Compensating MTF Measurements for Chart Quality Limitations

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Abstract

Objective measurements of imaging system sharpness (Modulation Transfer Function; MTF) are typically derived from test chart images. It is generally assumed that if testing recommendations are followed, test chart sharpness (which we also call "chart quality") will have little impact on overall measurements. Standards such as ISO 12233 [1] ignore test chart sharpness.

Situations where this assumption is not valid are becoming increasingly frequent, in part because extremely high-resolution cameras (over 30 megapixels) are becoming more common and in part because manufacturing test stations, which have limited space, often use charts that are smaller than optimum. Inconsistent MTF measurements caused by limited chart sharpness can be problematic in manufacturing supply chains that require consistency in measurements taken at different locations.

We describe how to measure test chart sharpness, fit the measurement to a model, quantify the effects of chart sharpness on camera system MTF measurements, then compensate for these effects using deconvolution– by dividing measured system MTF by a model of the chart MTF projected on the image sensor. We use results of measurements with and without MTF compensation to develop a set of empirical guidelines to determine when chart quality is

- good enough so that no compensation is needed, and

- too low to be reliably compensated.

Introduction

Camera MTF (sharpness) measurements are subject to a number of variations, some of which, like noise, are random and difficult to control, and some of which are systematic and can be corrected. Variations caused by limitations in chart sharpness are in the latter category. These variations are also affected by the Field of View (FoV) of the image used to test the camera, which is closely related to chart size for charts designed to fill the camera frame.

For a given print technology, increasing the FoV, which typically means increasing the spacing between the chart and camera, will increase the measured MTF— making it more accurate. However, there are many practical situations where space is limited and small FoVs are called for, and chart sharpness can significantly affect the measurements.

This paper describes a method for quantifying and correcting such measurement variations. The method has the following steps.

1. Measure the test chart MTF and fit it to an equation.

2. Compensate camera MTF measurements for the test chart sharpness.

3. Based on measurements with and without compensation for a variety of charts and test magnifications m_{test}, determine the conditions where (a) chart quality is good enough so no compensation is needed, and (b) chart quality is too low to be reliably compensated.

There is little mention of test chart sharpness in the literature, perhaps because when the ISO 12233:2000 standard was created, high-resolution cameras had only about one megapixel, and hence it was easy to print adequate test charts.

Measuring test chart MTF

The first step in compensating camera MTF measurements is to measure the test chart MTF. This should be done by photographing the same features used to measure camera MTF. We describe the process for slanted-edges, but other patterns, such as Siemens stars, could also be used. Since we have found that edge sharpness in inkjet charts can depend on the edge orientation, we measure up to four edges (the left, right, top, and bottom of a dark square on a light background).

We performed our chart measurements with a 24 Megapixel APS-C camera that has a 23.5x15.6mm sensor with a 3.88-micron pixel pitch. We used a mechanically-focused 60mm prime macro lens that had a scale that displayed magnification. This enabled us to maintain constant chart magnification m_{chart} for our tests, which is difficult to accomplish with lenses that have electronic focusing. We used m_{chart} = 1:2 (0.5×) for inkjet charts and m_{chart} = 1:1 (1×) for photographic paper and film charts, which are sharper. Chrome-on-Glass charts are too sharp to be measured with this setup.

FIGURE 1. CHART MTF MEASUREMENT SETUP

The setup (Fig. 1) consists of a custom-machined aluminum base and a sturdy aluminum extrusion column. Fine focus is controlled by a micrometric positioning sliding plate. The lens is fixed at m_{chart} = 1:2 or 1:1. Simple adjustments are used to keep the sensor plane is parallel to the test chart. A non-flickering LED ring light is used for reflective charts; a light box is used for transmissive charts.

When calculating chart MTF it is important to select large enough Regions of Interest (ROIs) to obtain consistent results. For inkjet charts, which can have rough edges, especially when photographed at chart magnification m_{chart} = 1:1 (1×), MTF50 can vary by as much as ±10% for small ROIs. To obtain good measurement consistency, we photographed inkjet charts at m_{chart} = 1:2 (0.5×), using region sizes ≥ 900×1300 pixels. For chart media other than inkjet, all of which are finer, we used m_{chart} = 1:1.

