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Managing Deviant Data in Spatial Frequency Response (SFR) Measurement by Outlier Rejection

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Abstract

The edge-based Spatial Frequency Response (e-SFR) method was first developed for evaluating camera image resolution and image sharpness. The method was described in the first version of the ISO 12233 standard. Since then, the method has been applied in a wide range of applications, including medical, security, archiving, and document processing. We address the mitigation of measurement error that is introduced when the analysis is applied to low-exposure (and therefore, noisy) applications, and those with small analysis regions. These applications can lead to both variation and bias being introduced. We investigated a way in which both ordinary image noise and defects, such as target wear and dust, can distort the SFR results. We apply statistical methods that are used in quality assurance and time-series analyses.

Introduction

The edge-based ISO 12233 method was first developed for digital cameras.[1,2] Since then, the method has been applied in a wide range of applications including, photographic scanners[3], medical x-ray, mobile imaging,[4,] and archiving[5] systems. However, with this broad application several of the assumptions of the method are no longer closely followed. This has led to several improvements aimed at broadening its application, for example for lenses with spatial distortion.[6]

We address the mitigation of measurement error that is introduced when the analysis is applied to low-exposure (and therefore, noisy) applications, and those with small analysis regions. Other sources include test-target wear and dust. We consider the origins of bias errors in the resulting SFR measurement and present a practical way to reduce them. We describe the screening of outlier edge-location values as a method for improved edge detection. This, in turn, is related to a reduction in negative bias in the resulting SFR.

Our approach is to consider the evaluation of image quality parameters as an estimation problem, based on the gathered data, often from digital images. Practical error and variation can be addressed in terms of bias and variation introduced into the estimated parameters. The objective was to develop simple, robust methods for reducing measurement variation and bias. We borrow from established statistical and quality assurance methods.

ISO 12233 Edge-SFR

The ISO 12233 standard for digital camera resolution includes several methods for the evaluation of camera performance. One is based on the analysis high quality edge features, and results in a measured spatial frequency response (e-SFR). Often, the measured SFR is referred to as the camera-system Modulation Transfer Function (MTF).

The Modulation Transfer Function is a well-known imaging performance measure, which can be measured in several ways. For this reason, the ISO standard refers to the result of the above method as an SFR. Nevertheless, under some conditions, we can interpret the e-SFR as an estimate of the sampled MTF based on the method of ISO 12233. To use a statistical analogy, consider the MTF as a parameter (e.g., the mean value of a distribution), and the e-SFR as one specific estimate (such as a computed sample mean) of that parameter.

The basic steps of the method are shown in Fig. 1 from Ref. 7, where more detail can be found. Based on image pixel data corresponding to an edge feature, an edge profile is computed in the direction across the edge.

This involves:

1. Acquiring the edge function: edge detection, projection of the image pixel values along the edge, and binning (accumulating) the values in a (4x) super-sampled function, interpreted as the Edge Spread Function (ESF).
2. Computing an equivalent line-spread function via a derivative operation
3. Application of a smoothing window function
4. Computing the Discrete Fourier Transform (DFT) of this windowed array

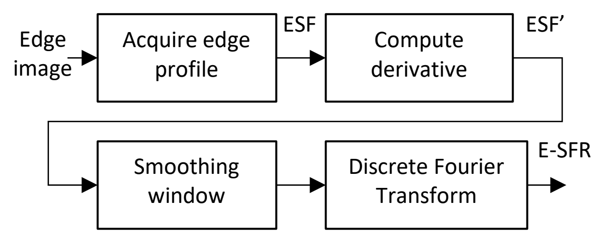

Figure 1: Major steps for e-SFR analysis, from Ref. 7.

In this report, we focus of key elements of the first step of the above Fig.1, Acquire Edge Profile. For a vertical edge feature these are:

1. Compute derivative in the pixel direction across the edge
2. Locate the center of the edge, row-by-row (a centroid is used in ISO 12233)
3. Fit a polynomial function to the set of edge locations
4. Project and accumulate the pixel values along the edge using the edge fit function at intervals of 0.25 the image pixel distance.

Notice that steps 2 and 3 compute the location (and shape) of the edge, based on the image pixel values. Since practical images contain variation, such as image noise, this becomes an estimation problem. The goodness of many estimates is usually evaluated by considering their bias and variation. Bias is often thought of as a predictable measurement error, from measurement to measurement, such as a 'noise-floor'. Measurement variation is sometimes called noise, which varies with each observation. Discussion of estimation error in image quality measurements can be found in Ref. 8.

