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Application of ISO Standard Methods to Optical Design for Image Capture

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Abstract
The ISO 12233 standard for digital camera resolution includes two methods for the evaluation of camera performance in terms of a Spatial Frequency Response (SFR). In many cases, the measured SFR can be taken as a measurement of the camera-system Modulation Transfer Function (MTF), used in optical design. In this paper, we investigate how the ISO 12233 method for slanted-edge analysis can be applied to such an optical design. Recent improvements to the ISO method aid in the computing of both sagittal and tangential MTF, as commonly specified for optical systems. From computed optical simulations of actual designs, we apply the slanted-edge analysis over the image field. The simulations include the influence of optical aberrations, and these can present challenges to the ISO methods. We find, however, that when the slanted-edge methods are applied with care, consistent results can be obtained.

Introduction
The ISO 12233 standard for digital camera resolution includes several methods for the evaluation of camera performance. Two of these, based on edge- and sinewave-analysis respectively, result in a measured spatial frequency response (SFR). Often, the measured SFR can be taken as a measurement of the camera-system Modulation Transfer Function (MTF), used in optical design.

Optical design for imaging usually involves the specification and modeling of the optical MTF at various image-field locations, spectral conditions, etc. Of course, the design of practical systems involves a balance between various characteristics, in addition to the MTF. A useful tool in optical design is the simulated image, whereby the properties of the optical system are computed. Here we investigate if, and to what extent ISO camera-resolution evaluation methods can be applied to optical design via these computed simulations.

Edge-SFR Measurement
We will focus on the ISO 12233 [1,2] method based on edge-gradient analysis.[3] The three basic steps[3] of this method are; acquiring an edge profile from the (image) data; computing the derivative across the edge, and computing the discrete Fourier transform of this derivative vector.

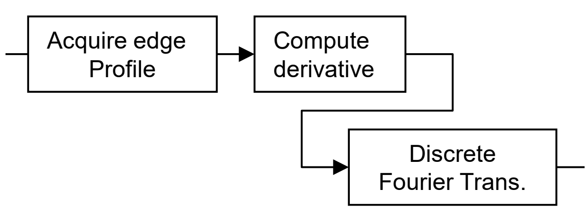

Figure 1: Edge-gradient analysis steps

This method relies on a high-quality edge test-feature in the captured image. Normally this is assumed to be a straight edge, rotated from the vertical or horizontal direction. The ISO 12233 method follows several specific steps aimed at reducing the influence of, e.g., image noise. The resulting SFR can be thought of as an estimate of the edge-based camera MTF. As with any estimate, it is subject to variation (measurement noise) and bias (distortion) when the assumptions on which it is based are violated.

One such violation is the curvature of the slanted-edge feature that can be introduced by optical aberrations. Recently the slanted-edge method has been modified to accommodate such distorted edges. For the undistorted case locating and modeling of the edge feature for a straight edge takes the form of a linear equation. The location of the edge within the image array is,

$$x = a_0 + a_1 y \qquad (1)$$

where x is the edge pixel location and y is the row, for a near-vertical edge feature. When image distortion leads to a curved edge, a polynomial can be fit to the detected edge, [4]

$$x = a_0 + a_1 y + a_2 y^2 + a_3 y^3 \cdots \qquad (2)$$

The reason that we present the equations as *f(y)* rather than the more common *f(x)* is that the edge *x*-location is computed line-by-line as part of the slanted-edge analysis. Fig. 2 shows a distorted edge and the result of the polynomial edge-finding method. As a result of applying the polynomial edge fitting of Eq. (2), the slanted-edge analysis has been applied to distorted edges, improving the resulting SFR results.[4]