Fitting measured MTF to an equation

The measured chart MTF must be fit to an equation in order to reliably perform MTF compensation, where the measured camera MTF is divided by the model of the chart MTF projected on the sensor. We have chosen a function that (a) is simple– only two parameters, (b) is a good match to our chart MTF measurements, and (c) is guaranteed to decrease at high spatial frequencies.

$$MTF_{chart}(f_{chart}) = \exp(-af_{chart} - (bf_{chart})^2) \qquad (1)$$

where f_{chart} is the spatial frequency in Cycles/Object mm on the chart. a and b are found using an optimizer to match Equation (1) with MTF measurements for $f \leq f_{30}$, the first frequency where MTF drops below 0.3 (30%). This is done because noise can dominate MTF measurements for $f > f_{30}$, as illustrated in Fig. 3.

Parameters a and b are stored in a file along with metadata (the name of the test chart image file, chart magnification m_{chart}, date, etc.) This file is read into the analysis program when chart compensation is to be applied. We have found that, apart from old charts made with unknown printers and settings, charts don't need to be measured individually. A compensation file based on media, printer type, and print settings should be sufficient.

Chart MTF measurement examples

Figure 2 illustrates an MTF measurement for a horizontal slanted-edge on an inkjet chart photographed with m_{chart} = 0.5×. The upper curve shows the average edge profile. The rise distance (14 pixels) is large enough so that camera software sharpening will not affect the results. The lower plot shows the measured MTF (**bold black** curve) and the fit to the MTF (**bold cyan** curve) from Equation (1) for $f < f_{30}$. The parameters for this fit are a = 0.10507 and b = 0.09407.
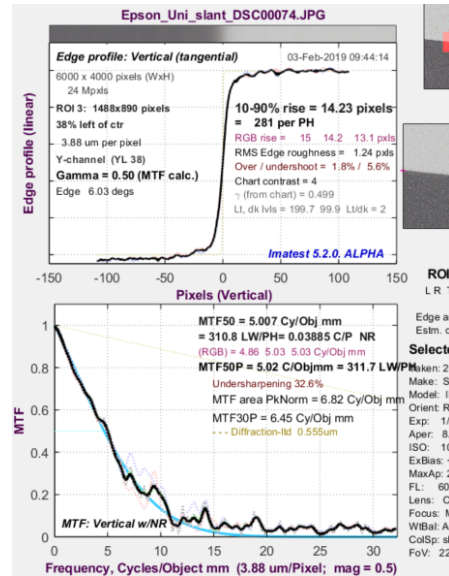

FIGURE 2. INKJET CHART MTF MEASUREMENT

Curious artifacts sometimes appear in chart MTF measurements. Figure 3 is the MTF of an edge from a chart printed with the edges along the directions of paper and print head motion (not slanted). Test charts printed this way are cut slanted. A strong MTF response peak, visible around 13.5 Cycles/Object mm, appears to be caused by periodicity in the inkjet dots. (It's not present when edges are printed slanted.) Fortunately, it's well outside the analysis passband as well as the frequencies used to calculate a and b in Equation (1).
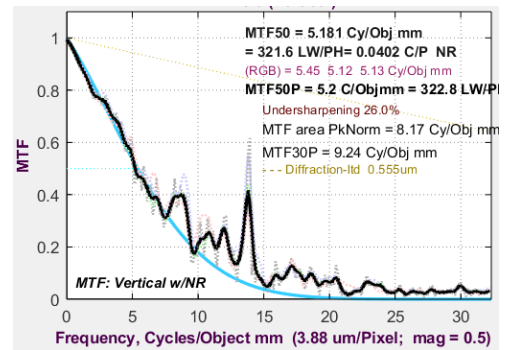

FIGURE 3. INKJET CHART MTF SHOWING RESPONSE PEAK

There are sometimes surprises in the MTF measurements. Chart MTF for photographic film printed on an LVT (Light Valve Technology) printer have a response indicative of sharpening (Fig. 4), apparently caused by uneven depletion of the film developer near edges—familiar to the author from his wet darkroom days. Note that the curve from Equation (1) (**cyan**) is a good match to the MTF curve, which has a sharpening bump.
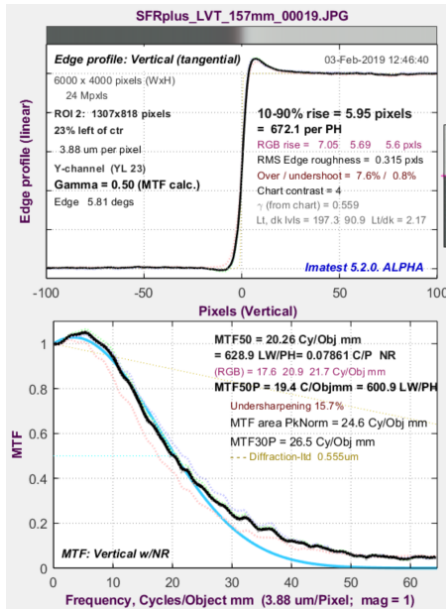
FIGURE 4. COLOR LVT FILM MTF SHOWING CHEMICAL SHARPENING

