MTR 00B0000017

MITRE TECHNICAL REPORT

Enhanced Noise Suppression in MITRE's *Sinemtf* Algorithm

June 2000

Norman B. Nill

Sponsor:	DOJ/FBI	**Contract No.:**	DAAB07-00-C-C201
Dept. No.:	G034	**Project No.:**	0700E02X

Approved for public release; distribution unlimited.

© 2000 The MITRE Corporation

MITRE

Center for Integrated Intelligence Systems
Bedford, Massachusetts

MITRE Department Approval: ______________________________
Joseph L. Howard

MITRE Project Approval: ______________________________
Norman B. Nill

Abstract

For several years, MITRE has been supporting the FBI in their certification program for commercial fingerprint capture devices. This certification process depends on meeting a specific set of image quality requirements, one of which entails measuring the spatial frequency response of the device, known as the Modulation Transfer Function (MTF). This document describes a noise smoothing enhancement, implemented in version 4.0 of the MITRE-developed, FBI-supported computer algorithm, *sinemtf*. This algorithm is routinely used to measure a fingerprint capture device's MTF for certification compliance verification. This new noise suppression technique is described, and real-case comparisons are made to the previous versions of *sinemtf*.

KEYWORDS: FBI, fingerprint, image quality, MTF, scanner, sinemt*f*, sine wave

Acknowledgments

The author would like to thank Wendy Etkind, Lead Software Systems Engineer, for persevering through the tangle of abstrusely connected code segments and successfully incorporating the enhancements discussed in this document into the *sinemtf* algorithm.

Table of Contents

List of Figures

List of Tables

Section 1

INTRODUCTION

For the last seven years MITRE has been providing technical support to the FBI for the certification of fingerprint capture devices. This support has helped to ensure a standard, satisfactory level of image quality for fingerprint comparisons, classification, feature detection, and automated search reliability, which in turn supports systems interoperability between national, state, and local law enforcement agencies. The certification process is primarily dependent on meeting a set of Image Quality Specifications (IQS). MITRE has analyzed IQS test data from several dozen fingerprint capture devices, representing the products of over 20 different vendors. One of the critical components of the IQS test suite is the testing performed to ascertain a fingerprint capture devices' spatial frequency response, known as the Modulation Transfer Function (MTF). Fundamentally, the MTF is a measure of the contrast transmission capabilities of an imaging system, as a function of spatial frequency. The MTF has proven to be an excellent measure of the sharpness and detail rendition capabilities of a fingerprint card scanner or live scan device; it indicates the devices' capability to capture fingerprints at a quality level that is needed for successful fingerprint matching, examination, and automated search. This test has successfully quantified the elusive term 'image quality' across fingerprint capture devices of many different designs. On a number of occasions in IQS certification test analysis, the MTF measurement process has also detected device problems, which were then fixed by the vendors, ultimately resulting in better fingerprint capture devices in the hands of the forensics and law enforcement users.

In the MTF analysis approach, the fingerprint capture device scans a sine wave target and the resulting digital image is processed through a MITRE-developed computer algorithm called *sinemtf*, which computes the devices' MTF. The *sinemtf* algorithm also computes the input - output gray level linearity of the device and checks to see if the device is producing any undesirable aliasing. A complete description of *sinemtf*, albeit of an early version, is available[1]. Figure 1 is a graphic of the basic computation steps in *sinemtf*.

---

[1] "Computer Program to Determine the Sine Wave MTF of Imaging Devices", N. B. Nill, D. J. Braunegg, B. R. Paine, MITRE Technical Report, MTR-96B025, June 1996; available at: www.mitre.org/technology/mtf

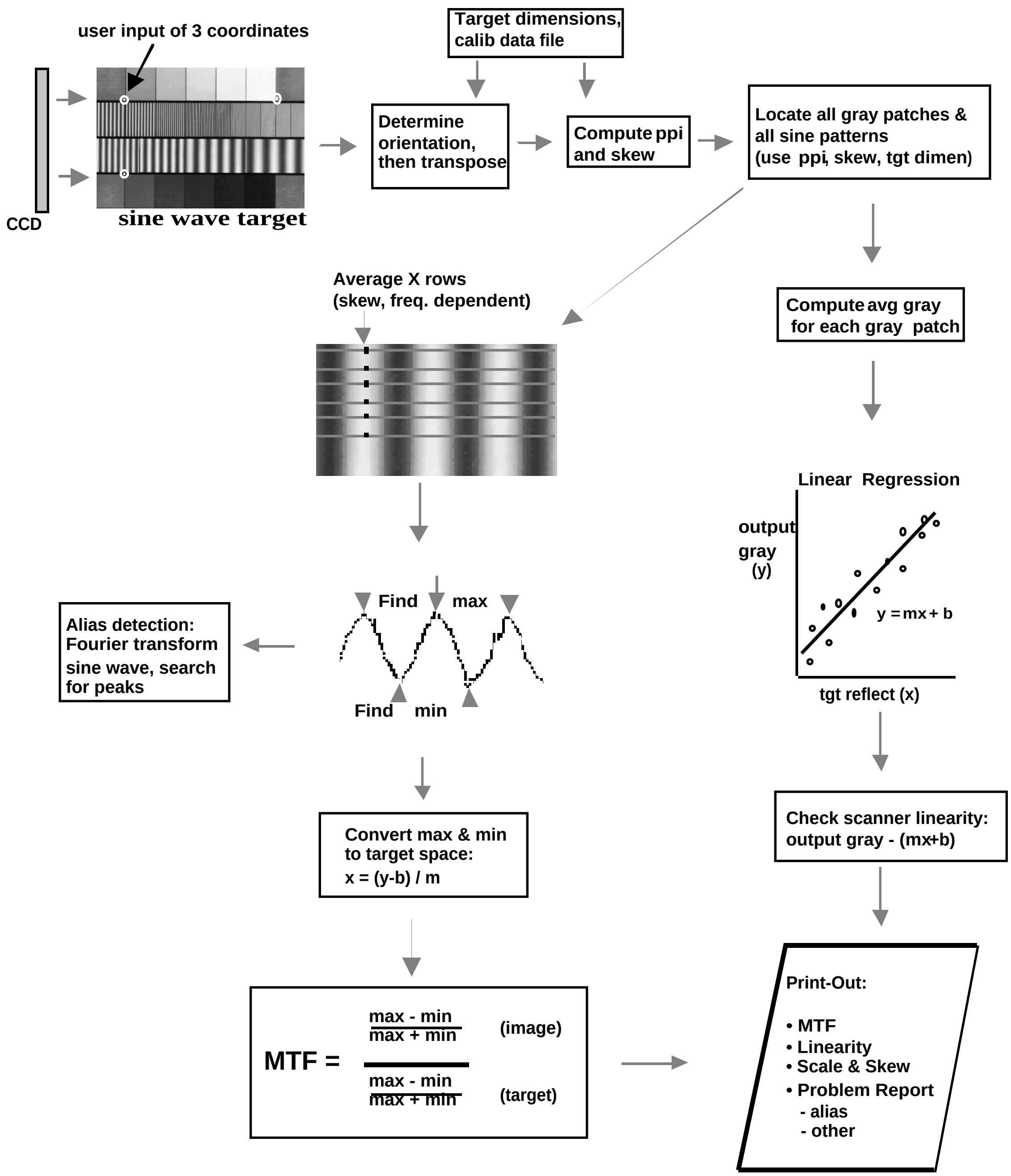

Figure 1. Basic Computation Steps in *Sinemtf* Program

As with any assessment tool applied to real-world data, improvements to the *sinemtf* algorithm are possible, such as improvements to better deal with the invariable presence of noise. The main motivation for the revision of *sinemtf* (to version 4.0) discussed in this document, is based on a review of the actual scanner MTFs measured, i.e., across fingerprint capture devices, across vendors, and across targets. From this review it has become evident that two anomalies commonly occur, as itemized in the following and illustrated in figure 2.

1. The MTF curve is often erratic in the 0 cy/mm to ~2 cy/mm low frequency region, taking the form of alternating, multiple peaks and dips in what should be a smooth curve of modulation values, whose magnitudes should smoothly decrease with increasing frequency.

