A Study of Slanted-Edge MTF Stability and Repeatability

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ABSTRACT

The slanted-edge method of measuring the spatial frequency response (SFR) as an approximation of the modulation transfer function (MTF) has become a well known and widely used image quality testing method over the last 10 years. This method has been adopted by multiple international standards including ISO and IEEE. Nearly every commercially available image quality testing software includes the slanted-edge method and there are numerous open-source algorithms available. This method is one of the most important image quality algorithms in use today. This paper explores test conditions and the impacts they have on the stability and precision of the slanted-edge method as well as details of the algorithm itself. Real world and simulated data are used to validate the characteristics of the algorithm. Details of the target such as edge angle and contrast ratio are tested to determine the impact on measurement under various conditions. The original algorithm defines a near vertical edge so that errors introduced are minor but the theory behind the algorithm requires a perfectly vertical edge. A correction factor is introduced as a way to compensate for this problem. Contrast ratio is shown to have no impact on results in an absence of noise.

Keywords: MTF, SFR, slanted edge, image quality, sharpness

1. INTRODUCTION

The slanted-edge method of measuring the spatial frequency response (SFR) as an approximation of the modulation transfer function (MTF) has become a well known and widely used image quality testing method over the last 10 years. This method has been adopted by multiple international standards including ISO and IEEE.[1] Nearly every commercially available image quality testing software includes the slanted-edge method and there are numerous open-source algorithms available. This method is easily one of the most important image quality algorithms in use today.

The algorithm itself has remained relatively unchanged since it's original publication in ISO 12233:2000.[2] Despite the consistency of the algorithm, in the latest 2014 revision of the ISO 12233 standard there was a major modification to the recommended target. In the original 2000 edition of ISO 12233 the target was required to have a minimum edge contrast of 40:1. The revised standard specifies the edge contrast to be 4:1.[3] This change reflects a change in understanding of the slant edge measurement, with high contrast the measurement becomes unstable and so the contrast was lowered. The standard also defines a 5° slanted edge rather than another edge angle. There is very little published evidence as to why these specifications are made for the slanted-edge measurement. This raises a question, how stable is the slanted-edge method and under what testing conditions will it be most stable?

Mathematically there are several known limitations of the slanted-edge algorithm. First and foremost is the angle of the the edge being measured relative the the sensor array. The relative edge angle must not be at $n\frac{\pi}{4}$ increments where n is an integer value. Should the angle fall on one of these "whole angle" increments the algorithm will be missing frequency information that is calculated from the phase-offset portions of an edge relative to the sensor. This paper builds on the work done by Peter Burns[4] and Don Williams[5] to help characterize targets and environments.

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Table 1: Real-world data set variables

Variable	Values
Edge Angle	5, 10, 15
Contrast Ratio	1.4, 2.1, 4.3, 4.8, 11.3, 33.7
ISO Speed	100, 400, 1600, 6400

2. EXPERIMENTAL

2.1 Capture

In order to validate that simulated edge regions can be used, a data set was acquired from a Canon EOS 6D of a series of slanted edges. The camera was set up on a stable tripod at a distance of 190 cm from the targets. The targets were illuminated with 4000K illumination at 355 lux with a uniformity of 95% across the measured field.

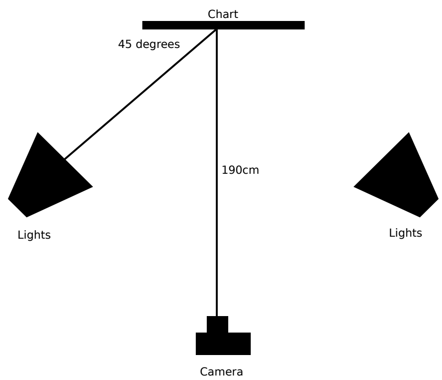


Figure 1: Diagram of lighting setup

A series of images was acquired across a range of slanted edge angles, contrast, and noise levels (See Table 1). The contrast level and edge angle was varied by switching out targets. The noise level was varied by changing the ISO sensitivity of the camera. The exposure was kept constant by varying the shutter speed inversely to the ISO sensitivity.

The lens model used to capture the data set was a Canon EF 24-70mm $f/4$L IS USM set to an aperture of $f/5.6$ and a focal length of 70 mm. Manual focus was set and maintained for all images captured. The data set was captured in CR2 uncompressed raw and large, max quality JPEG formats and for each variable combination 10 images were captured. The raw image files were converted to linear TIFF files for processing, removing gamma encoding as a variable.