MTF compensation

To calculate MTF compensation, the chart spatial frequency in Cycles/Object mm, f_{chart}, must be transformed into Cycles/Pixel (C/P) on the image sensor. For test magnification m_{test},

$$f(\text{C/Obj mm}) = f(\text{C/P}) \times m_{test} \times \text{pixels/mm} \qquad (2)$$

The MTF of the chart projected on the image sensor is

$$MTF_{projected}(f) = MTF_{chart}(f(\text{C/P}) \times m_{test} \times \text{pixels/mm}) \qquad (3)$$

Finally, the chart-compensated MTF is

$$MTF_{chart-comp}(f) = MTF_{measured}(f)/MTF_{div}(f) \qquad (4)$$

where

$$MTF_{div}(f) = \max(MTF_{projected}(f), 0.3) \qquad (5)$$

Limiting the minimum value of MTF_{div} to 0.3 prevents excessive high frequency noise boost. And as we have shown in Fig. 3, chart MTF measurements at frequencies where MTF drops below 0.3 ($f > f_{30}$) can be strongly affected by chart noise (especially for inkjet charts), and hence are not reliable.

Camera testing and verification

The effects of chart compensation were tested using a 10-megapixel digital camera (a Panasonic Lumix LX5 from 2010) that had

- a small 5.4x8.1mm sensor with 2.14-pixel size to ensure low test magnification m_{test} for most of the charts, intended to keep lens performance relatively consistent throughout the tests,

- RAW output to minimize nonlinear signal processing commonly found in JPEG files,

- A high-quality zoom lens set to 50mm (35mm-equivalent) at f/4.

With this camera, we expected MTF measurements to be affected only slightly for the largest charts, which are designed to fill the image frame, and hence have the largest Fields of View (FoVs). We expected MTF measurements to be degraded significantly for the smallest charts.

Fig. 5 illustrates the two types of slanted-edge chart used in our testing: Imatest SFRplus (a grid of slanted squares with bars at the top and bottom) and eSFR ISO (an enhanced version of the ISO 12233:2014 edge SFR chart). Both charts have 4:1 contrast slanted-edges, as recommended in ISO 12233:2014. Sizes varied over a range greater than 10:1. These charts were printed over several years on a variety of media— inkjet and photographic paper (reflective), and color photographic film (transmissive).

The reported Fields of View (FoVs) are typically slightly larger than the active area of these charts. Both chart types have geometrical features that facilitate the calculation of test magnification m_{test}. For each image, four edges — Left (L), Right (R), Top (T), and bottom (B) from the square closest to the chart center — were analyzed for compensated and uncompensated MTF.

Since we didn't know the history of the charts, MTF for sample edges was measured individually for each chart.
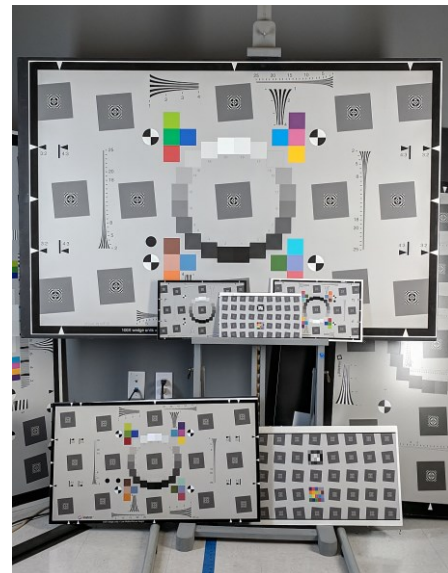

FIGURE 5. SOME OF THE TEST CHARTS USED TO VERIFY MTF COMPENSATION

Compensated and uncompensated results

MTF measurements in Figures 6-9, each from an edge near the center of four very different test charts, illustrate the effects of chart MTF on results. Uncompensated MTF is shown as a **magenta** line. Compensated MTF is a **bold black** line. MTF_{div} is a **cyan** line. MTF_{50} (the spatial frequency where MTF drops to 50% of its low frequency level) is the key summary metric for comparing results.