2. The modulation values in this low frequency region often go above 1.0, whereas this should not occur[2].

The next step was to investigate reasonably probable causes for these two commonly occurring anomalies, which resulted in identifying the following candidate causes:

- noise
- target calibration inaccuracies
- imaging system nonlinearity
- image enhancement filter.

Although there is some evidence of the presence of each of these four causes in specific cases, <u>it is concluded from analysis that the preponderant cause of the two MTF anomalies is noise.</u> The main thrust of this document, therefore, is to explore the noise issue in more depth, and describe the changes made to the *sinemtf* algorithm to increase noise suppression, implemented in *sinemtf* version 4.0. A discussion of the other three, secondary causes is also included in this document.

[2] More specifically, if the device does not apply an enhancement filter to scanned images, and the device's input – output gray scale relation is linear, then the sine wave modulation has a theoretical maximum value of 1.0.

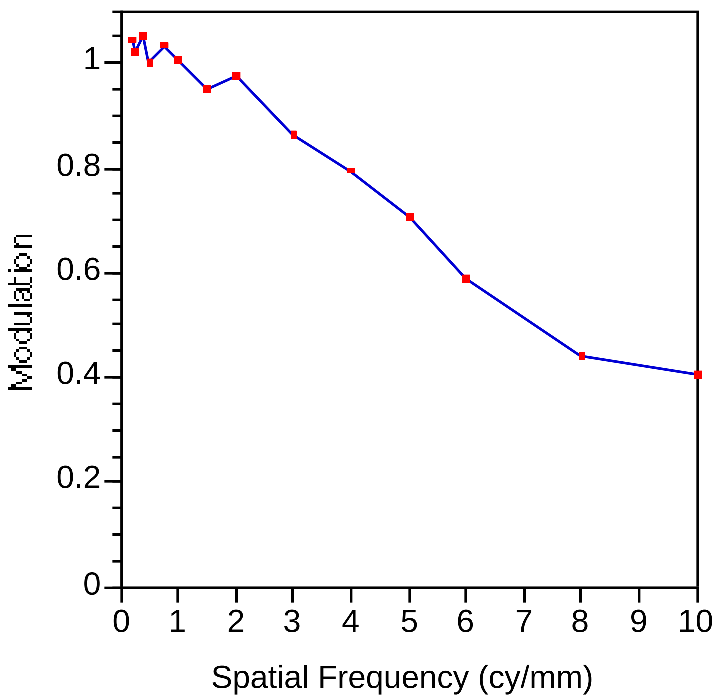

Figure 2. MTF Anomalies (Erratic Curve Shape and Modulation > 1.0 in Low Frequency Region)

For reference, note that the IQS specifies a scanning resolution of 500 pixels per inch (ppi) for fingerprint card scan and live scan capture devices, which equates to a Nyquist frequency (the highest frequency of interest) of 9.84 cy/mm. The IQS requirement for a latent fingerprint scanner[3] is 1000 ppi, corresponding to a Nyquist frequency of 19.68 cy/mm. The commercial, off-the-shelf sine wave targets[4] used for measuring a device's MTF contain a series of sine waves of different frequencies (see graphic in figure 1). The closest frequencies on the target, to the 9.84 and 19.68 cy/mm Nyquist frequencies of the devices being measured, are 10.0 and 20.0 cy/mm, respectively. These are sufficiently close to the device's Nyquist frequencies to substitute for them.

[3] A latent fingerprint scanner scans a latent fingerprint that was previously transferred to or recorded onto a two dimensional reflective material, such as photographic paper. A live scan device directly captures the fingerprint of a subject who places his/her finger on the device, via direct imaging (no ink impressions).

[4] Manufactured by: Sine Patterns, LLC, 3800 Monroe Ave., Pittsford, NY 14534; www.sinepatterns.com

Section 2

BACKGROUND: NOISE SUPPRESSION VIA ROW AVERAGING

In order to decrease the effects of noise in the sine pattern image prior to computation of modulation values, it is advantageous to average corresponding pixels in the direction perpendicular to the sinusoidal variation, as illustrated in figure 1. By averaging as many rows as is practicable, this approach effectively increases the signal to noise ratio, resulting in a more stable and more accurate MTF. If the skew angle were known to be zero, and assuming uniform target and scanner illumination, then pixels across the entire height of the sine pattern measurement box height could be averaged together. For example, in the zero skew case approximately 180 rows could be averaged for a scanner operating at 500 ppi, with the typically-used, model M13-1X sine wave target. 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.

Figure 3 illustrates the effect of skew: 27 pixels of a linear detector array are scanning across a sine wave target at a small skew angle of 3 degrees. The relative size of the pixel, compared to the size of the sine wave period, is such that the sine wave frequency is 29 percent of the scanner's Nyquist frequency. It is clear from inspection of figure 3, that if one were to average the outputs of all 27 detector pixels, at any given instant in time, then pixels representing *different parts* of the sine wave period would be averaged together, which would result in computing a falsely low modulation value. However, there is a determinable number of contiguous pixels that could be safely averaged together; this is the group that occupies nearly the same part of the sine wave period being scanned at any one instant (approximately 6 pixels in this case). <u>Implementing this maximum number of pixels that can be safely averaged together is the chosen method of noise suppression; identifying this number of pixels under different conditions and exploring the impact of this approach are the main topics of the remainder of this document</u>.

Note that it would be unacceptable to overcome the skew problem by digitally rotating the sine image ("deskewing") such that it is perfectly aligned with the detector array. This would entail arbitrary angle rotation and its attendant pixel interpolation, which would change the original sine image’s pixel locations and corresponding gray levels, and lead to a false estimate of modulation.