2.2 Data Processing

The algorithm used to calculate the slanted-edge MTF for all results is a modified version of the ISO standard. The version used here included a noise reduction process on non-edge areas of the region and a second-order fit to the edge instead of a first-order fit. Overall this has reduced the variability present in the results, however the relative differences remain constant. A follow-up study is planned to show the precise impact of these changes on results.

Table 2: Reported slanted-edge results

MTF50	MTF30	Light Mean Pixel Value	Dark Mean Pixel Value	Edge Angle

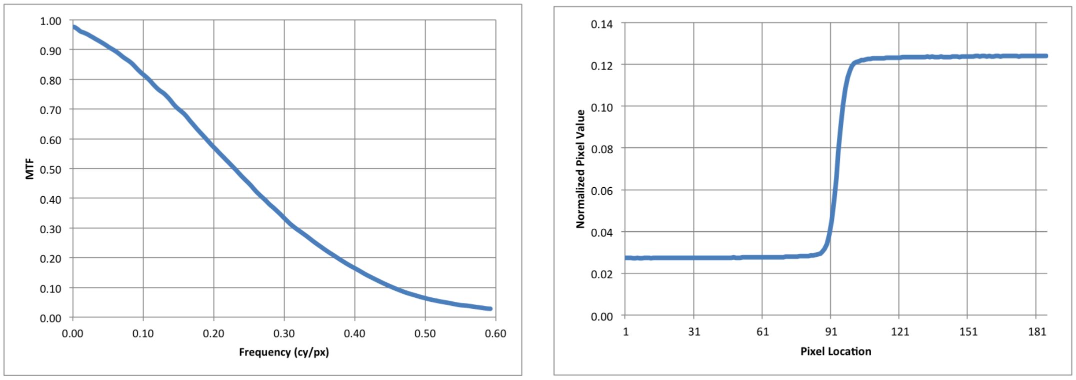


Figure 2: Mean MTF plot and edge profile for ISO 100, 5°Edge Angle, 4.3:1 Contrast data set

A region was selected that would be of a reasonable size and would cover the edge in all images. The metrics shown in Table 2 were reported along with the MTF curve out to just past the Nyquist frequency and the edge profile (See Figure 2).

For each reported result the mean and standard deviation was calculated across all 10 images in each variable set. An example of the final reported data is shown in Table 3.

Table 3: Example of results for ISO 100, 5° Edge Angle, 4.3:1 Contrast data set

Result	Mean	Std. Dev.
MTF50	0.230	0.013
MTF30	0.317	0.018
Light Mean	32.159	0.065
Dark Mean	6.740	0.019
Edge Angle	4.635	0.002

3. SIMULATED DATA GENERATION

In order to expand the range of testing without having a monumental task of data acquisition, a simulated data set was generated to correlate with the real-world data set. Two simulated data sets were generated: One to match the design of the real-world data set varying similar values and one to cover a much wider range of variables. All data was generated using a MATLAB anti-aliased edge generator which applied an Gaussian-based simulated point spread function (PSF). All noise added to the simulated edges was standard Gaussian noise with a zero-mean and constant variance.

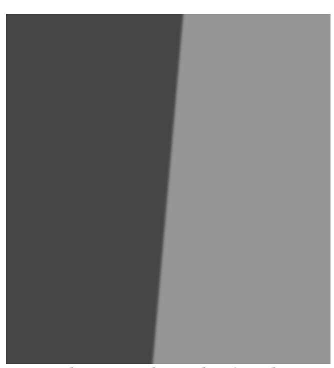
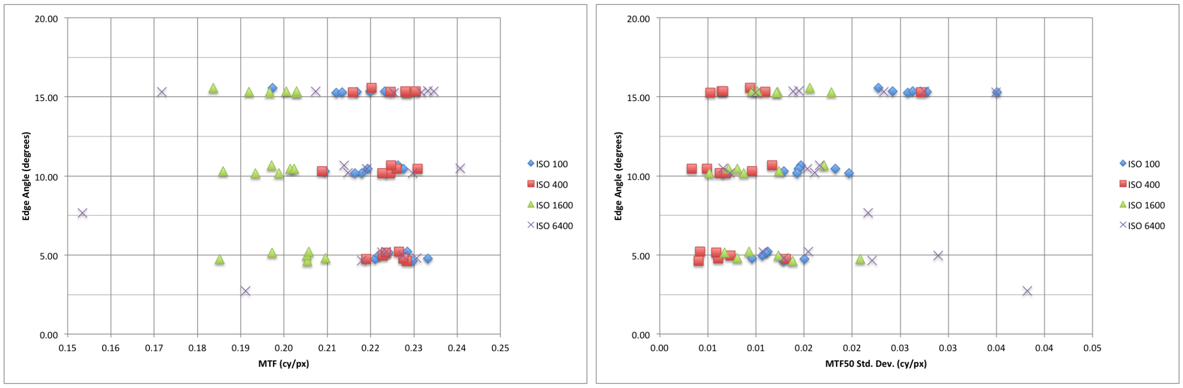


