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Best Practices for Imaging System MTF Measurement

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Abstract

The modulation transfer function (MTF) describes how an imaging system modifies the spatial frequency content of a scene. Many performance metrics and specification requirements are strongly dependent on the MTF as it provides information on the limiting resolution of the imaging system. In this correspondence we will identify potential issues that can contribute uncertainty or bias into the MTF measurement, and suggest best practices to avoid such issues. Beginning with a full 2D derivation of the tilted edge measurement technique, we identify potential areas where differences between laboratories can occur due to the setup, imaging system, measurement procedure, or the measurement processing. We show specific examples of how the system's non-uniformity (including defective pixels) can affect the observed MTF. Additionally, we show examples of target to target variation and the effects of dynamic range. A summary table is provided on best practices to reduce the impact of the identified potential areas of difference. In support of the reproducible research effort, the Matlab functions associated with this work can be found on the Mathworks file exchange [1].

Introduction

The blur in a linear and shift invariant (LSI) imaging system is characterized by the modulation transfer function (MTF) [2]. The MTF describes how an imaging system modifies the spatial frequency content of a scene. Theoretically, a camera system's MTF is a multiplication of its individual camera components' MTF (optics, detectors, etc.) which can be readily derived using Fourier Optics [2]. However, manufacturing tolerances and miscellaneous errors can result in a transfer function much different than the theory would predict. Therefore, accurate performance estimates require that the system MTF be measured.

There are several techniques for measuring the MTF of an unknown sensor. The MTF can be measured from the image of a well characterized target, where knowing the spatial power spectral density (PSD) of the target enables the effects of the unknown system to be removed. Much success has been found using random targets (with known statistical behaviors) due to the relatively flat PSD and ease of system MTF identification [3]. The MTF can also be obtained from measurements of the contrast threshold function (CTF) by using a Siemens Star target [4] or a bar target [5, 6].

MTF measurement techniques may also involve measuring the line spread function (LSF) or edge spread function (ESF) [7]. The LSF is the derivative of the ESF, which is related to the MTF through a Fourier transform. MTF measurement methods utilizing the LSF ultimately depend upon how narrow of a line can be generated and, again, will depend upon how much signal is available through a small slit. The ESF measurement technique is perhaps the most common [8, 9], due to its natural occurrence in imaging scenes, ease of fabrication of a sharp edge, and availability of large signal.

Each of the above techniques have different experimental challenges and assumptions. In this correspondence we outline potential issues that can corrupt, contribute uncertainty, or introduce a bias into the calculation of the MTF for the ESF measurement method.

The paper is organized as follows: Section 2 contains a full-two dimensional analytical derivation of the ESF method for MTF measurement, Section 3 discusses the potential issues that can introduce measurement differences between laboratories, Section 4 shows an example of how fixed-pattern non-uniformity corrupts the MTF measurement and discusses how to mitigate the problem, Section 5 presents a summary of the best practices, and Section 6 discusses future work to further improve 'lab to lab' MTF validation techniques.

MTF from a tilted Edge

The basic image [raw(u,v,t)]can be expressed as a combination of a static scene and spatial/temporal noise [10]:

$$raw(\mathrm{u},\mathrm{v},t) = \mathrm{sig}(\mathrm{u},\mathrm{v}) + noise(\mathrm{u},\mathrm{v},t) \tag{1}$$

The signal observed [sig(u,v)] can be affected by a system specific spatial non-uniformity in the form a per-pixel gain [$G(\mathrm{u},\mathrm{v})$] and offset [$\mathrm{O}(\mathrm{u},\mathrm{v})$]:

$$\mathrm{sig}(\mathrm{u},\mathrm{v}) = G(\mathrm{u},\mathrm{v})\mathrm{sig}_{raw}(\mathrm{u},\mathrm{v}) + O(\mathrm{u},\mathrm{v}) \tag{2}$$

For the ideal image, the signal, $\mathrm{sig}_{raw}(u,\mathrm{v})$, is found as

$$\mathrm{sig}_{raw}(u,\mathrm{v}) = C\int_0^\infty \lambda Q(\lambda)\left(L_{scene}(\mathrm{u},\mathrm{v},\lambda) * psf(\mathrm{u},\mathrm{v},\lambda)\right)d\lambda\,. \tag{3}$$

Here the constant $C \propto \tau P_A g_0 / hc4(F\#)^2$,where τ is the integration time, P_A is the pixel area, $F\#$ is the ratio of the focal length to aperture diameter, λ is the wavelength, h is Planck's constant, c is the speed of light, $Q(\lambda)$ is the combined system effective spectral response, and $psf(\mathrm{u},\mathrm{v},\lambda)$ is the wavelength dependent cascade of point spread functions.