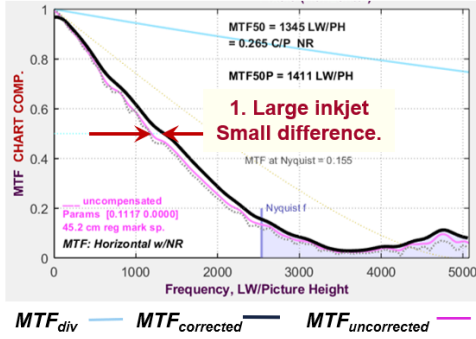MTF_{div} —— $MTF_{corrected}$ —— $MTF_{uncorrected}$ ——

FIGURE 6

The large inkjet chart in Fig. 6 (147×97cm Field of View FoV) has MTF_{50} = 1166 LW/PH (uncompensated) and 1345 LW/PH (compensated). Correction makes only a small difference in the MTF measurement, as expected. The MTF_{50} difference is largely caused by a small noise-related response bump.
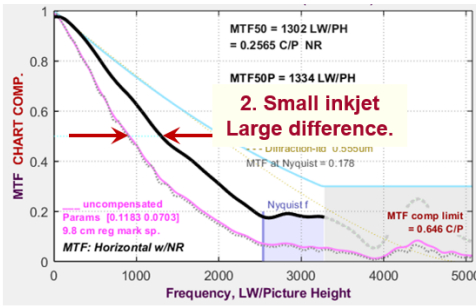

FIGURE 7

The small inkjet chart in Fig. 7 (32×21cm FoV) has MTF_{50} = 922 LW/PH (uncompensated) and 1302 LW/PH (compensated). Correction makes a significant difference. Results would be inaccurate without it. f_{30} is far enough above the Nyquist frequency to ensure good measurement results.
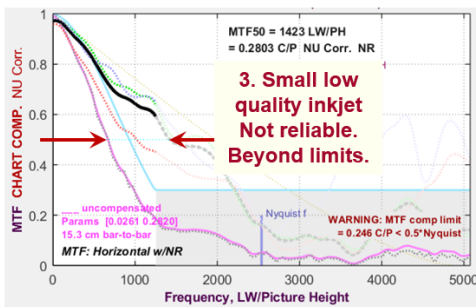

FIGURE 8

The small, low-quality inkjet chart in Fig. 8 (25×17cm FoV) has f_{30} well below the Nyquist frequency. *Results are not reliable*. This chart is inadequate for measuring the quality of this camera system.
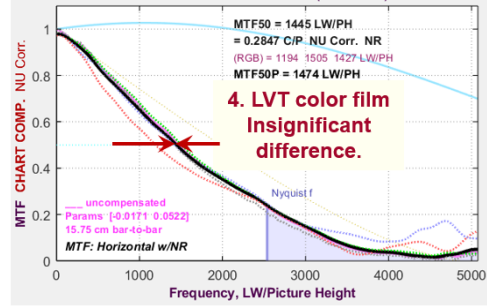

FIGURE 9.

The small but extremely high quality LVT film chart in Fig. 9 (26×17cm FoV) has MTF_{50} = 1466 LW/PH (uncompensated) and 1445 LW/PH (compensated). The chart MTF response bump causes a slight *decrease* the corrected MTF response.

Results summary

Figures 10 and 11 contain detailed results for five SFRplus and five eSFR ISO charts of various sizes and media. This somewhat arbitrary grouping was chosen because the results would not all fit on a single figure. The four groups of five bars on the left (light magenta background) represent uncompensated MTF_{50}. The four groups of five bars on the right (light yellow background) represent compensated MTF_{50}. Compensated MTF_{50} is generally larger and much more consistent, as indicated in Table 1, below.

Each group of five bars represents MTF_{50} results for slanted edges from different charts. Groups are labeled by the edge near the image center used for analysis. The four groups on the left (L, R, T, B) contain uncompensated MTF_{50}. The four groups on the right (L comp, R comp, T comp, B comp) contain the compensated MTF_{50} of the corresponding edges.