Figure 3: Example simulated 5° edge with no noise



(a) MTF50 in cycles per pixel plotted as a function of detected edge angle

(b) Standard deviation of MTF50 plotted as a function of detected edge angle

Figure 4: Plots for real world results

4. RESULTS

4.1 Real World Data

The real world data sets allow us to show the approximate variability under certain circumstances and to estimate the effect of certain variables when compared to simulated data. The full data set shows some interesting aspects of the camera itself in addition to the more general aspects. Figure 4 shows that despite the raw images and lack of signal processing, the camera gave systematically lower results at ISO 1600 compared to the higher noise ISO 6400. It also shows that, as might be expected, the highest ISO and likely highest noise had the greatest variability and most outliers. Ignoring the outliers however, the edge angle estimation remains very accurate at all target angles and all noise levels. Furthermore the variability within an noise level remain very similar at all edge angles with no obvious systematic change. Contrast appears to have little effect on real world data that is outside the variability caused by noise.

Edge angle does appear to have an impact on variability in some systems however. At ISO 100 the variability of MTF50 clearly increases with edge angle. Since this does not seem to occur at any other noise level it is possible that this an artifact of the signal processing in the camera. Further study is needed to determine if this is the case.

Figure 5 shows the effect of contrast ratio on the real world data set. Generally the lower contrast ratios have a lower MTF50. This can primarily be expected based on the noise, however an examination of the noise does not fully support this assumption. More study of these results is required and may be discussed in a future paper.

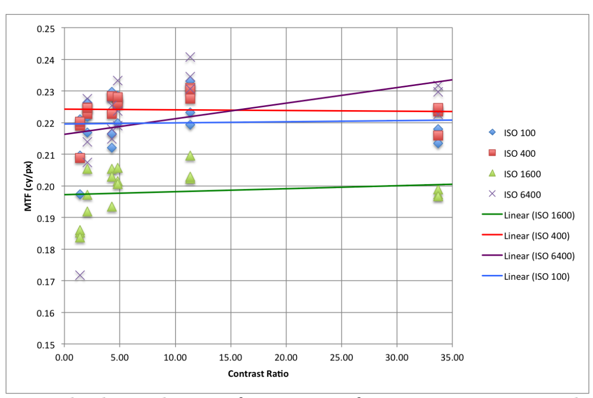


Figure 5: MTF50 in cycles per pixel plotted as a function of contrast ratio and colored by ISO of the data set with linear trendlines