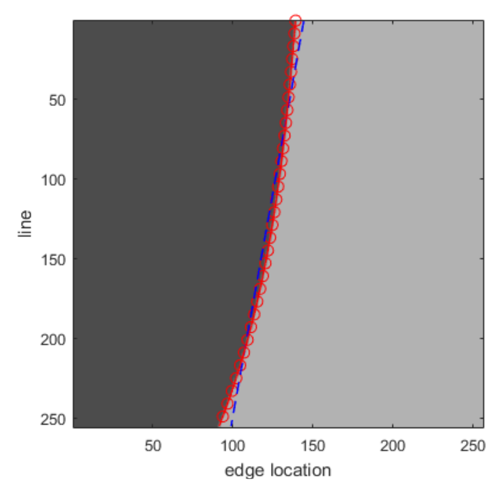

Figure 2: Computed distorted edge image with detected edge location: linear (blue dash) and 3rd order polynomial (red circles) from Ref.4

SFR: Straight and Curved Edges

For many optical systems, the imaging requirements, and therefore the design, call for rotational symmetry. In this case, a test chart with the layout of Fig. 3 provides features that are well-placed to evaluate, e.g., the MTF on radial lines from center to edge, characteristics commonly specified in optics. Since the curvature of the edge-features varies over such a range, this provides a good test of the robustness of the updated SFR analysis described above.

We start by applying the modified edge-SFR method to ideal input test images that we will then use in our optical simulations. To investigate how well the modified method for edge-SFR analysis works, we apply it to three different regions (edge, mid, and center) with corresponding levels of edge curvature, as shown in Fig. 3. This image array is for an ideal lens and therefore should show no field-dependent variation.

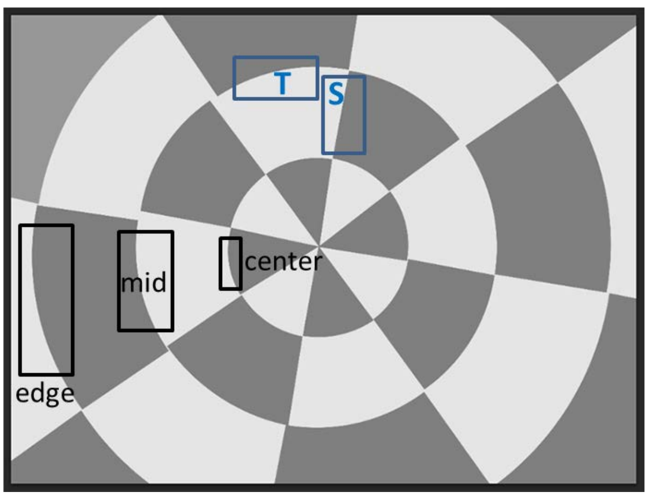

Figure 3: Computed test image used as input to optical simulations with two sets of regions used for analysis. T and S refer to regions for tangential and sagittal MTF analysis, respectively.

Two sets of results are presented. Figure 4 shows the result when using a 3rd-order polynomial fit to the edge. We assume a 3um detector sampling. There is a reduction in the computed SFR as we approach the image center. This bias is due to the greater curvature there, compared to the outer features. This variation is significantly reduced when we use a 5th-order edge fit, however. This is shown in Fig 5.

Sagittal and Tangential MTF

Since the pixel-sampling of digital images is usually done in a regular rectangular array, we normally report camera and scanner SFR results along the pixel (-x) and row (-y) directions. The original edge-SFR method adopted in ISO 12233 was restricted to near-vertical and near-horizontal edges. Subsequently, an improvement to the method to accommodate the effective sampling of the computed edge-profile was introduced.

Nevertheless, the method is most often used in this way. For optical design, however, the MTF is usually specified and measured in the sagittal and tangential directions due to the (desired) rotational symmetry. Figure 3 shows regions-of-interest (ROIs), labelled S and T, which we used to evaluate the effective edge-SFR in these directions.