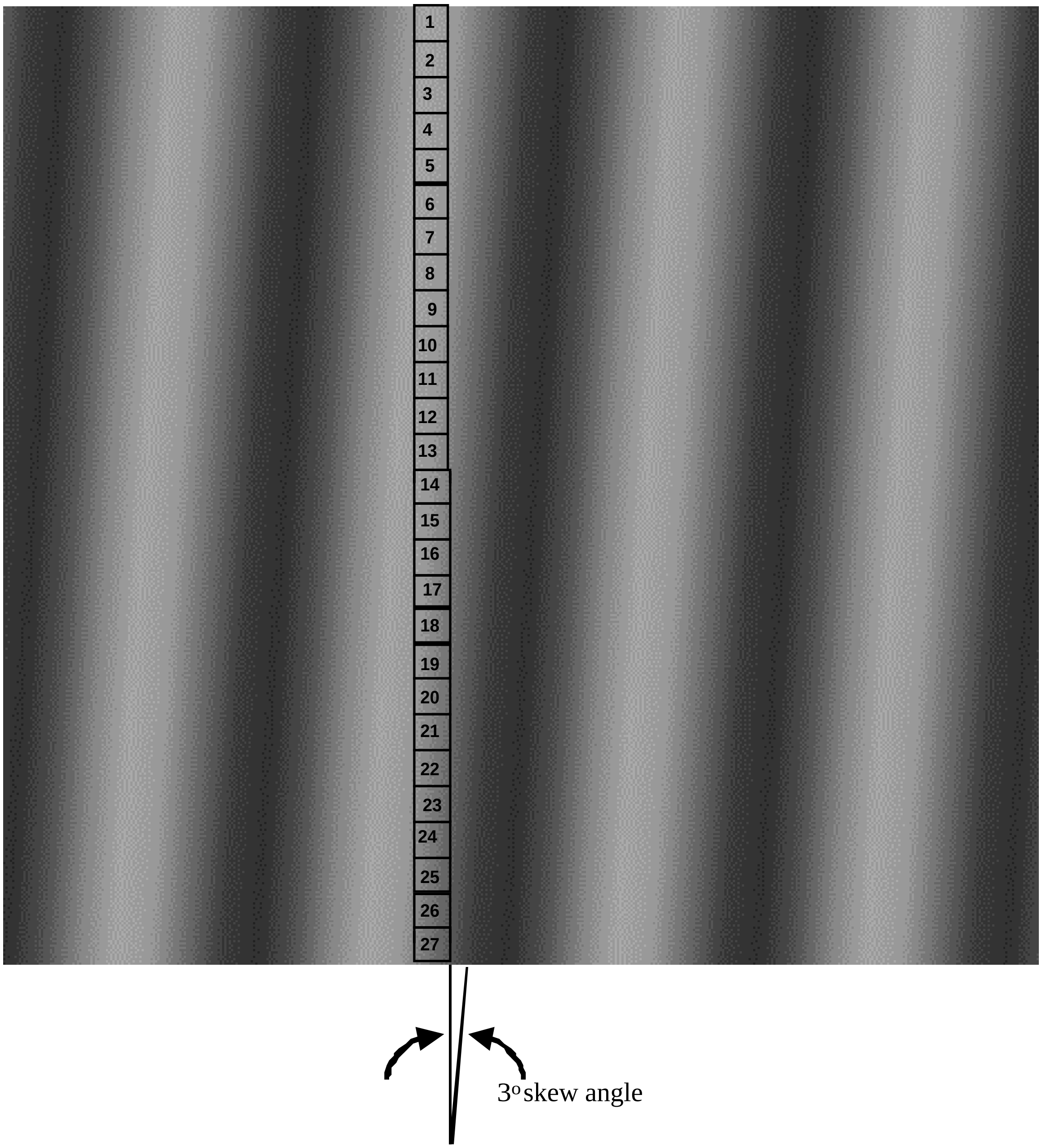

Figure 3. Skew Between Sine Wave Target and Detector Array

Section 3

QUANTIFYING THE ROW AVERAGING TECHNIQUE

All previous *sinemtf* algorithm versions, disseminated from January 1994 (version 0.5) to January 2000 (version 3.2), apply the amount of row averaging that allows up to a 1% loss in modulation at the Nyquist frequency, due to skew. The calculation of this 'reduction MTF', due to a non-zero skew angle between the scanner detector array and a sine wave target being scanned, is obtained from a published formula[5], which is given in Equation 1 in a slightly modified form to better suit the problem at hand:

$$MTF_{reduction} = \frac{\sin(\pi L \alpha f)}{\pi L \alpha f} \qquad (1)$$

where,

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

n = number of pixels to be averaged

ppi = scanner pixels per inch

f = spatial frequency in cy/mm

α = skew angle in radians.

In the case of a skew angle magnitude of less than 1.5^o, the application of equation 1 results in 6 row averaging on the 10 cy/mm sine wave pattern, the Nyquist frequency of a 500 ppi scanner. This 6 row averaging is then also applied to all lower frequency sine wave patterns. To cover all cases of skew, the *sinemtf* algorithm utilizes the breakpoints tabulated in Table 1.

[5] "The Effect of Slit Misalignment on the Microdensitometer MTF", R.A. Jones, Photographic Science and Engineering, November–December 1965, Vol. 9, No. 6, pp. 355–359. There are other approaches to modeling the skew effect which give the same results; for example, an approach implicitly described in: "MTF of Charge-Coupled Devices", J.C. Feltz and M.A. Karim, Applied Optics, February 1990, Vol. 29, No. 5, pp. 717-722.

Table 1. Previous Sine Row Averaging Logic (*sinemtf* v0.5 to v3.2)

Skew Angle Magnitude	Number of Rows Averaged at any Sine Frequency
$\lvert skew\rvert \leq 1.5^o$	6
$1.5^o < \lvert skew\rvert \leq 3.0^o$	3
$\lvert skew\rvert > 3.0^o$	1

The new row averaging logic in *sinemtf* version 4.0, applies a variable number of rows averaged, depending on the sine wave spatial frequency, and with the criterion that there be no more than a 1/2% reduction in modulation, due to skew, at any given frequency. Application of this logic results in the number-of-rows-averaged as given in Figure 4 for the case of skew angle magnitudes $\leq 1.0^o$, and in Tables 2 and 3 for all skew angle combinations. These values were derived from the process detailed in Appendix A, which utilizes equation 1 as its starting off point. Several features of this new row averaging approach are as follows:

• The number of rows averaged in *sinemtf* v4.0 is clamped to a maximum value at very low spatial frequencies, i.e., it is clamped to 10% of the ppi. This is done to avoid averaging over a large distance which may not be entirely uniform, i.e., may be nonuniform either due to "density wedging" on the sine wave target itself[6], or due to nonuniform illumination at the fingerprint capture device's detector plane.

• In both the new (v4.0) and previous *sinemtf* versions, 6 rows are averaged at the Nyquist frequency, when the skew angle magnitude is less than or equal to 1.0^o. For this case, therefore, *sinemtf* v4.0 computes nearly the same modulation value[7] at Nyquist frequency as was computed with previous versions.

---

[6] "Use of Sinusoidal Test Pattern Arrays for MTF Evaluation", R.L. Lamberts, *Engineering Notes* of Sine Patterns, LLC; available on the Internet at: www.sinepatterns.com/MTF/EngNotes.htm

[7] The Nyquist frequency modulation value would be identical, between v4.0 and previous versions, if precisely the same sine pattern rows and columns were utilized. Because scale is handled differently in v4.0, however (see Appendix B), there is a small difference in rows and columns utilized, potentially resulting in a small difference in computed modulation.

• Utilization of the ‘peak MTF’ concept continues to be implemented for all frequencies in IQS certification compliance assessments. In the ‘peak MTF’ computation, the modulation is selected from the single period, across all row averaged sets, that has the highest modulation. The algorithm computes all possible, independent, row averaged sets within the measurement box in a given sine frequency pattern. The measurement box size is a function of target sine pattern size, allocated safety margin, and ppi scale. The number of row averaged sets is equal to the number of rows in the measurement box height divided by the number of rows in one row averaged set.

The noise suppression method implemented in *sinemtf* v4.0 is simple, logically correct, performs the desired noise smoothing, allows continued use of the 'peak MTF' concept, and is an enhancement to the legacy code, rather than requiring all new coding. There are, however, other methods of noise suppression, three of these are briefly described in the following.

1) One approach is to use the average MTF at low spatial frequencies and retain the constant 6 row averaging, utilized in the peak MTF, at mid to high spatial frequencies. [The average MTF has always been computed in *sinemtf* as a user-selectable option, it computes the modulation averaged over all modulation sample measurements at a given frequency.] This approach was investigated, but was found to (usually) produce a sharp transition in modulation values, between the average MTF frequencies and peak MTF frequencies, leading to a discontinuity in the overall MTF curve. A frequency-dependent weighting function could smooth out this discontinuity, but it would essentially be an ad hoc, arbitrary ‘fix’ to make this approach produce a smooth curve. Also, this approach only utilizes 6 row averaging in the mid frequency region.

2) Another approach is to realign all rows traced across a sine pattern, such that, for example, the pixel in column 22 of any realigned row corresponds to a sine wave peak. All rows could then be averaged together, column by column. In effect, this approach aligns the phases of the sine wave periods across the different rows. This approach has promise but can become quite complex to successfully implement, due to such problems as perturbations in the sine wave periodicity across the sine pattern. Also, it is not clear that this approach could compute the desired 'peak MTF', as opposed to the average MTF.

3) A least squares type of statistical regression curve, fitted to a sinusoidal waveform, could be applied to individual rows or small groups of rows across the sine pattern. This would give a result akin to the average MTF, as opposed to the desired peak MTF.

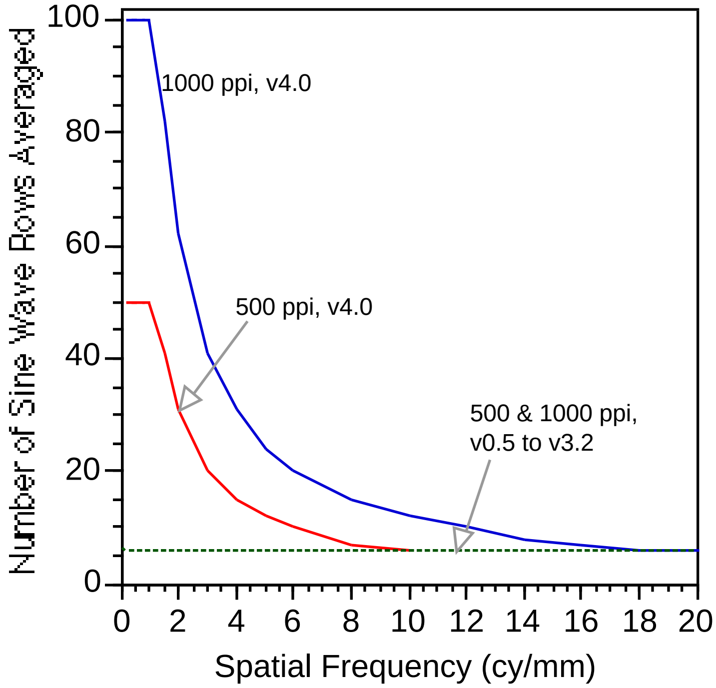

Figure 4. Row Averaging in *Sinemtf*
|skew| ≤ 1.0° in v4.0
|skew| ≤ 1.5° in v0.5 to v3.2