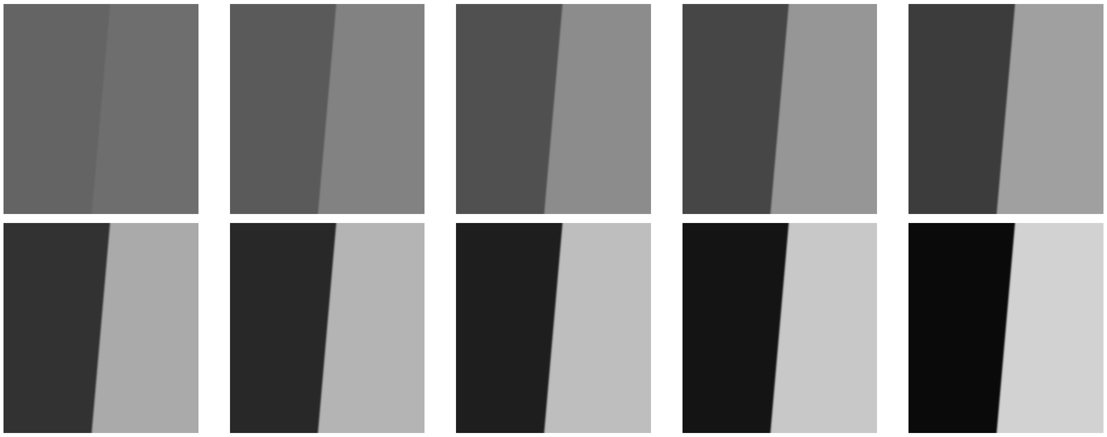


Figure 6: Simulated contrast data set with varying contrast and constant edge angle

4.2 Contrast

Given that the contrast ratio change is the only significant change made to standards using the slanted-edge calculation in the last 10 years this will be the first issue we look at here. Since these images are completely simulated and there is no radiometric data to associate with the pixel values, it is assumed that these files have a gamma of 1.0. It is also assumed that the simulated values, for the purposes of determining relative contrast of the edge, directly correspond to luminance (Y) values from CIE XYZ (e.g. 255 pixel = 1.0 Y).

As seen in Figure 7, the MTF50 remained extremely stable across all contrast levels with no noise present. The overall standard deviation in the MTF50 was less than 0.075%. Statistically speaking, these results are absolutely equivalent.

However these measurements were made in an absence of noise. When significant noise is present the contrast does gain certain importance. Figure 8 shows the MTF50 across the same set of contrast ratios with simulated noise with a sigma of 0.001 applied. The lowest contrast (1.1:1) clearly indicates a failed measurement. The addition of the noise was enough to bring the signal to noise ratio so low that the edge was undetectable. Leaving the outlier of the lowest contrast ratio, the remaining contrasts show effectively the same results as the edges with no noise. The overall standard deviation is higher (2.0%) but this is within the variability created by the noise itself.

4.3 Angle

The well described theory behind the slanted-edge MTF measurement[6,7] explains that the reason behind slanting the edge is to get phase offsets in different cross-sections of the same edge. These phase offsets are used to calculated an oversampled edge profile, allowing for detection of frequencies near and above Nyquist. Ideally, the slanted edge would only be slanted enough to pass across a minimum number of sampling sites (pixels) to get

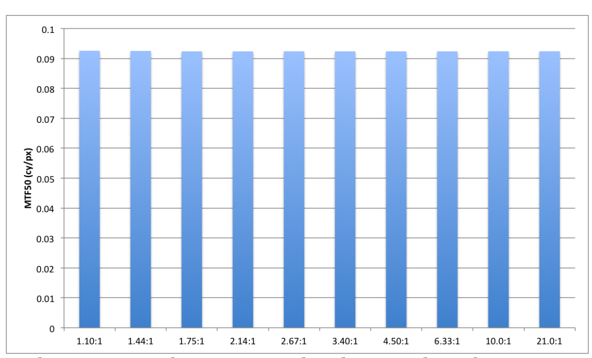


Figure 7: MTF50 in cycles per pixel across multiple simulated contrast ranges (See Figure 6)

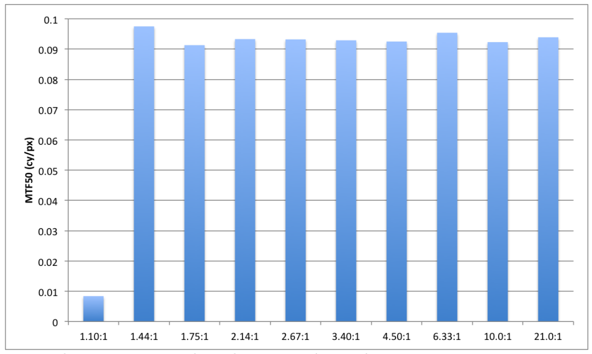


Figure 8: MTF50 in cycles per pixel across multiple simulated contrast ranges with added Gaussian white noise

the needed phase offset. In practice it is not possible to repeatably capture an image of an edge so close to 0° or 90° . The standard most often used became ~5° so as to allow for variation in the capture while still remaining close to that edge.