The scene spectral radiance [L_scene(u,v,lambda)] for the MTF measurement can be described as a combination of a spatially varying spectral illumination and the spatially varying monochromatic target

$$L_{scene}(x,y,\lambda) = E_{source}(x,y,\lambda)tgt(x,y) \tag{4}$$

where x and y denote the native target space coordinate system shown below in Figure 1.

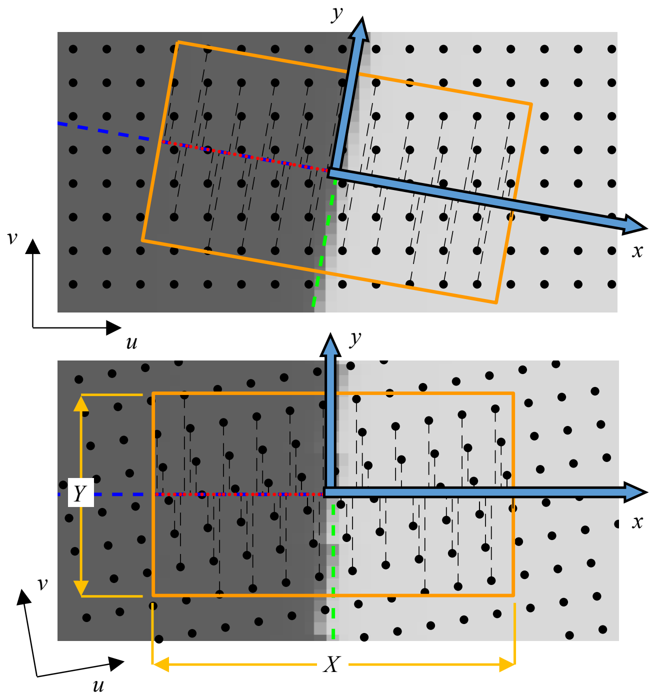

Figure 1. Demonstration of the projection of 2 dimensional sampling of an imaging array onto the axis orthogonal to the edge target in image space [u,v] (Top) and in target space [x,y] (Bottom).

Where here we are defining the target in the target reference frame

$$\begin{bmatrix} u \\ v \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta & C_u \\ -\sin\theta & \cos\theta & C_v \end{bmatrix} \begin{bmatrix} x \\ y \end{bmatrix} \quad (5)$$

where θ is the orientation of the tilted edge target, and (C_u, C_v) denotes the center of the region of interest (ROI) in image coordinates. The target can be expressed as the summation of two edge targets, a bright and dark side, each potentially contributing their own spatial non-uniformity

$$tgt(x,y) = u(x)\left(\mu_{bright} + \sigma_{bright}(x,y)\right) + \left(1-u(x)\right)\left(\mu_{dark} + \sigma_{dark}(x,y)\right) \quad (6)$$

where μ_{bright} and μ_{dark} represent the average reflectivity of the two sides, $\sigma_{bright}(x,y)$ and $\sigma_{dark}(x,y)$ account for the spatial non-uniformity of the target. In the measurement, noise is suppressed by averaging both in time and space to give the one dimensional (ESF):

$$esf(x) = rect\left(\frac{x}{X}\right)\int_0^T \int_{-Y/2}^{Y/2} raw(x,y,t)\,dydt \quad (7)$$

From the ESF, the line spread function is found by taking the derivative with respect to x.

$$lsf(x) = \frac{d}{dx} esf(x) \quad (8)$$

The OTF is defined as the Fourier Transform of the LSF

$$OTF(\xi) = F\{lsf(x)\} \quad (9)$$

Finally, the MTF is the DC normalized magnitude of the OTF.

$$MTF(\xi) = \frac{|OTF(\xi)|}{OTF(0)} \quad (10)$$

An important observation to take note of is that the measured MTF from a tilted edge samples one angle of the 2 dimensional MTF function (the angle orthogonal to the edge). Additionally, the MTF measured is a spectrally weighted average of the chromatic MTF, where the weights depend on the source, target reflectivity, and effective spectral response of the system under test [11].