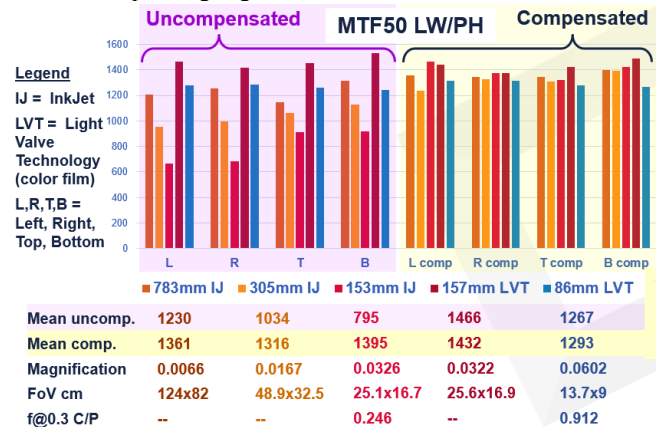|	L	R	T	B
Mean uncomp.	1230	1034	795	1466	1267
Mean comp.	1361	1316	1395	1432	1293
Magnification	0.0066	0.0167	0.0326	0.0322	0.0602
FoV cm	124x82	48.9x32.5	25.1x16.7	25.6x16.9	13.7x9
f@0.3 C/P	--	--	0.246	--	0.912

FIGURE 10. SUMMARY RESULTS FOR FIVE SFRPLUS CHARTS UNCOMPENSATED MTF_{50} ON LEFT; COMPENSATED ON RIGHT.

In Fig. 10, the five bars in each group are for **(1)** a large inkjet chart (124×82 cm FoV), **(2)** a medium inkjet chart (49×32 cm FoV), **(3)** a small inkjet chart (25×17 cm FoV), **(4)** 8×10-inch color LVT film (26×27 cm FoV), and **(5)** small color LVT film (14×9 cm FoV).

The medium and small inkjet charts showed the greatest improvement. The small LVT chart may have had consistently lower corrected MTF_{50} because it had a larger magnification than the other charts, which might have affected lens performance.
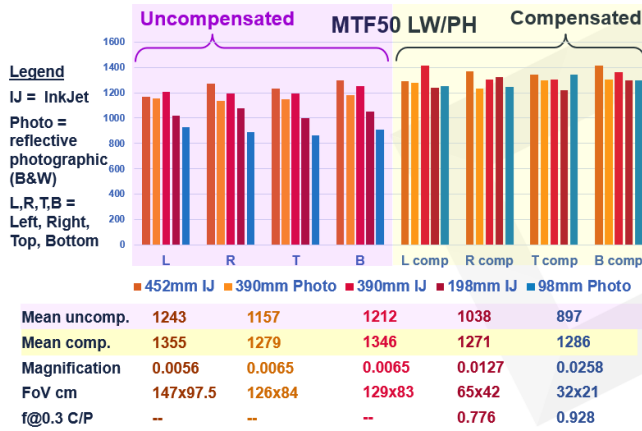
FIGURE 11. SUMMARY RESULTS FOR FIVE eSFR ISO CHARTS UNCOMPENSATED *MTF*₅₀ ON LEFT; COMPENSATED ON RIGHT.

In Fig. 11, the five bars in each group are for **(1)** a large inkjet chart (147×97 cm FoV), **(2)** a medium-large photographic paper chart (126×84 cm FoV), **(3)** a medium-large inkjet chart (129×83 cm FoV), **(4)** a medium inkjet chart (65×42 cm FoV), and **(5)** a small photographic paper chart (32×21 cm FoV). The small photographic paper chart showed the greatest improvement.

The key takeaway from Figures 10 and 11, summarized in Table 1, is that compensated results are larger and have a lower standard deviation σ, i.e., they are more consistent and hence more accurate.

Table 1. Summary results for Figures 10 and 11

Chart group (Figure)	*MTF*₅₀ LW/PF Uncompensated		*MTF*₅₀ LW/PF Compensated	
	mean	Sigma (σ)	mean	Sigma (σ)
SFRplus (Fig. 10)	1158	255	1359	57
eSFR ISO (Fig. 11)	1109	142	1307	40

Predicting test chart suitability

Equations (1) through (5) can be used to predict the suitability of a test chart for a specific application.

We should note that our guidelines for chart suitability assume that the camera is relatively sharp, i.e., not out of focus or blurred for another reason, such as poor lens quality. A reasonable criterion for a "sharp camera" is that it makes good use of available pixels, which would be the case when the unsharpened *MTF*₅₀ > 0.1 Cycle/Pixel (C/P). Typical values are around 0.15 – 0.3 C/P for high quality cameras.

After running numerous images, we developed the following guidelines for chart suitability, based on the projected chart MTF at the Nyquist frequency (0.5 C/P), MTF@ f_{Nyq}, on the image sensor.