Measurement variation and e-SFR

The broad adoption, and adaptation, of the e-SFR method is a sign of its utility. However, in some cases, this presents challenges to the edge-finding and fitting steps. In Fig. 2 we see examples of test images presented for evaluation.

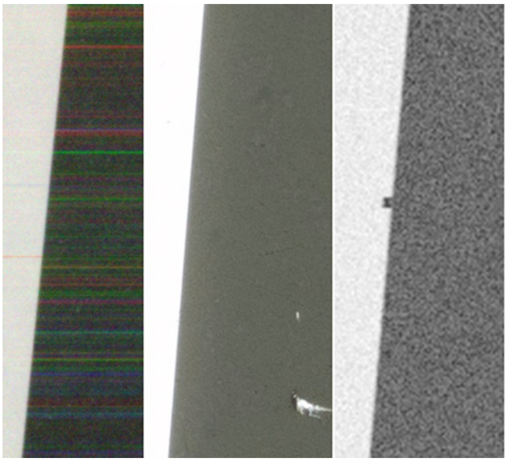

Figure 2: Examples of test images that can present problems

The edge on the left is from a high-volume large-document scanner with a linear (one-dimensional) detector. The color striping is likely due to dust accumulation. The middle edge is from a photographic film scanner, where a large defect in the lower right is seen. Image noise and a local edge deviation are seen in the sample on the right.

Outlier Identification and Exclusion

As discussed above, a key part of the e-SFR measurement is the detection and fitting of the test edge in the image. If we consider the test edge on the right of Fig 2, we can display the residual difference between the computed edge location for each row and the fitting equation. This was done and is shown in Fig. 3. As we can see, the local deviation is identified. Based on this type of result, a simple outlier-rejection step was added. In Fig 3. The locations whose residual error exceeds 2σ are identified by the red asterisks (*). We note that other values are also identified as 'outliers' by this method. The σ value was computed once from the entire edge location vector (*i.e.*, a two-pass estimation did not seem needed).

A simple method was used to exclude the identified values from the fitting of the edge, and computing of the super-sampled edge profile. A masking vector was populated with the identified locations to be excluded. Omitting the outliers in the edge-fitting is a simple operation, and an alarm level of 5% was added. When projecting the image data along the fitted edge, we excluded entire rows (for a vertical edge) from the computation. Figure 4 shows the steps used.

Masking and exclusion operations were implemented as part of the reference e-SFR implementation from ISO 12233. The intended result was an improved edge fitting and resulting SFR result.

To quantify the influence of both ordinary image noise and isolated detects, a simulation was performed, starting with an ideal computed edge. The image was corrupted in two ways. First, image noise was added where the signal-to-noise ratio (signal difference/noise standard deviation) was 12.3, quite visible. For a second image, a single translation of about 4 pixels was introduced to the above noisy image. The resulting test images are shown in Fig. 5.