As the PSF and MTF can vary in space for any real camera system, the MTF observed is valid only locally for the selected region of interest, and multiple measurements across the full field would be required for complete characterization. The accuracy of the approximation will depend on the magnitude of change.

Of course, all measurements of physical devices require some amount of sampling and quantization. Utilizing 2 dimensional sampling of the 1 dimensional edge target allows for spatial frequencies beyond Nyquist to be measured accurately [8] [9]. This can also be seen in Figure 1.

Potential Measurement Differences

There are a number of areas that can lead to differences in MTF measurements of the same system. A complete list can be found in Section 6, a few highlights will be mentioned here. Some of these items should be avoided, as they can corrupt the MTF measurement. Other issues correspond to systematic differences, meaning both measurements are valid, but describe different features of the MTF characterization. Finally, there are items that should be addressed through careful setup calibration and measurement process.

Non-linear processing

Most modern digital camera systems employ some amount of automatic processing. If this processing is data (i.e., scene) dependent, then repeating the conditions of the measurement can be extremely difficult. Notable non-linear processes include: compression, most demosaicing algorithms, edge enhancements, and some color matching methods. The ideal measurement condition is at the highest bit depth, with full manual control of global gains and offset, prior to demosaicing. Performing the measurement through the Bayer pattern allows for frequencies beyond Nyquist to be measured and to eliminate the potential for data dependent demosaicing. A non-linear opto-electronic conversion factor (OECF) should be identified and inverted prior to calculation [12], otherwise the observed MTF will change with magnitude of the signal.

Systematic variation

The ROI size and location can have an impact for a spatially varying MTF. If the ROI is too small, it can crop the low frequency behavior from the measurement. Chromatic differences between the setup from two different labs can lead to measuring different MTFs. Additionally, the angle of the target (if severely different) can also attribute differences. Other differences can occur from the measurement procedure, namely determining focus. For all of these items, the best practice is to report the conditions and confirm measurements align to program specifications.

Spatial uniformity and calibration

Additional issues can arise due to the behavior of the system under test (SUT). For example, noise in the MTF measurement due to a poor signal to noise ratio can result in an unwanted bias [10]. The sensor's non-uniformity $G(x,y)$ and $O(x,y)$ from Eq. (2), together with defective pixels which may change with time and power cycles, can create artificial structure. Unwanted structure can also be introduced from the edge target (due to either the source or target non-uniformity). For each of these effects, careful calibration and consideration can aid in increasing measurement confidence. We demonstrate examples of the significance of these spatial variations in the next section.

SUT and Setup spatial non-uniformity

To demonstrate the importance of considering spatial uniformity, a series of experiments were conducted to evaluate the different physical origins. As noted above, spatial variations can arise from the light source, the target, or even the SUT. The ideal illumination setup is one where sufficient uniformity is achieved and there is no variation while the light source is translated. Addressing and removing spatial non-uniformities from the light source are typically easier than the others, depending on the experimental setup. To identify illumination as a dominating contribution, simply moving the light source around while monitoring the real-time MTF or a contrast stretched image can suffice.

Impact of System Non-Uniformity

Spatial non-uniformity from the SUT arises from variations in the per-pixel response (gain and offset), which can change with time and power cycle. These spatial variations are system dependent and should be identified and removed prior to reporting an MTF measurement. To identify the presence of this type of non-uniformity, it is useful to monitor the MTF or a contrast stretched image and move the camera around. If the non-uniformity travels with the image, this is due to the camera.