Table 2. Number of Sine Rows Averaged @ 500 ppi (*sinemtf* v4.0)

cy/mm	$0.0^o \le$ |skew| $\le 1.0^o$	$1.0^o <$ |skew| $\le 2.0^o$	$2.0^o <$ |skew| $\le 3.0^o$	$3.0^o <$ |skew| $\le 5.0^o$
0.1875	50	50	50	50
0.25	50	50	50	49
0.375	50	50	50	33
0.5	50	50	41	24
0.75	50	41	27	16
1	50	31	20	12
1.5	41	20	13	8
2	31	15	10	6
3	20	10	6	4
4	15	7	5	3
5	12	6	4	2
6	10	5	3	2
8	7	3	2	1
10	6	3	2	1

Notes: One row averaging at all frequencies if skew > 5.0^o.
Maximum number of rows averaged is 10% of ppi value.

Table 3. Number of Sine Rows Averaged @ 1000 ppi (*sinemtf* v4.0)

cy/mm	$0.0^o \le$ |skew| $\le 1.0^o$	$1.0^o <$ |skew| $\le 2.0^o$	$2.0^o <$ |skew| $\le 3.0^o$	$3.0^o <$ |skew| $\le 5.0^o$
0.25	100	100	100	99
0.375	100	100	100	66
0.5	100	100	82	49
0.75	100	82	55	33
1	100	62	41	24
1.5	82	41	27	16
2	62	31	20	12
3	41	20	13	8
4	31	15	10	6
5	24	12	8	4
6	20	10	6	4
8	15	7	5	3
10	12	6	4	2
12	10	5	3	2
14	8	4	2	1
16	7	3	2	1
18	6	3	2	1
20	6	3	2	1

Notes: One row averaging at all frequencies if skew > 5.0^o.
Maximum number of rows averaged is 10% of ppi value.

The new skew angle breakpoints of 1, 2, 3, and 5 degrees in *sinemtf* v4.0, were established based on an assessment of actual scanner skew angles computed from *sinemtf*, across 53 MTFs computed from 26 capture devices across 18 vendors. The results, given in Figure 5, show that in no case have sine wave test images submitted for IQS certification exceeded a skew angle of ± 0.75 degrees. By fixing the first breakpoint at 1.0 degrees for the 1/2% MTF loss criteria, an additional safety factor is built-in, for number of rows averaged for IQS certification cases. That is, the maximum modulation loss of 1/2% occurs only if the skew is 1.0 degrees; there is less than 1/2% loss for skew angles less than 1.0 degrees. The other breakpoints: 2.0, 3.0, and 5.0 degrees, follow a reasonable logical progression for those isolated cases of larger skew angle.

At first glance, one might conclude that the true device MTF is the MTF output by *sinemtf*, divided by the skew MTF given in equation 1, for the computed skew angle. However, the calculated skew angle has some error, both because the calculation is dependent on user inputs of visually judged corner coordinate locations, and because the individual patterns in the target itself can each have small angular offsets[8]. For example, it would not be unusual for *sinemtf* to calculate a skew angle of $+0.3^{o}$ in one direction, and a skew angle of -0.2^{o} in the orthogonal direction. *Sinemtf* v4.0 uses the average of the two signed skew angles that are computed in the two orthogonal directions, which is a better estimate of the true skew angle.

[8] The most recent formal statement of sine target misalignment tolerances is given in the target manufacturer's 1993 catalog, where it is stated that the misalignment of any sine wave target pattern could be up to ±0.1 degrees.

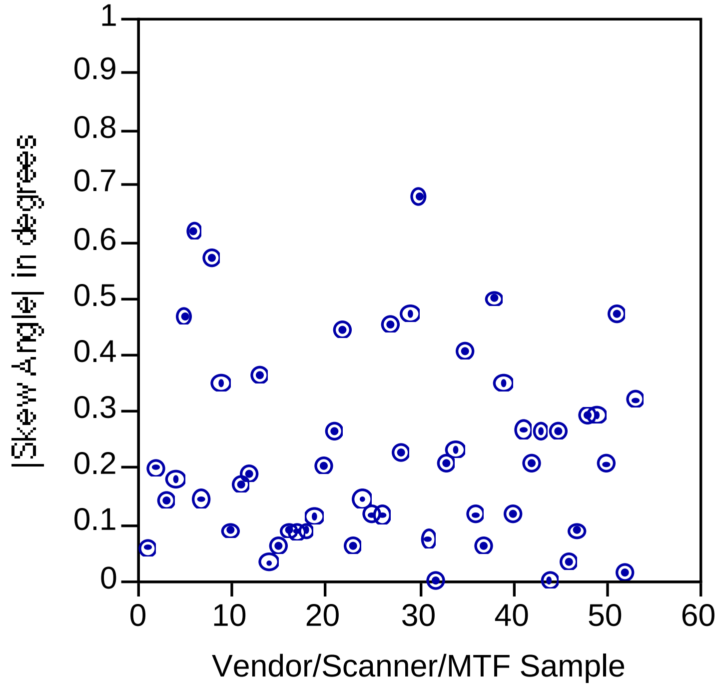

Figure 5. Measured Skew Angle between Target and Scanner

Data Point = abs{ [(± vertical skew) + (± horizontal skew)] / 2 }

Section 4

SUPPORTING ANALYSIS

4.1 Impact of Row Averaging

Increasing the row averaging decreases the effect of noise on the calculation of modulation and should smooth out the erratic behavior of the MTF in the low frequency region. Referring back to Figure 4 and Tables 2 and 3, it is seen that *sinemtf* v4.0 implements significantly more row averaging than the earlier *sinemtf* versions, except at Nyquist frequency. When comparing results of the same test data processed through *sinemtf* v4.0 and *sinemtf* v3.2, it is clear that the increased row averaging of v4.0 does have the desired effect of decreasing the erratic behavior of the MTF in the low frequency region; it also decreases the MTF's propensity for going above 1.0 modulation in the low frequency region.

Figure 6 illustrates the increased row averaging effect on the MTF. This example is from a 1000 ppi scanner submitted for IQS certification, which exhibited modulation values significantly above 1.0 when processing via *sinemtf* v3.2. It is seen that the low frequency modulations are decreased to a level at or below 1.0 modulation when processing via *sinemtf* v4.0.

Figure 7 shows the average difference in MTF, between *sinemtf* v3.2 and v4.0, where each MTF curve represents the average from 13 different scanners, all operating at 500 ppi and all with skew angles less than one degree. *Sinemtf* v3.2 utilizes constant 6 row averaging at all frequencies and v4.0 utilizes 50 row averaging in the low frequency region, gradually diminishing to 6 row averaging at the 10 cy/mm Nyquist frequency. It is seen that the largest difference is in the low frequency region and the difference gradually diminishes until the two curves overlap at the Nyquist frequency.