Table 2. Guidelines for test chart suitability

MTF@ f_{Nyq}	Recommendation
> 0.9	Compensation is optional; has little effect.
0.7 – 0.9	Compensation is recommended, but uncompensated results may be useful for relative measurements (comparisons between devices).
0.3 – 0.7	Compensation is required for reliable results.
< 0.3	**Chart quality is inadequate.** Compensated results are not reliable. See example in Fig. 8.

Fig. 12 shows results of a test chart suitability calculation for the chart/camera combination of Fig. 7. The compensation file had $a = 0.1138$ and $b = 0.07027$. Three of the following four parameters are manually entered.

- Vertical field = 212 mm.
- μm per pixel = 2.14.
- Sensor height = 5.431 mm.
- Magnification = 0.02562.

In typical operation the three geometrical parameters (vertical field, μm per pixel, and sensor height) are entered, and magnification m_{test} = sensor height / vertical field. From Table 2, we see that the key result, MTF@ f_{Nyq} = 0.41, indicates that the chart is being used close to its operating limit (MTF@ f_{Nyq} = 0.3), and MTF compensation is definitely required.
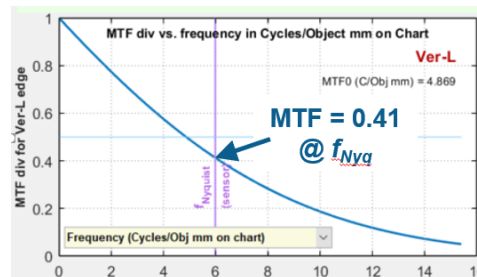

FIGURE 12. CHART QUALITY CALCULATOR

Limitations

Analysis is not reliable at spatial frequencies where the test chart MTF projected on the image sensor, MTF@ f_{Nyq}, drops below 0.3. This is well beyond the normal recommended limits.

Greater care is required when analyzing chart measurements. The correct compensation file should be specified and the correct test magnification m_{test} (or geometric parameters for calculating m_{test}) must be entered.

Chart compensation does not (yet) work well for strongly barrel-distorted (fisheye) images, where radial magnification is a function of distance from the image sensor, and hence radial and tangential magnification may differ.

Noise at high frequencies– especially above f_{Nyq} – may be strongly boosted. Response above f_{Nyq} should usually be ignored.

Conclusions

MTF compensation improves the consistency and accuracy of camera MTF measurements made from different test charts (often at different locations), especially when charts are used near their megapixel limits. Some MTF variation, primarily due to noise, remains after compensation. In our verification tests we may have observed some MTF variation caused by differences in lens performance at different test magnifications.

MTF compensation files should be created for each printer/media/setting combination. Except for old charts where these details are not known, charts don't need to be measured individually.

We have determined two limits related to MTF compensation:

1. an upper limit, MTF50 @ Nyquist ≥ 0.9, beyond which chart compensation has little effect,

2. a lower limit, MTF50 @ Nyquist < 0.3, beyond which compensated results are unreliable,

MTF compensation effectively doubles the megapixel usability limits for most test charts.

We have been using the chart MTF measurement techniques described here to improve the quality control of our printed test charts.

Reference

[1]   ISO 12233:2017 Photography – Electronic still picture imaging – Resolution and spatial frequency response [Online], www.iso.org/standard/71696.html

Author Biography

Norman Koren became interested in photography while growing up near the George Eastman House photographic museum in Rochester, NY. He received his BA in physics from Brown University (1965) and his Masters in physics from Wayne State University (1969). He worked in the computer storage industry simulating digital magnetic recording systems and channels for disk and tape drives from 1967-2001. He founded Imatest LLC in 2003 to develop software and test charts to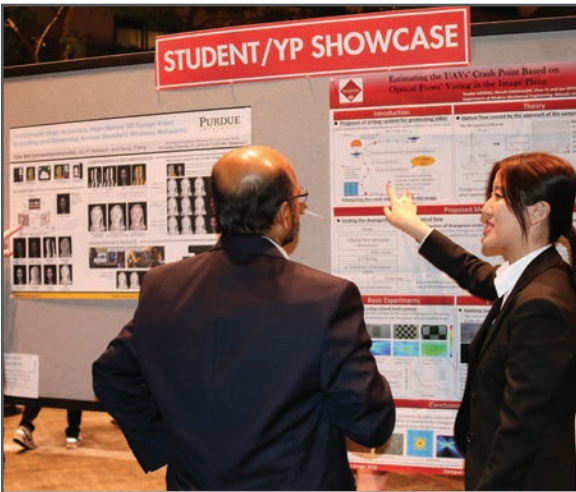 measure the quality of digital imaging systems.