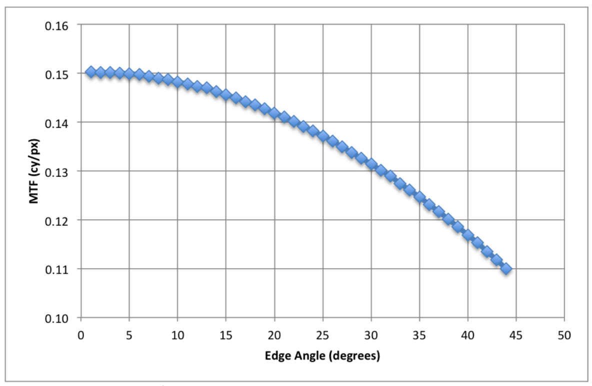


Figure 9: Plot of MTF50 values varying with edge angle

There is a problem with this 5° angle that has not yet been addressed in any standard or paper. As you move away from perfectly vertical/horizontal, you start to invalidate one of the primary assumptions of the slanted-edge measurement. Specifically the assumption that the edge is in fact perfectly horizontal or vertical. When calculating the edge spread functions (ESF) and line spread function (LSF) the assumption is that the profile is being taken normal to the edge. In a digital sampling system it is difficult to get normal edge profiles for non-sampling-aligned edges without needing to interpolate or otherwise introduce sampling errors. Therefore most algorithms do not attempt this and, assuming that the edge is near aligned to the sampling grid, accept whatever minor errors might be introduced. Figure 9 is an example of the kind of error this can introduce as you change edge angle. Note the axes, the y-axis has been scaled to emphasize the change occurring. The total difference between 1° and 44° is 37% and the change is clearly systematic, as the edge angle moves closer to 45° from aligned with the sampling grid the lower the MTF gets.

Simply put, there is a need to correct the line spread function to account for the rotation. The trigonometric relationship of the corrected line spread width is fairly simply. Figure 10 shows the geometric relationship and Equation 1 shows the mathematical relationship.

$$d = l\cos(\theta) \tag{1}$$

Where l is the width of the line spread function, d is the width of the line spread function normal to the edge, and θ is the angle of the edge relative to the sampling grid.

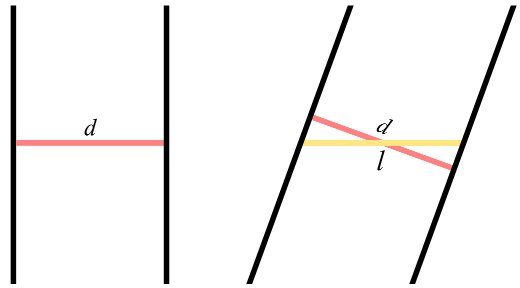


Figure 10: Example of 20° rotated edge profile

In effect, the LSF must be scaled to correct for the rotation. Equation 2 shows the mathematical scaling of the LSF.

$$LSF_{corr}(x) = LSF(x\cos(\theta)) \tag{2}$$

Where $LSF_{corr}(x)$ is the corrected line spread function, $LSF(x)$ is the uncorrected line spread function, and x is spatial position on the LSF.

With this correction applied the angular difference becomes dramatically smaller (See Figure 11)

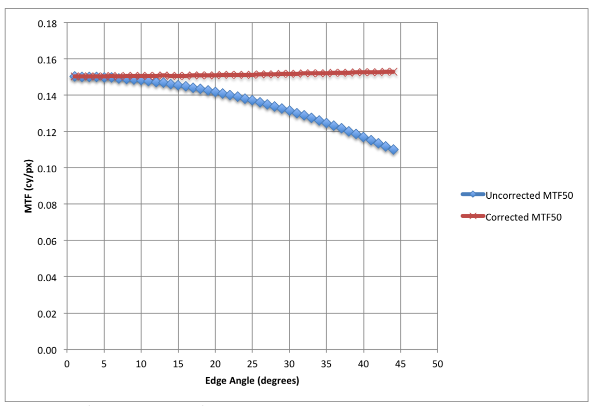


Figure 11: Plot of MTF50 for uncorrected and corrected measurements

The rotation correction improves the results but there is still a slight upward trend in the corrected data. Figure 12 shows an exaggerated plot of the corrected MTF. The overall difference is only 1.6% of the total MTF but the distinctly systematic trend is worth noting.