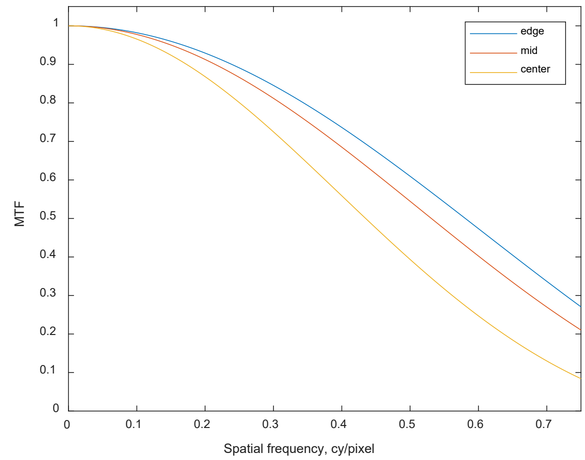

Figure 4: MTF results following a third-order edge fit

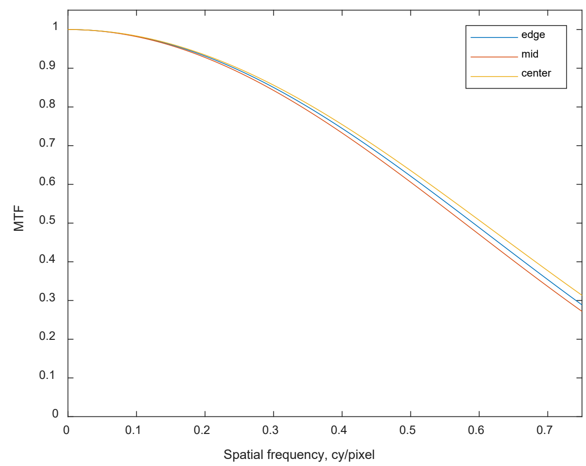

Figure5: 5th-order edge fit results

The tangential MTF is evaluated in the direction normal to a circle as shown in Figure 3. The sagittal (or radial) MTF is evaluated from an edge along a radial line from the center of the field of view. A bar target measuring tangential resolution would have bars tangential to the circle. A bar target measuring sagittal (or radial) resolution would have bars along a radial line. In our case for this test chart, the sagittal direction test feature is seen as a straight edge, and the tangential SFR is evaluated using an arc.

Figure 6 shows the results, which closely match, as they should. In this case we used a 5th-order edge fit in both cases. While this high-order polynomial was not necessary for the sagittal edge, the results show no apparent disadvantage due to over-fitting.

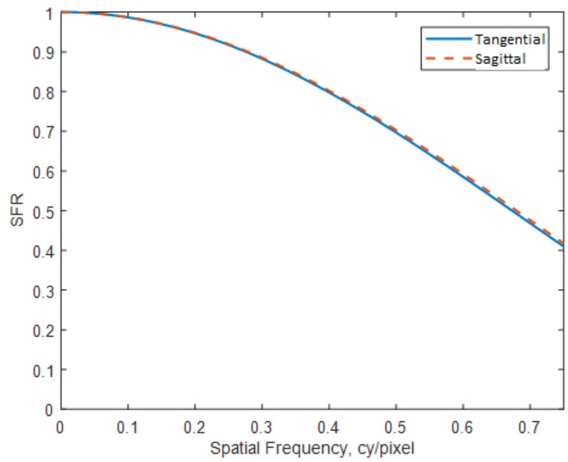

Figure 6: Comparison of Computed Edge-SFR results for sagittal and tangential directions for ideal test image file (5th-order edge fit)

Optical Design and Image Simulation

So far we have been applying the modified edge-SFR method to test-chart images useful to optical simulations. We now address simulation of actual designs.

Optical design for imaging usually involves the specification and modeling of the optical MTF at various field locations, spectral conditions, etc. Often computed simulated images are generated. These include the influence of wavelength-dependent performance, and optical aberrations.

Stand-alone specialized software was originally developed to can compute a simulated image incorporating the aberrated performance of a lens.[5] This feature is now widely available in commercial optical design software. Custom input scenes, such as typical image-quality assessment targets, can be used to evaluate both nominal and predicted as-built performance. Sample aberrated output can help make decisions about which of a few competing designs should be built. Often, tradeoffs must be made between different aberration balances, slightly different MTF performance and manufacturability. A set of simulated images gives designers and managers an easy-to-interpret sense of the impact of the tradeoffs on the user experience.