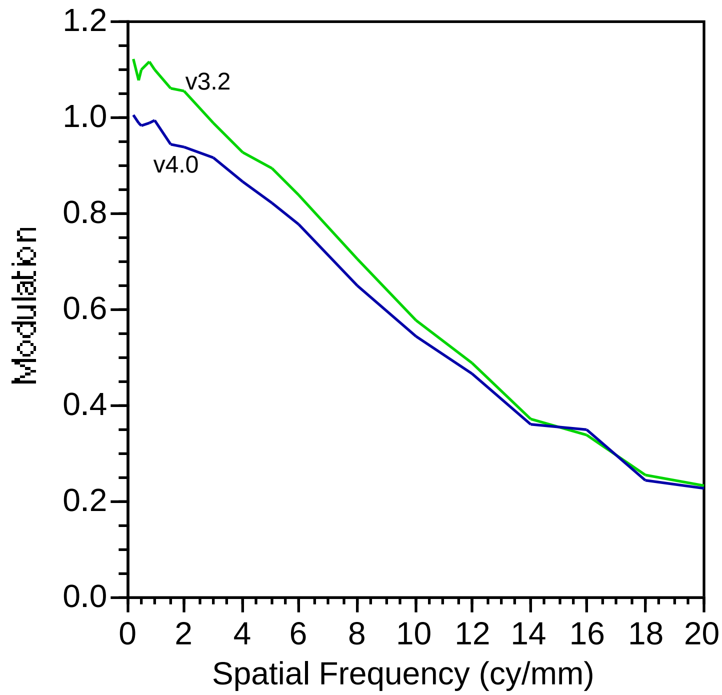

Figure 6. Effect of New Row Averaging on Single Scanner MTF

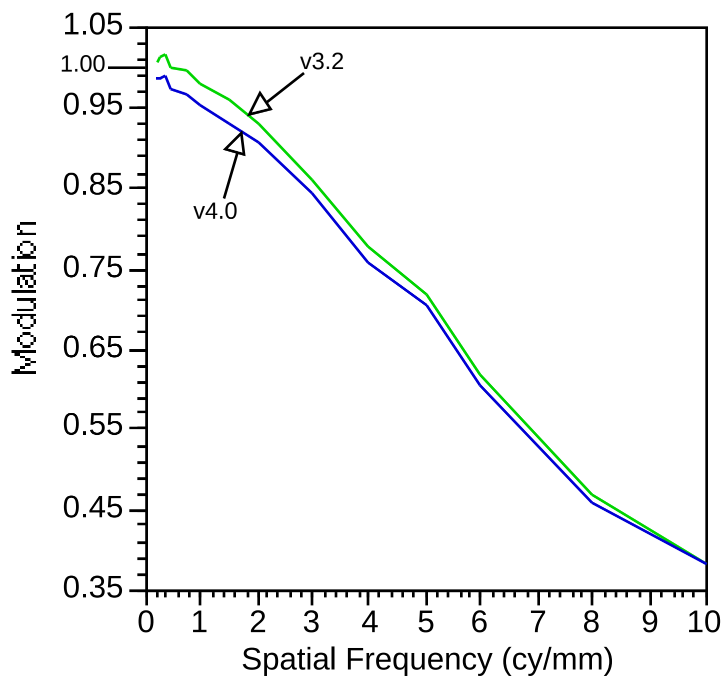

Figure 7. Average Effect of New Row Averaging on Multiple Scanner MTFs

Figures 8 and 9 illustrate the suppression of a noise spike by the increased row averaging in *sinemtf* v4.0. A one cy/mm sine pattern from a sine image submitted for IQS certification had a white speck artifact in one of the sine wave peaks, shown in figure 8. With the original 6 row averaging in *sinemtf* v3.2, this artifact resulted in a falsely high modulation on the MTF curve at one cy/mm. With the new 50 row averaging in *sinemtf* v4.0, this false peak is greatly diminished, giving a better estimate of the true MTF, shown in figure 9.

This is a difficult (and atypical) case for *sinemtf* to handle because, for IQS certification testing, we seek the 'peak modulation' MTF. In this mode, the program seeks out the single, row-averaged peak and adjacent valley combination which results in maximum modulation. Since this artifact is white, falls squarely on a peak, and covers several rows (~6 rows), it is not easily distinguished from true signal. However, v4.0's eight-fold increase in number of rows averaged at one cy/mm, does substantially decrease its impact.

Theoretically, noise removal could also be applied to the individual row sample values, prior to computing the average value across rows. For example, a statistical trimmed mean computation could be applied, which would remove outlier samples (assumes outliers are noise). However, such techniques have less accuracy as the sample size decreases; whereupon there is a danger of removing true signal sample values from the final row average. Although 50 samples at one cy/mm may be sufficient, 6 samples at Nyquist frequency would be a very difficult case to handle for 'outlier removal' algorithms.

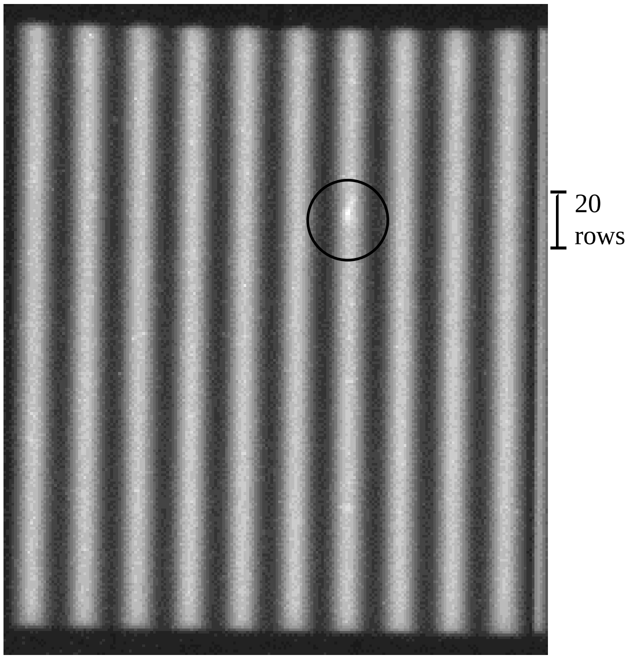

Figure 8. White Speck on One cy/mm Sine Image

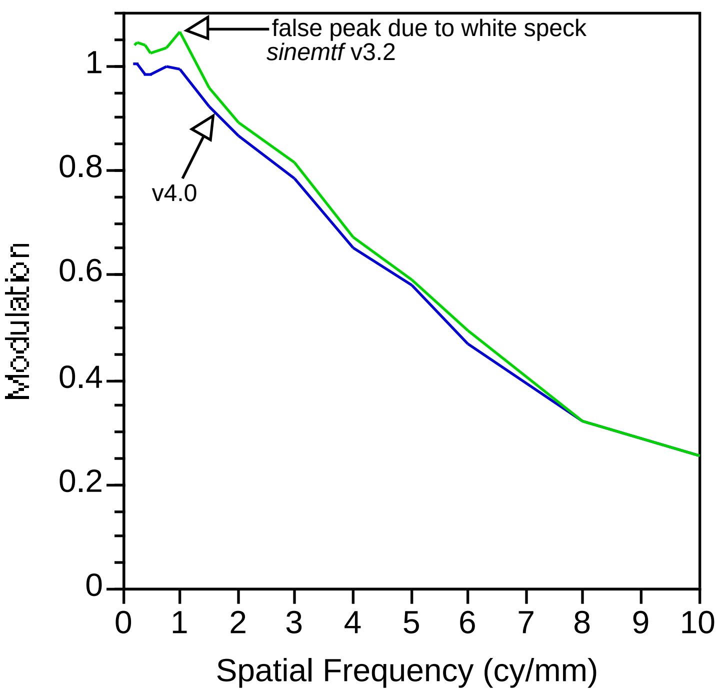

Figure 9. Suppression of 'White Speck' Noise via *Sinemtf* v4.0

4.2 Other Possible Causes of Erratic MTF

As mentioned in section 2, there are several other possible causes for the erratic MTF at low spatial frequencies, the three reasonable possibilities are:

• target calibration inaccuracies

• imaging system nonlinearity

• image enhancement filter.

These items are explored in more detail in the following. However, the main conclusion is that, although each of these items does appear to play a role in erratic MTF behavior in *isolated* cases, the evidence suggests that they are not a normal occurrence. In the vast majority of cases, the erratic MTF behavior is due to noise.

4.2.1 Target Calibration Inaccuracies

It is hypothesized that the modulation values of the sine target itself, which are measured by the target manufacturer for each serial-numbered target, may be in error in the low frequency region. This was investigated by comparing the MTFs generated from 17 scanners to the target modulations from the associated 17 different, serial-numbered, sine wave targets. If the dips and peaks in the scanner MTFs follow the dips and peaks of the reciprocal of the target modulations, then it would imply that this erratic behavior in the MTFs is really due to errors in the supplied target data. That is, the true scanner MTF should be smoothly decreasing with increasing frequency, but even if the true scanner MTF had dips and peaks in its curve, the probability is near zero that these true dips and peaks would align with, or track, the dips and peaks of the totally independent target modulation values[9].