The impact of SUT non-uniformity can manifest as artificial structure in the MTF calculation as seen as the blue curve in Figure 2. Even once the spatial non-uniformity has been corrected (through a flat field correction), the presence of defective pixels can also significantly impact the calculation (shown as the red curve in Figure 2). The magnitude of the effect depends on the severity and number of defects. In general, defective pixels should be identified and ignored in the calculation. When both the per-pixel non-uniformity is corrected, and defective pixels are ignored, an accurate estimate of the MTF, corresponding to the black curve, can be found.

Impact of Target-Spatial Variation

After the non-uniformity from the illumination and SUT have been addressed, any remaining spatial variation can be attributed to the target. Expanding Eq. (8) and neglecting scaling constants, the LSF can be expressed in terms of the dynamic range and derivatives of the target non-uniformity:

$$
\begin{aligned}
lsf(x) = {} & psf_\theta(x) * (\mu_{bright} - \mu_{dark}) + \ldots \\
& psf_\theta(x) * q_b^{'}(x) u(x) + \ldots \\
& \mathrm{psf}_\theta(x) * q_d^{'}(x)(1 - u(x))
\end{aligned}
\quad . \qquad (11)
$$

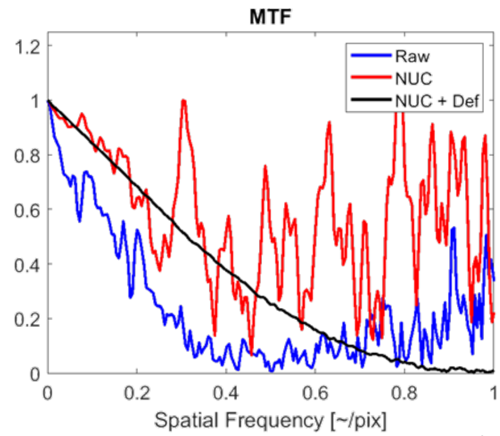

Figure 2. MTF measured with and without a per-pixel non-uniformity correction as well as ignoring defective pixels

Here $psf_\theta(x)$ is the integrated psf along the angle of the edge, $q_b^{'}(x)$ and $q_d^{'}(x)$ are the spatial derivatives of the integrated target non-uniformity for the bright and dark sides respectively. In the absence of target spatial non-uniformity, the second two terms are 0 and we have the ideal measurement.

To demonstrate the effects of target spatial non-uniformity on the observed MTF measurement, 5 different targets were measured; an opaque collimator target (7.8% and 50.5%), an E-SFR target (16.1% and 51.4%), a high quality print (10.0% and 50.6%), a low quality print (20.6% and 49.0%), and a spectralon step chart (11.3% and 49.2%). All targets can be seen in Figure 3.

Care was taken to ensure the illumination was uniform. For each measurement, the targets were aligned to the center of the SUT, the edges were rotated to the same angle (10 degrees), and the exact same ROI was used. Prior to the measurements, the SUT was flat field corrected, and 120 frames were averaged to reduce the impact of noise.

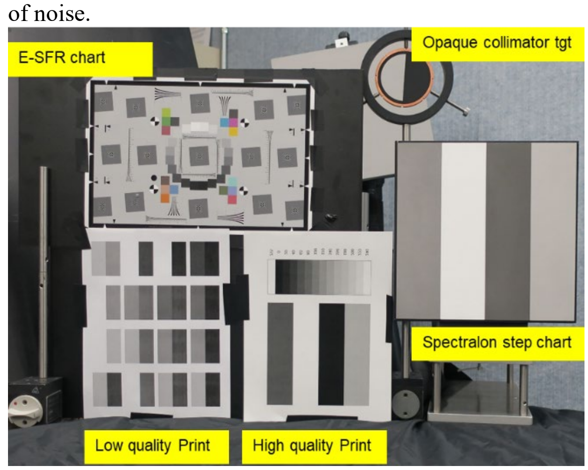

Figure 3. Image of different targets for MTF comparison

A comparison of the MTFs found is presented below in Figure 4. As can be seen, the variations in the MTF measurement increase with spatial frequency. There is a spread of 20% modulation at 0.5 ~/pix between the collimator target and the spectralon. The spectralon target appears to give the largest MTF, however this is due to a slight tilt in the ESF from the target non-uniformity, resulting in an apparent boost. The most accurate MTF is assumed to be the collimator target. This target was illuminated independently on the dark and bright sides, and the bright side was placed far away and out of focus.

