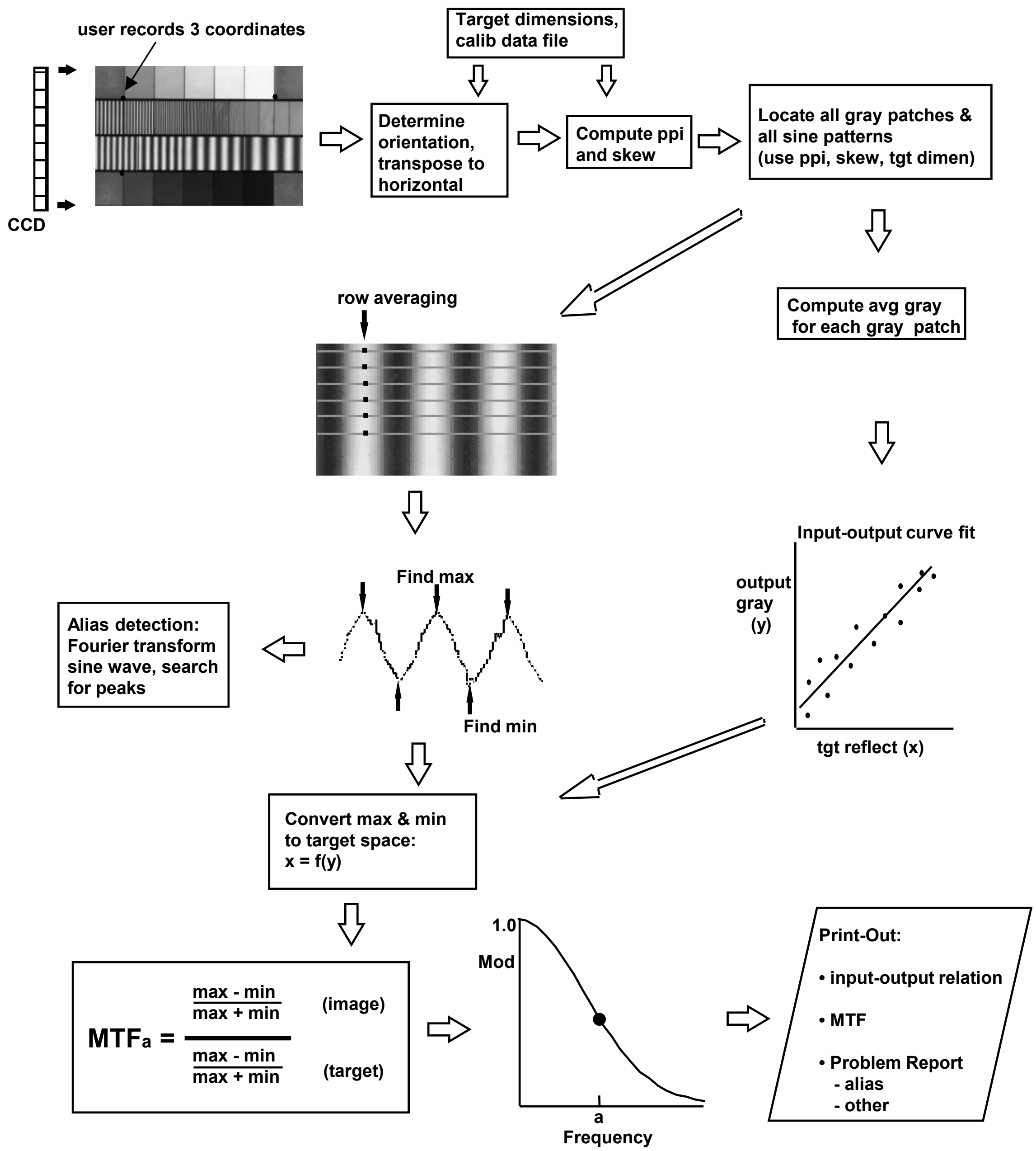

Figure C-1 Basic Processing Steps in MITRE's *mtf* Application

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Glossary

AFIS	Automated Fingerprint Identification System
avg	average
BMP	Basic Multilingual Plane
bpp	bits per pixel
CCD	Charge-Coupled Device
CD	Compact Disk
CJIS	Criminal Justice Information Services division of FBI
CMOS	Complementary Metal Oxide Semiconductor
COTS	Commercial-Off-The-Shelf
CTF	Contrast Transfer Function (square wave transfer function)
cy/mm	cycles per millimeter
DFT	Discrete Fourier Transform
EBTS	Electronic Biometric Transmission Specification
FBI	Federal Bureau of Investigation
FIPS	Federal Information Processing Standard
geo	geometric accuracy assessment program
GSA	General Services Agency
HPSD	Homeland Security Presidential Directive
IAFIS	Integrated Automated Fingerprint Identification System
INCITS	InterNational Committee for Information Technology Standards
IQF	Image Quality of Fingerprint
ISO	International Organization of Standardization
JPEG	Joint Photographic Experts Group
mm	millimeter
MTF	Modulation Transfer Function (sine wave transfer function)
NA	Not Applicable
NFIQ	NIST Fingerprint Image Quality
NIST	National Institute of Standards and Technology
PGM	Portable GrayMap (image file format)
PIV	Personal Identity Verification
ppi	pixels per inch
SFR	Spatial Frequency Response
snr	Signal-to-Noise-Ratio, noise and uniformity assessment program
spec	specification
tgt	target
TIFF	Tagged Image File Format
WSQ	Wavelet Scaler Quantization