Simulation from Design

The image simulations used in our study were generated using commercial optical design software. The first step is to compute a grid of point spread functions (PSFs) for each wavelength of interest. The number of PSFs in the grid is chosen based on the size of isoplanatic patches in the image plane. Larger optical aberrations in the lens design yield smaller isoplanatic patches and a denser grid.

The ideal input image (or test chart layout) file is convolved over each isoplanatic patch with the point spread function grid in each wavelength. The simulated image file is built up but superposition of the convolution results. The final simulated image file may have multiple spectral layers or a single monochrome layer. Relative illumination, distortion, and lateral chromatic aberration in the lens are then accounted for. Source and detector spectral characteristics are handled by appropriately weighting the convolution at each wavelength. We chose a green, or luminance, weighting to match with common color image capture.

Comparison of PSF and Edge Methods

Our first example lens was taken from US patent 8,947,793. It has a 16mm focal length for a Micro 4/3 sensor camera, operating at f/1.7. On this format, it has a full diagonal field of view of 73° so it is a moderately wide-angle camera lens. The maximum optical distortion is -8.7%. This would normally be corrected for in the camera firmware, but was not done in the simulation.

Two simulations were run using Zmax OpticStudio[6] software. One simulation comprised a series of equally-spaced small dots (point sources). The second used the 'pie chart' of Fig. 3 as the input. The simulated point-spread function for a near-center position is shown in Fig. 7. For comparison, the corresponding PSF for the position near the 'edge' location of Fig. 3 is shown in Fig. 8.

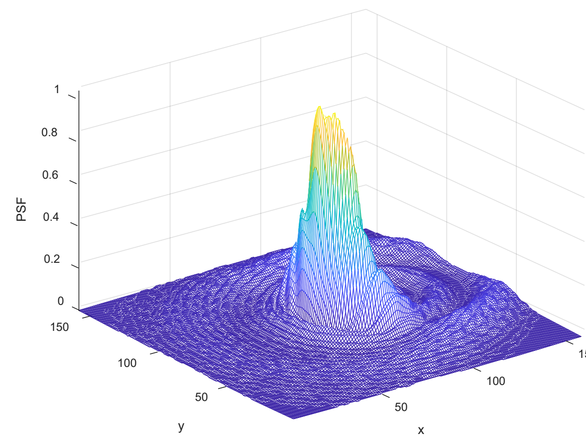

Figure 7: Simulated point-spread function for the fisheye lens near the center of the optical field. The sampling for this computed array is 0.22 um.

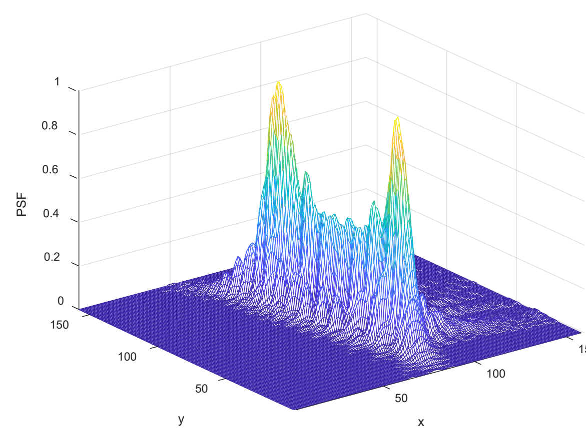

Figure 8: Simulated PSF for the fisheye lens near the edge of the optical field

Each of the two corresponding simulated images provides a way for us to estimate (compute) the MTF. From the pie-chart of Fig. 2 we can use the edge-SFR method used above. From the dot-pattern image array we can also directly compute the MTF. In this case each simulated image dot can be taken as a local, sampled PSF.