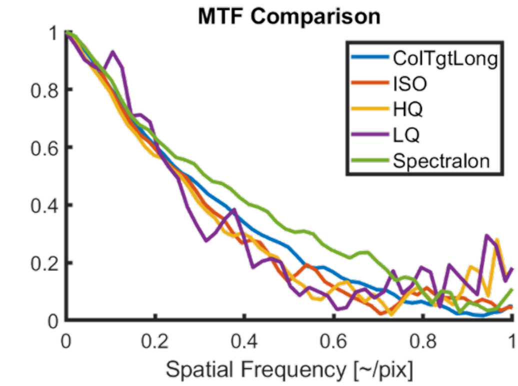

Figure 4.Comparison of MTF's observed from 5 different targets

Not shown here, but additional ROIs were also considered to evaluate the location dependent variation and evaluate uncertainty. The total variation of the collimator target was less than 2%, while the low quality target exceeded 15%.

Impact of Dynamic Range

As show in Eq. (11), the contribution to the MTF from target non-uniformity depends on dynamic range between the bright and dark sides compared to the derivative of the variation. To examine this impact experimentally, a dual illumination target was used. Using a dual illumination opaque target enables us to probe only one side of the target non-uniformity, and effectively negate the other by placing it beyond the depth of field.

The dark side of the target was held at an effective reflectivity of 17% while the bright side was scaled between 2 and 87%, resulting in the ESF seen in Figure 5.

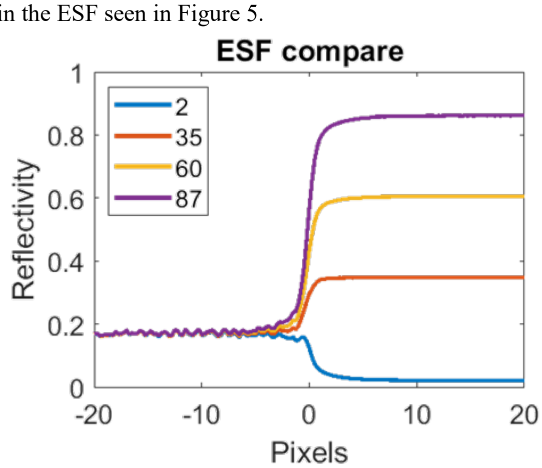

Figure 5. Comparison of ESF vs dynamic range

As can be seen in Figure 6, the as the dynamic range increases, the impact of the target non-uniformity is reduced.

Although the ideal target would have no spatial contribution, as shown in Eq. (11), maximizing dynamic range can compensate for the influence of target spatial non-uniformity and allows an accurate MTF to be found.

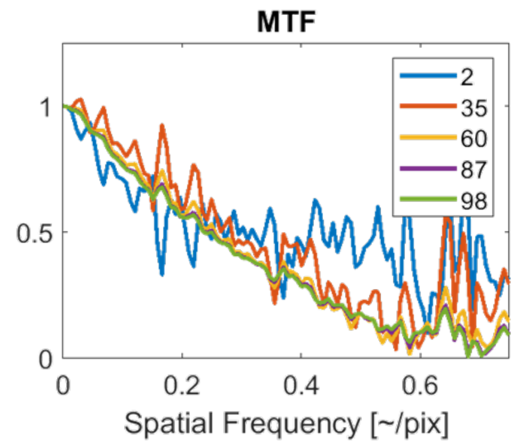

Figure 6.Comparison of MTF's observed vs. dynamic range

Best Practices

Accurate MTF measurement will depend on what state the camera can be placed in for the measurement. If data dependent output is the only option (such as compression), there is a much higher chance that the observed MTF will be different for different scenes. This makes comparisons between laboratories difficult and may result in incorrect camera assessment against a specification. As discussed in the previous sections, there are a variety of issues that can lead to different observed MTF measurements. Here in Table 1, we summarize potential courses of action to increase confidence of an accurate measurement:

Table 1: Degradation Summary Table

Name	Action
Illumination spectral shape	Confirm spectral shape to match program specifications Measure and report
Illumination spatial variation	Consider flat field check in absence of target Numerically remove (caution)
Illumination Flicker	Change source
Target spectral shape	Confirm spectral shape to match program specifications Spatially uniform, and scalar relationship between bright and dark Measure and report

Target spatial non-uniformity	Confirm target uniformity with known reference Use high precision targets (double illumination)
Target / Camera Motion	Constrain as much as possible Average ESF instead of frames Quantify and report motion Reduce exposure
Edge Angle	Measure 2D MTF Report
Temporal Noise	Frame average Increase SNR Model uncertainty
Camera spatial non-uniformity	Flat field correction If offset only, increase SNR
Defective pixels	Identify and ignore
Spatial varying MTF, ROI location	Confirm location with specifications Report
Non-LSI process (data dependent)	Turn off Report uncertainty
Quantization, saturation	Do not saturate Ensure sufficient dynamic range
Non-linear OECF	Confirm or Invert non-linearity Operate in linear region
Demosaicing	Turn off, measure through Bayer pattern, Report
Setting Focus / Chromatic aberrations	Agree on focus definition, how multiple bands are combined
ROI size (along edge)	Look at multiple ROIs and convergence
ROI size (orthogonal edge)	Look at LSF to approach zero Report / seek consensus
Calculation found incorrect edge	Adjust angle Increase SNR
Calculation interpolation error	Change angle Adjust ROI

Summary and Future Work

Accurate and repeatable MTF measurements are difficult, and require consideration of a large number of items, many of which interact with one another. When setting up a new MTF measurement station, it is important to use a calibrated camera with a known MTF, ideally with a higher spatial resolution than the desired system under test. Confirming the setup does not introduce degradations, or quantify the magnitude of the degradation, and can be very useful in facilitating comparisons of measurements.
Additionally, utilizing Monte Carlo methods to model potential uncertainty is a useful tool. The methods implemented in this work can be found in [1]. Future work will advance the use of the Monte Carlo methods to bound the use of targets and provide tools for deconvolution of target effects.

References

[1] Haefner, D. P., https://www.mathworks.com/matlabcentral/profile/authors/4173815-david-haefner

[2] J. W. Goodman, Introduction to Fourier Optics, New York: McGraw-Hill, 1996.

[3] A. Daniels, G. Boreman, and A. Ducharme, "Random transparency targets for modulation transfer function measurement in the visible and infrared regions," Opt. Eng., vol 34, no. 3, 1995.

[4] C. Loebich, D. Wueller, B. Klingen, and A. Jaeger, "Digital camera resolution measurement using sinusoidal Siemens Stars," in IS&T/SPIE Electronic Imaging], 65020N, 1-11 (2007).

[5] G. Boreman, and S. Yang, "Modulation Transfer Function Measurement Using Three- and Four-bar Targets," Appl. Opt. 34, pp. 8050-8052, 1995.

[6] D. Sitter Jr, J. Goddard, and R. Ferrell, "Method for the measurement of the modulation transfer function of sampled imaging systems from bar-target patterns," Appl. Opt. 34, pp. 746-751, 1995.

[7] S. Park, and Z. Rahman, "Fidelity analysis of sampled imaging systems," Optical Engineering 38, pp. 786-800, 1999.

[8] P. Burns, "Slanted-edge MTF for digital camera and scanner analysis," in PICS 2000: Image Processing, Image Quality, Image Capture, and Systems Conference, pp. 135-138, 2000.

[9] ISO 12233:2017, Photography — Electronic still picture imaging — Resolution and spatial frequency responses

[10] D. Haefner and S. Burks, "Noise estimation of an MTF measurement," Proceedings of SPIE Vol. 8355, 835506, 2012.

[11] J. Hixson, D. Haefner, and B. Teaney, " Comparing and contrasting different broadband MTF definitions and the relationship to range performance predictions," Proc. SPIE 9071, 907105, 2014.

[12] D. Haefner, "MTF measurements, identifying bias, and estimating uncertainty", Proceedings of SPIE Vol. 10625, 1062506, 2018.

Author Biography

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