It turns out that when the image has a larger Gaussian PSF applied, the remaining error is reduced. Figure 12 also shows the angle set with a wider Gaussian applied to the edges. The axes on Figure 12 are the same scale but shifted to center on the new data. The mean MTF is much lower, due to the blur, but relative difference angle-to-angle is dramatically lower. The overall difference is now 0.23%, an order of magnitude lower than before. The source of this error can be found in the PSFs used. Figure 13 shows the small Gaussian applied to the first data set adjacent to the much larger Gaussian applied to the second.

The sampling of the small Gaussian is such that the normally rotationally-invariant Gaussian function has directional factors as you approach 45°increments. The larger Gaussian mitigates those factors with denser sampling. This kind of error was introduced by the generation of the simulated data. Real world data will not have the same kind of sampling error and can ignore this factor.

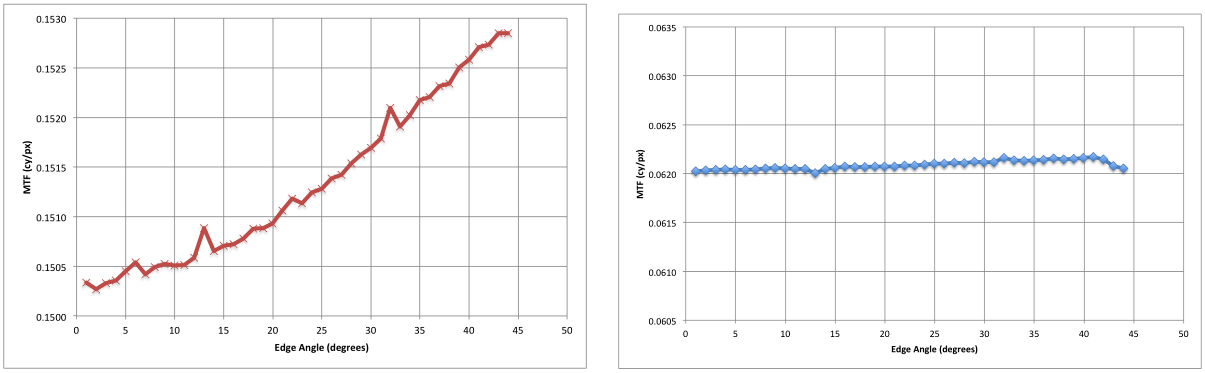


Figure 12: Corrected MTF and corrected MTF with a smoother PSF applied

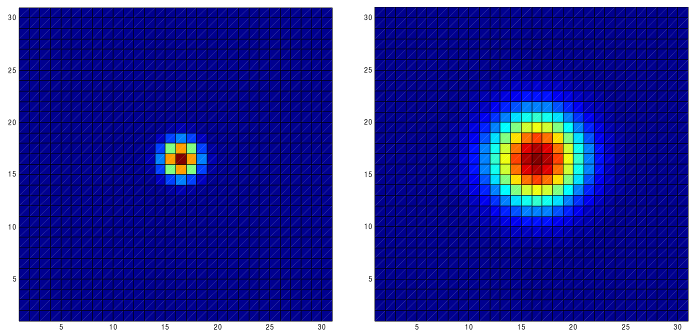


Figure 13: Gaussian PSFs applied to the first and second data set

5. CONCLUSION

The amount of data generated by this study is much too large to cover in a single paper. Significant follow-up studies will be required to fully explore the details, particularly of the real world data. In summary: Simulated data shows that contrast has no effect on MTF unless significant noise is present. In both simulated and real world systems low contrast edges are more susceptible to noise, however there are additional side effects present, possibly related to the camera, that require further study. The core algorithm as defined by ISO 12233 has significant error as the edge angle deviates from aligned with the sampling grid. If a rotational correction is applied based on the edge angle it is possible to mitigate these effects in real world data. In the simulated data there is additional error related to the sampling of the PSF used to generate the data.

In a practical sense this brings up a number of problems related to measuring the image quality of different cameras. The real world data here shows that even raw data acquired from a camera has processing applied that makes comparison and accurate characterization very difficult. It also highlights the need for automated and controlled environments. Even a relatively well controlled environment that meets the ISO definition of the measurement conditions for resolution had significant variability in certain sets within the remaining uncontrolled variables. If it is not possible to properly characterize a camera without this volume of data acquisition, a much more automated system is necessary.

The full real world data set, the MATLAB code for generating slanted edges, and the measured data is available for download from www.imatest.com/publications.

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