Since the optical MTF is defined as the modulus of the Fourier transform of the PSF, we can compute this from the arrays shown in Figs. 7 and 8. The computed two-dimensional MTF based on the arrays of Fig. 7 is shown in Fig. 9.

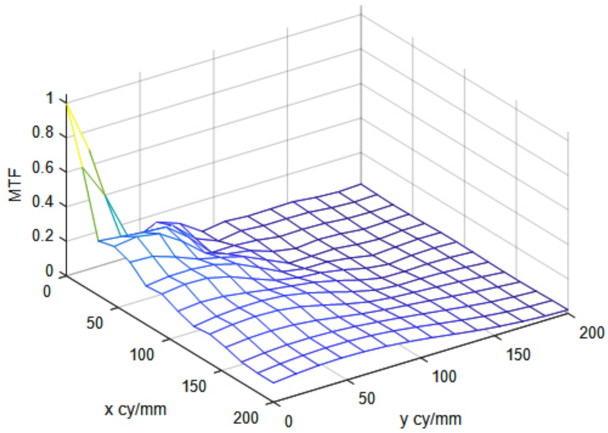

Figure 9: MTF computed directly from the simulated image of a single point (impulse-response) near the center of the image field.

Figure 10 compares this direct PSF-based measure with that from the corresponding edge-based method. When we account for the effective image sampling, good agreement is observed. Note, however, that our simulated images are essentially noise-free. They exhibit little or no pixel-to-pixel variation due to the detector, which is present in captured images. The direct estimation of the MTF from a PSF is not normally used for system evaluation, as the results would be unstable. The slanted-edge method was developed and adopted because its results are far more noise-resistant. That said, the agreement in Fig. 9 between the two methods is important. It shows a good connection between optical design, simulation, and ISO-standard system evaluation methods.

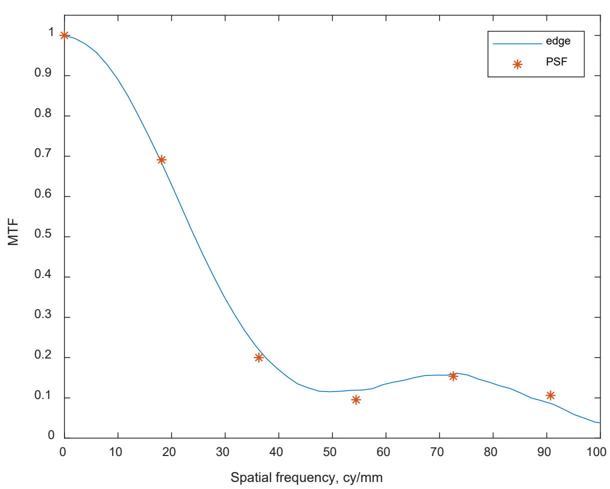

Figure 10: Comparison of directly computed (via PSF) and slanted-edge MTF

Intra-image Characteristics

When specifying and evaluating imaging performance we are usually interested in several measures, and though each may be important, their influences are not independent. For example, we have previously discussed the effect of lens geometrical distortion on edge-based MTF measurements. In the same way these are mitigated by polynomial edge fitting, we now turn to lens vignetting, or light fall-off.

We now address multiple optical aberrations using a second lens design example. This is taken from US patent 4,412,726. It was scaled to a focal length of 8.23 mm and an aperture of f/4. It was also evaluated over the Micro 4/3 format. The full diagonal field of view is 170°, so it is a fisheye lens. The maximum optical distortion is -88.5%. Code V optical design software was used.[7]

The simulated image of a dot-pattern test chart is shown in Fig. 11. Although the geometrical distortion is most noticeable, light fall-off is also present. This is more clearly seen in the contour plot of Fig. 12, where the concentric closed lines show the vignetting.