In almost every one of the 17 cases compared, the MTF shape does not follow the reciprocal of the associated target modulation curve shape. These results indicate that inaccuracies in target modulation values are not a significant contributing factor to the erratic MTFs at low frequencies. For illustration, figure 10 shows an example of the single case where the MTF does follow the target modulations, compared to the much more typical result in Figure 11, where the MTF does not follow the target modulations.

---

[9] The magnitudes of the target modulations can, validly, have dips and peaks, just depending on the physical properties of the master target from which each serial-numbered target is made. Also, it should be noted that even if the MTF dips and peaks do not follow the target modulation dips and peaks, there is still some possibility that the target modulations are in error, but the possibility is more remote.

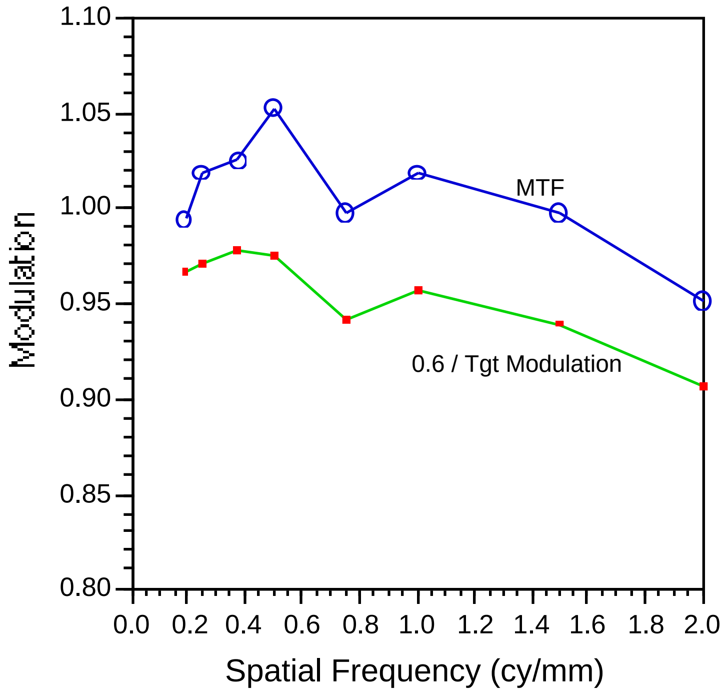

Figure 10. Probable Target Calibration Error
(MTF Tracks Reciprocal of Target Modulation)

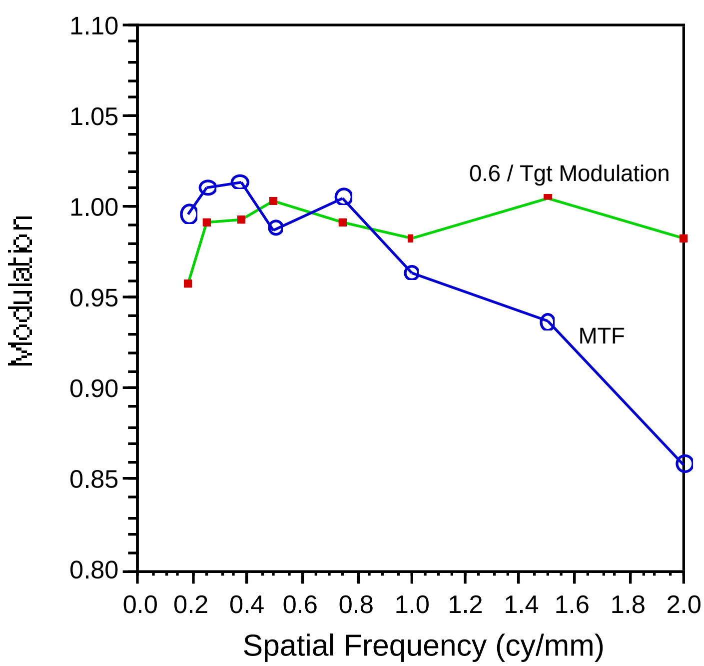

Figure 11. No Indication of Target Calibration Error
(MTF Does Not Track Reciprocal of Target Modulation)

4.2.2 Imaging System Nonlinearity

In the normal processing mode of *sinemtf*, it is assumed that a linear relationship exists between the target reflectance values and image gray levels of the scanned target. The 'best fit' relationship is obtained via a linear, least squares regression computation performed in *sinemtf*, which utilizes the 14 density patches that surround the sine wave patterns, the target reflectance values of these patches (supplied by the target manufacturer), and the corresponding image gray levels computed by *sinemtf*. This linear, straight line relationship is then used to convert sine wave peaks and valleys, as determined in image gray level space, to their equivalent values in target reflectance space, where the modulation computation for the MTF is performed[10].

If the target space – image space relation is grossly nonlinear, then the scanner under test fails the IQS linearity requirement and further testing is halted. If a smaller nonlinearity exists, however, the IQS linearity requirement may be met, but some amount of error may still be induced into the computed MTF. The question then arises: what is the effect on the MTF of a nonlinearity whose magnitude is such that it just barely passes the linearity requirement? In the general case, the effect on the MTF is variable. In the specific case of a nonlinearity which produces a smooth, continuous curve that is well-fit by a second order polynomial, it has been found from observation that the effect is to falsely boost the modulation values at low spatial frequencies. This type of nonlinearity can, therefore, be the cause of MTF values going above 1.0 at low spatial frequencies.

This is illustrated in figures 12 and 13. Figure 12 is the image gray level - to - target reflectance relation from an actual vendor scanner. The linearity requirement is met, because the largest deviation of a sample point from the best fit straight line is 7.2 gray levels, whereas the IQS allows up to 7.65 gray level deviation. However, there is a definite, second order curvature to the sample points, which is well-fit by a second order (quadratic) polynomial. Figure 13 plots the MTF (v4.0) as computed using two methods: first, using the single straight line computed from linear regression across all sample points, which is the normal processing mode ("LinReg"); and second, using the MTF as computed from a pointto-point fit[11] to the actual curvature shown in figure 12 ("Pt-to-Pt straight line"). It is

---

[10] 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 scanner under test 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 of the scanner under test.

[11] In this user-optional processing mode of the *sinemtf* algorithm, unique straight line segments are constructed for each pair of adjacent sample points, in order to follow the sample's actual curvature; in other words a "piecewise linear" approach is used.

seen in figure 13 that in this case, where the input / output relation has a nonlinear component, the normal *sinemtf* processing mode ("LinReq") produces modulation values above 1.0. That this is due to the nonlinearity is evidenced by the fact that the rise above 1.0 is greatly diminished when the nonlinearity is taken into account in the *sinemtf* processing ("Pt-to-Pt straight line").

One might conclude from the preceding that a more accurate estimate of the true MTF would be achieved by using the point-to-point straight line fit instead of the normally-applied straight line from linear regression. However, the linear regression method has an inherent noise smoothing capability which the point-to-point method lacks. This is important because there are only 11 unique target density patch values covering the total 0 to 255 gray range. The point-to-point method can result in disjointed line segments, leading to errors of a different kind.

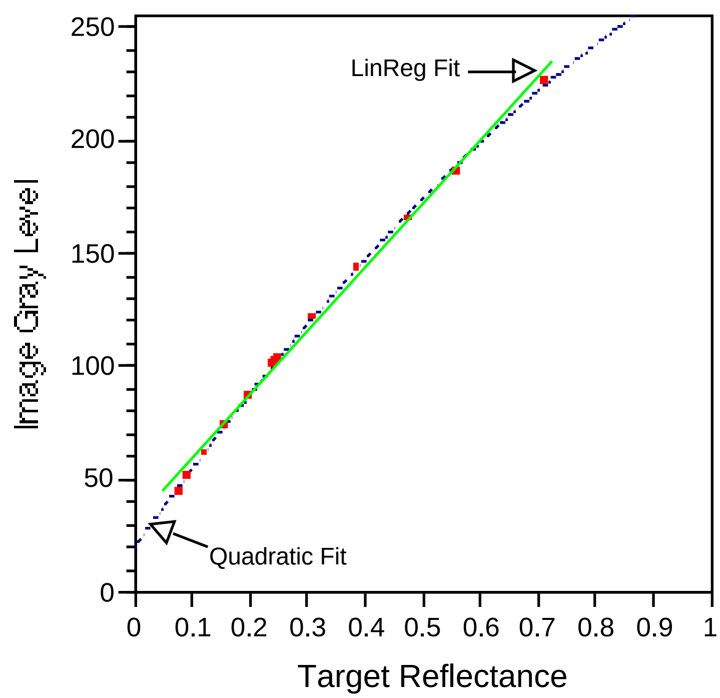

Figure 12. Nonlinearity in Scanner Input - Output Relation

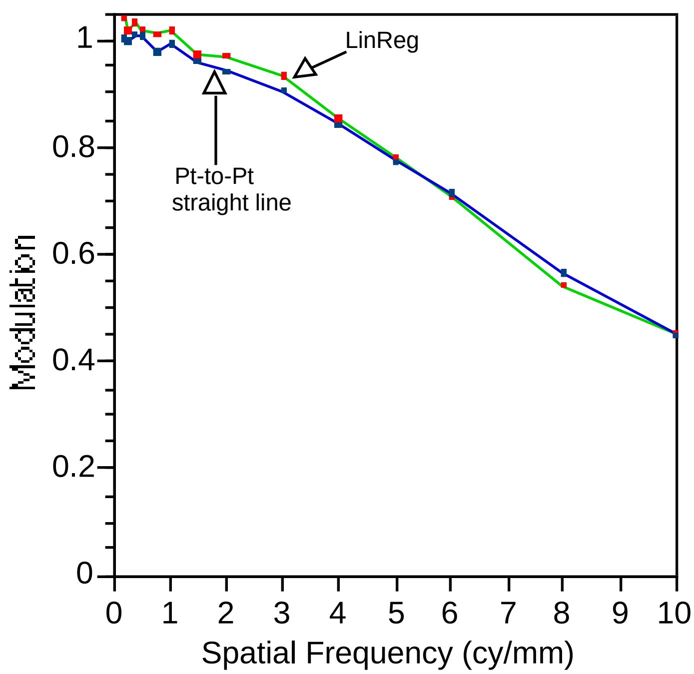

Figure 13. Effect of Nonlinearity on Low Frequency MTF

4.2.3 Image Enhancement Filter

There are many different filters that can be applied to an image in an attempt to enhance detail, these are usually called sharpening, edge enhancement, or 'MTF boost' filters; all such filters have an effect on the system's MTF. These filters can be applied in the spatial domain via convolution with the image, or in the frequency domain via multiplication with the image's frequency spectrum. Applying such filters to the image signal processing associated with fingerprint scanners is undesirable, however, because it has the potential to introduce artifacts that were not in the original fingerprint[12]. Such a filter could, however, validly be applied after the fact, i.e., when the already-scanned fingerprint is viewed on a softcopy display for examination or matching. At that stage, the effect of the filter on a particular fingerprint image can be readily seen (compared to original) and it is a reversible process, since the original, unfiltered image is still available.

Vendors seeking FBI certification of their fingerprint capture devices are aware of the undesirability of introducing a strong enhancement filter into the fingerprint capture device's signal processing stream. However, a spatial sharpness filter might be applied in the signal processing by the original equipment scanner manufacturer, e.g., on the analog signal side prior to digitization. Filter application at such a primitive signal stage would not usually be accessible to the fingerprint device vendor for override, and its presence could be the cause of MTF modulation values going above 1.0 in the low frequency region, where the MTF values are already near 1.0 (without filter enhancement). Although the MTF boost, due to an enhancement filter, might occur at all frequencies, it's presence would be more difficult to detect at mid to high MTF frequencies because of the natural fall-off of the system MTF with increasing frequency, greatly diminishing the possibility of modulations going above 1.0 in this region.

Figure 14 illustrates the effect on the MTF of a particular type of sharpness filter that mainly boosts low spatial frequencies. Specifically, a sharpness filter was applied to a sine wave image and both the original image and the sharpen-filtered image were processed through *sinemtf* 4.0. In this case, the low frequency hump (modulation > 1.0) is real signal, i.e., it is not due to noise, so we would not want the new noise suppression algorithm to suppress this hump. In fact, figure 14 shows that *sinemtf* v4.0 does retain real signal values above 1.0 modulation, which is the desired result.

---

[12] Enhancing an image by adding frequency information, without knowledge of the imaging system's MTF, is a hit and miss game, i.e., it may truly enhance the image, or it may falsify parts of the image. This is to be contrasted with 'object restoration', whose aim is to restore the image to its original object form. Object restoration requires specific knowledge of the imaging system that created the image, such as the system MTF.

In a review of all scanner MTFs measured to date for IQS certification testing, no case was found that could be explicitly tied to introduction of an enhancement filter. That is, all cases of low frequency modulation values above 1.0 could be traced to noise, target calibration errors, or nonlinearity. It is possible that enhancement filters have been applied in some of these cases, but if so, they were fairly weak enhancements.

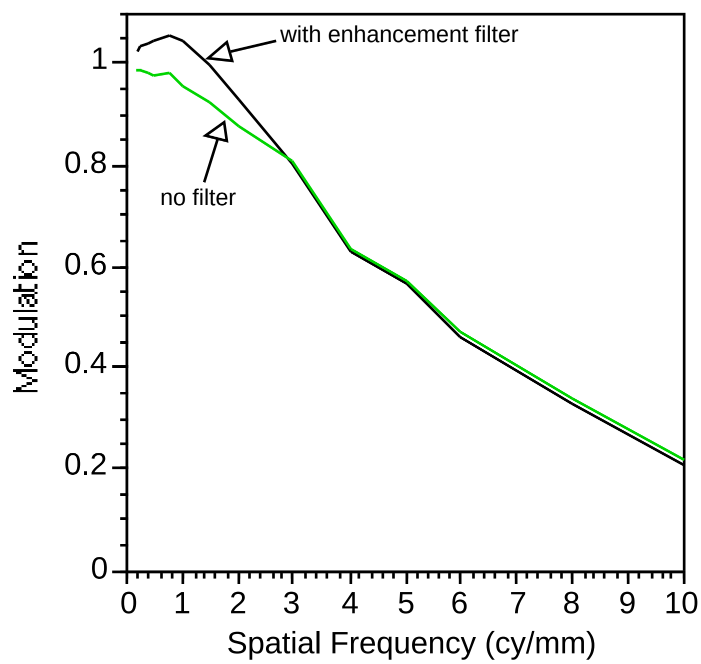

Figure 14. MTF of Unfiltered and Filtered Sine Wave Image (Processed via Sinemtf v4.0)

Appendix A

DETERMINATION OF NUMBER OF ROWS TO AVERAGE

Equation 1 (see section 3) defines the reduction in the MTF due to a non-zero skew angle between the sine wave target and the detector array of the imaging system under test. This equation includes three parameters which can be defined for a specific case, i.e., scanner ppi, spatial frequency of interest, and skew angle; and it defines the parameter whose value is to be determined, i.e., number of pixels to average. By considering equation 1, together with a specific maximum acceptable percent loss in modulation due to skew, then the corresponding maximum number of sine wave rows that can be averaged at any given frequency can be found.

This logic was programmed to produce tabulated data of number of rows to average, as a function of spatial frequency, skew angle, and allowable percent loss in MTF. This computer code is given at the end of this Appendix. For the selected case of 1/2% maximum allowable MTF loss and skew angle magnitude breakpoints of 1.0, 2.0, 3.0, and 5.0 degrees, the computed number of rows to average were then plotted against spatial frequency, and a least squares power curve was fitted to the data, as illustrated in figure 15. The curve fit step was implemented to obtain a convenient formulary for coding into *sinemtf*; it also smooths-out small irregularities in the computed number-of-rows (irregularities due to the necessity to truncate to whole integers). The raw data closely fit the power curve model, with correlation coefficients greater than 0.9990 in each case.