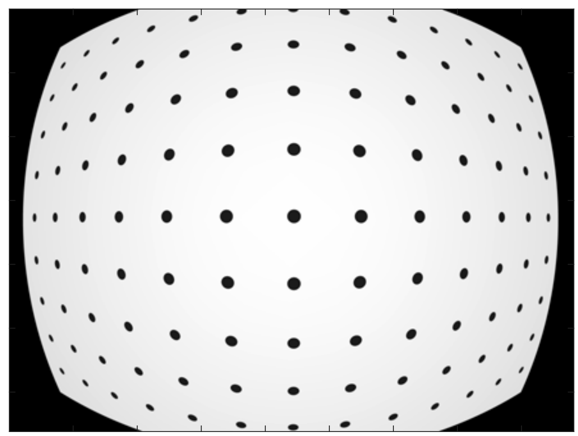

Figure 11: Simulated image of the dot pattern for the fisheye lens design

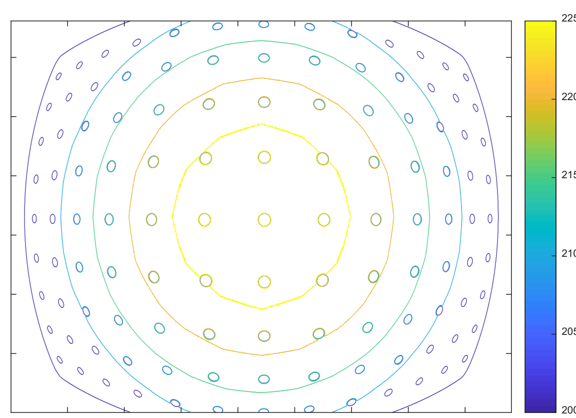

Figure 12: Contour plot of the image array corresponding to Fig. 11 on an 8-bit [0-255] scale

Vignetting and SFR Measurement

One of advantages of the edge-based SFR method is the compact nature of the (edge) evaluation feature. This facilitates, e.g., the simple evaluation at various location in the image field. However when significant vignetting is present, this can introduce variation (error) in to the computed SFR. Non-uniform illumination from the lens can increase the computed SFR by effectively sharpening the edge if light fall-off is away from the edge. Alternatively, it can reduce the SFR is fall-off appears to reduce the edge contrast.

This is described by Koren and Koren[8] who suggest a correction as part of the slanted-edge analysis. The proposed method fits the light region of the computed edge profile with a polynomial (usually linear function) and subtracts this. The correction is limited to the high-values (lighter) end of the profile vector.

Figure 13 shows an example edge-profile computed from the simulated fisheye lens design, as an intermediate step in the ISO 12233 method. Here we have implemented the uniformity correction of Ref. 8, however it is shown applied to both ends of the vector. Note the x-axis is in units of the super-sampled edge-profile, so the sampling distance is ¼ of the pixel, as per the ISO standard.

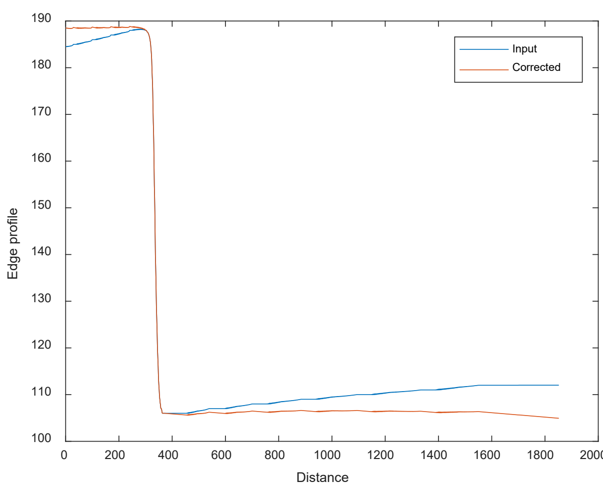

Figure 13: Edge profile derive from simulated fisheye lens design

The influence of the simulated non-uniformity across the edge is evident in Fig. 14. We show the uncorrected results, exhibiting an apparent positive bias at low spatial-frequencies. This is reduced when we apply the one-sided, (high) correction as we might expect. When we add the second correction to the low-signal side, we see a further reduction.