Specifically, the logic implemented in *sinemtf* v4.0 to compute the number of rows to average (R), is as follows:

$$R = 5.9970579 * F^{-1.015904} \qquad ,\text{for} \quad 0 \le |\text{skew}| \le 1 \text{ degrees}$$

$$R = 2.8639964 * F^{-1.029771} \qquad ,\text{for} \quad 1 < |\text{skew}| \le 2$$

$$R = 1.8645913 * F^{-1.03381} \qquad ,\text{for} \quad 2 < |\text{skew}| \le 3$$

$$R = 1.0397801 * F^{-1.06002} \qquad ,\text{for} \quad 3 < |\text{skew}| \le 5$$

$$R = 1 \qquad ,\text{for} \quad |\text{skew}| > 5$$

with the constraints,

If:	R > (0.1*ppi)	,then R = 0.1*ppi
If:	R > H	,then R = H
If:	R < 1	,then R = 1

where,

R = number of rows to average (rounded to whole number).
F = normalized frequency = f / Nyquist frequency = f * 50.8 / ppi.
f = sine frequency in cy/mm, from target data file (input to *sinemtf*).
ppi = directional pixels per inch; *sinemtf* calculation for horizontal & vertical.
Nyquist frequency in cy/mm = ppi / 50.8.
H = number of rows in sine pattern measurement box height (calculated by *sinemtf*).
|skew| = absolute value of: [(±vertical skew) + (± horizontal skew)]| / 2.

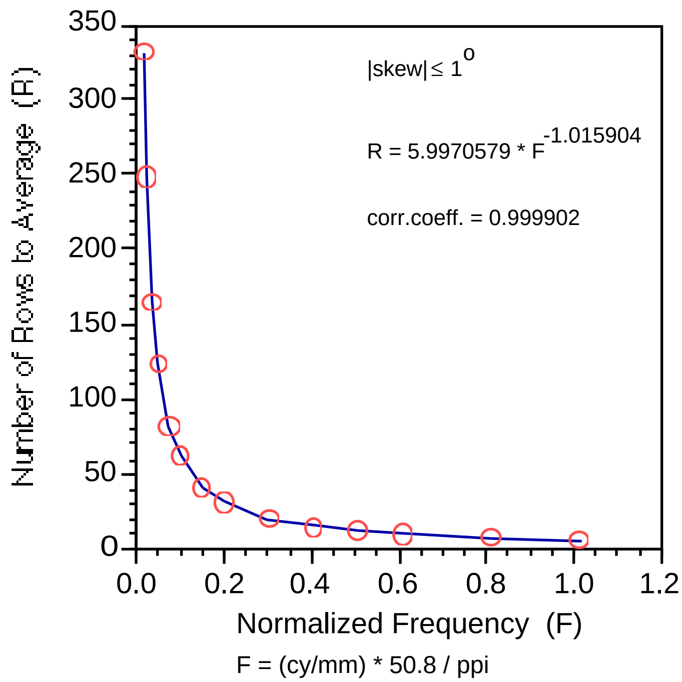

Figure 15. Power Curve Fit to "Number of Rows to Average"

The following is a listing of the Fortran-90 computer program, which computes and tabulates the number of sine wave rows to average, as a function of sine wave spatial frequency, skew angle, Nyquist frequency, and percent allowable loss in MTF.

```
! Determine maximum number of sine wave rows that can be safely averaged,
! (function of: allowable percent loss in MTF, sine wave spatial frequency,
!  Nyquist frequency, skew angle, spec MTF)
! Utilizes Skew MTF concept, ref:
!                   "Effect of Slit Misalignment on Microdensitometer MTF",
!                   R.A. Jones, Phot.Sci.Eng, Nov-Dec 1965, V9, pp. 355–359

REAL :: spec500(19), spec1000(19), freq(19), angle(7), L, skewspec(19,2)
INTEGER :: numrows(19,2)

data spec500 /1.,1.,1.,1.,1.,.905,1.,.797,.694,.598,.513,.437,.312,.2,1.,1.,1.,1.,1./
data spec1000 /1.,1.,1.,1.,1.,.925,1.,.856,.791,.732,.677,.626,.536,.458,.392,.336,.287,.246,.21/
data freq /.187,.25,.375,.5,.75,1.,1.5,2.,3.,4.,5.,6.,8.,10.,12.,14.,16.,18.,20./
data angle /.75,1.,1.5,2.,3.,4.,5./

pi = 3.141592654
numberofangles = 7

PRINT*, ' '
PRINT*, 'enter allowable percent loss in MTF'
READ*, xxx
fraction = 1. - .01 * xxx

OPEN(2,FILE='SkewResults',STATUS='unknown')

DO i = 1, numberofangles
        radang = angle(i) * .01745329252
        WRITE(2,*) ' '
        WRITE(2,*) 'skew= ',angle(i), ' degrees        Allowed % Loss = ',100.*(1.-fraction)
        WRITE(2,*) '......cy/mm.....spec500....skewXspec...#rows........spec1000...skewXspec....#rows'
```

……..(continued on next page)……..

```
            DO n = 1,19             ! loop thru frequencies

                  DO m = 1,2
                        ppi = 500.*float(m)
                        iflag = 0
                        previous = 0.

                        DO k = 1, 1000          ! loop thru number of rows averaged
                              L = float(k) * 25.4/ppi
                              x = pi * L * radang * freq(n)
                              skewmod = sin(x) / x
                              IF(skewmod < fraction) then
                                    numrows(n,m) = k-1
                                    iflag = 1
                                    skewspec(n,m) = previous * spec500(n)
                                    IF(m==2) skewspec(n,m) = previous * spec1000(n)
                                    EXIT            ! exit the DO k= loop
                              ENDIF
                        previous = skewmod
                        END DO
                        IF(iflag == 0) numrows(n,m) = 99999
                  END DO

                  WRITE(2,22) freq(n), spec500(n), skewspec(n,1), numrows(n,1), &
                              spec1000(n), skewspec(n,2), numrows(n,2)
22                FORMAT(3F12.3, I7,5x, 2F12.3, I7)
            END DO
END DO
CLOSE(2)
PRINT*, ' +++++++  DONE  +++++++'
PAUSE
END
```

Appendix B

OTHER ENHANCEMENTS TO *SINEMTF* VERSION 4.0

The sine wave row averaging for noise suppression is the major enhancement made to *sinemtf* version 4.0. However, this version also includes other enhancements, which are briefly described in the following.

1. Vertical and horizontal scales are treated independently. This allows for correct processing of a sine image which was captured with an imaging device that has a real scale difference in the two directions. The two computed directional scale values are used in all computations, rather than the direction-averaged single scale value, which was used in all previous code versions.

2. The density patches in the input data file can now have any labels, e.g., the white patch no longer need be labeled 'F'. However, the whitest image patch MUST correspond to the highest reflectance target patch, otherwise will get runtime message:
"Image polarity may be wrong, try re-running with reversed image polarity."
[On the other hand, the blackest image patch need not correspond to the lowest reflectance target patch.]

3. The Unix type command line entry has been changed to a menu display with user selection of runtime options. However, for those diehard command-line enthusiasts, there is a 'hidden' command line interface, which works by typing the image properties as arguments on same line as program executable, for example:

```
mtf  test.tif   tgt.dat   223   236   1223   235   221   728   h
```

Above example will run test.tif image with tgt.dat file, ULcorner at 223, 236; URcorner at 1223, 235; LLcorner at 221, 728; horizontal image orientation.

4. The aliasing test is now applied to the frequency range: 30% of Nyquist to Nyquist frequency; previous code versions tested in range: 5 cy/mm to Nyquist frequency.
For a given frequency and any skew angle (v4.0):

> C = number of cases to test for aliasing,
> C = measurement box height / number of rows averaged,
> If C is greater than 10, then C = 10,
> then aliasing is said to be present at the given frequency if at least C/3 of the tested cases have detected aliasing,
> If C/3 < 1 then aliasing is said to be present if just 1 case detects aliasing.

5. MTF results are automatically compared to IQS 500 ppi spec or IQS 1000 ppi spec; but if user selects option “n”, then output is not compared to IQS spec values.

6. For Windows 95/98/NT platforms, the runtime display now appears in a scrollable window.

8) Other:

- Added output of absolute value of average of vertical and horizontal skew angles.
- “Low dynamic range” check deleted (not of practical use).
- If "c" or "p" option is selected with "e" option, then the gray level -to-target reflectance values corresponding to the point-to-point piecewise straight line fits are printed-out for all 256 gray levels.
- Code developers are listed in “r” option.

GLOSSARY

avg	average
cy/mm	cycles per millimeter
FBI	Federal Bureau of Investigation
IQS	Image Quality Specification
MTF	Modulation Transfer Function
ppi	pixels per inch
sinemtf	MITRE's computer program to compute MTF from a sine wave target
tgt	target
v	version