While the application of the above correction method appears to improve the SFR measurement in this case, we suggest applying it with care. We observe, e.g., that the effect of this method can vary with the length of the edge-profile array. This in turn is normally proportional to the size (width) of the region of interest (ROI) in the test image that is selected for SFR analysis.

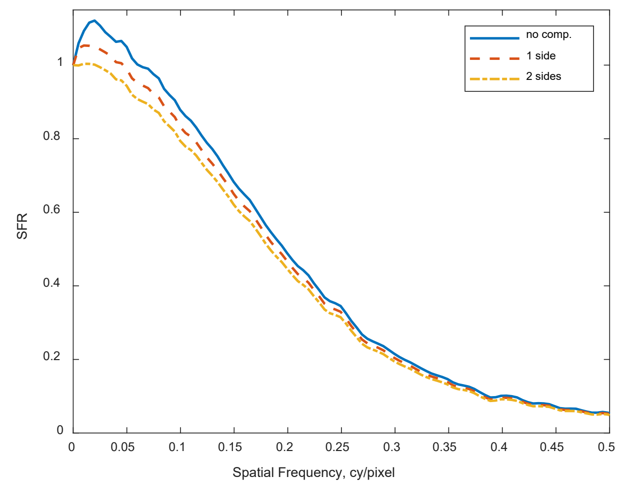

Figure 14: Computed SFR results with and without non-uniformity correction for the case shown in Fig. 13

Conclusions

Sets of real and computed test images have long been used in the development and refinement of imaging performance methods. We have extended this approach to investigate the use of simulated images from practical lens designs. These datasets include the influence of optical aberrations and are therefore well-suited for testing by methods based on captured images.

Practical lenses have intra-image variation, such as geometrical distortion and vignetting, which can challenge analysis methods that are based on assumptions of local consistency. For slanted-edge analysis, the requirement of a straight edge in the image has been lifted after advanced edge-fitting was introduced.[4] We have applied these edge-SFR methods in both tangential and sagittal lens MTF evaluation with good results when up to a 5th order edge fit was used. There appeared to be no disadvantage due to over-fitting the edges.

Correction for illumination (on the detector) non-uniformity was also investigated. This effect due to lens vignetting is naturally included in the optical simulations. For the cases tested we found an improvement in the results following a suggested correction of the edge-profile data.

We should note that when we are applying the ISO 12233 method to a system (lens, detector and image processing) compensation for lens distortion and shading will often be included in the imaging path. Several specific steps of standard methods are chosen to reduce measurement bias (distortion) and variability due to pixel-to-pixel image noise.

Thus a natural extension of this work would be the inclusion of detector noise and capture profile.[9-11] In these cases, the ISO methods are used to evaluate the imaging system, including the residual influence, or net-effect, of such operations.

Acknowledgement

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Peter Burns is a consultant for imaging system evaluation, modeling, and design. Previously he worked for Carestream Health, Xerox, and Eastman Kodak. A frequent speaker at technical conferences, he has taught imaging courses for clients and universities for many years.

Don Williams is founder of Image Science Associates, which focuses on quantitative imaging performance/fidelity evaluation for digital capture systems. His clients include national libraries, museums, and those with dental, mobile and automotive applications.

John Griffith has more than 40 years of experience in optical design, engineering, and management. He has worked on projects with part diameters ranging from 150 um to 4 meters. Over the last 10 years, his focus has been on polymer optics for consumer electronics.

Heidi Hall is Director of Engineering at Moondog Optics and previously worked at Eastman Kodak, Flextronics and Digital Optics. She has extensive hands-on experience in MTF testing of lenses, SFR testing of camera module, and the use of simulations to predict image performance.

Scott Cahall is an optical designer and founder of Moondog Optics, an independent design firm serving clients in the consumer, medical, and entertainment industry. He previously worked for Jenoptik, Eastman Kodak, and Corning Precision Lens. He concentrates (sometimes too hard…) on optical systems for mobile devices, virtual/augmented reality, and 3-D machine vision.