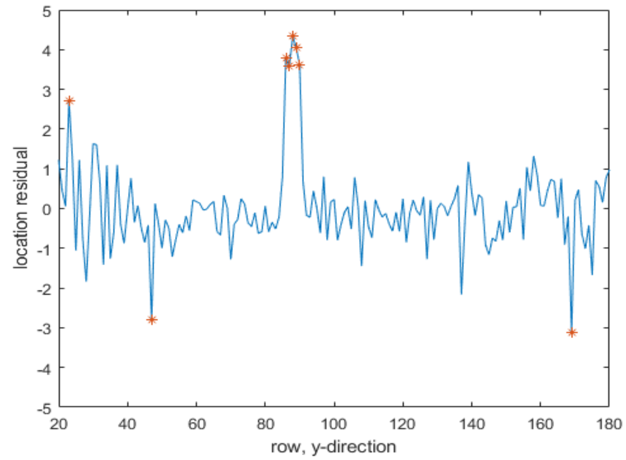

Figure 3: Residual edge location for right image of Fig. 2

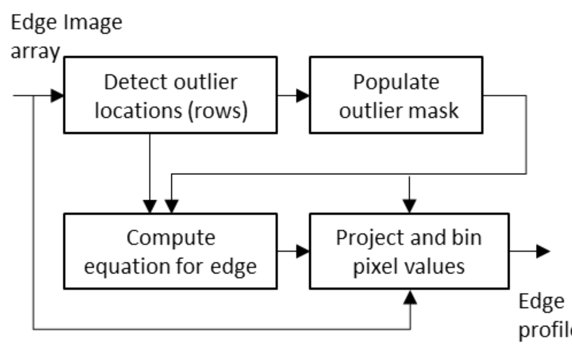

Figure 4: Outline of the outlier rejection method

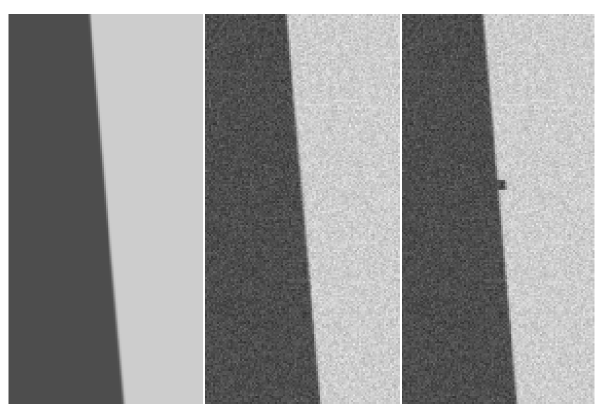

Figure 5: (l-R) Noise-free, noisy, and noisy with an added defect.

In fig. 6 we see the results of the SFR evaluation for both noise-free and the two modified images. The two solid lines are for the no-correction condition.

Correction for the edge-angle alone is seen to offer modest improvement for the example, where the results, although different, appear to be superimposed. However, outlier rejection for both the angle and edge-profile estimation reduced the measurement bias, particularly at low frequencies.

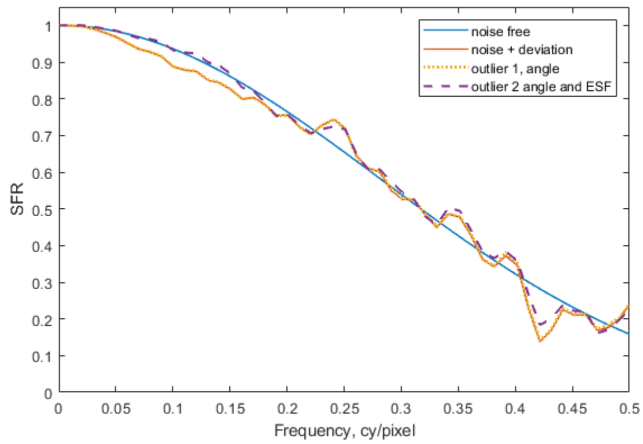

Figure 6: SFR results from the simulation experiment with outlier rejection

Rejection in the Absence of Outliers

The application of the above outlier rejection was shown to be of benefit in reducing bias in the e-SFR results when local edge deviations are present. Any intervention, however, should be required to *not* introduce bias or variation for cases when no local edge defect is present. We can think of this as a *do no harm* requirement. This can be a concern for any statistical signal-processing operation. Some samples from an in-control data set will be detected as potential outliers, depending on the (probability) threshold selected.

To evaluate this, we start with the same computed edge, with a known profile and e-SRF. This has relatively high levels of image noise fluctuations that were added to this image array. Two types of noise fields were used, spatially uncorrelated (white), and correlated. The correlation between neighboring pixels was introduced by a 2x2 convolution operation before adding the noise array to the edge image. Figure 7 shows an example image from this study.

For this high-noise case, the results for 30 independent realizations were computed. From this set, the frequency-by-frequency mean e-SFR was computed. These mean SFR results, with and without outlier rejection, are shown in Fig.8. The original noise-free case is also shown.

We can conclude that the image noise does introduce a positive bias, as expected, at high frequencies. However, the introduction of the outlier-rejection step does not introduce any additional measurement bias, when compared to the result without this step. This is a positive finding since the number of detected outliers was approximately 5%. This is consistent with the threshold statistic of 2σ, although the distribution of ordinary edge locations was not assumed here.

Further Testing

For many system evaluation situations, it is common to mitigate the effect of image or test target defects by the selection of the analysis region (ROI). This manual selection is not practical for high-volume and multi-edge analysis, but it can provide a reference for our next example. The edge image is shown in Fig. 9, with two clear defects in the lower right area.

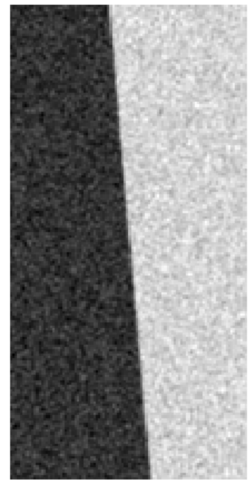

Figure 7: Example edge image with a signal-to-noise ratio (range/standard deviation) of 11 dB, for the correlated noise case (100x200 pixels)

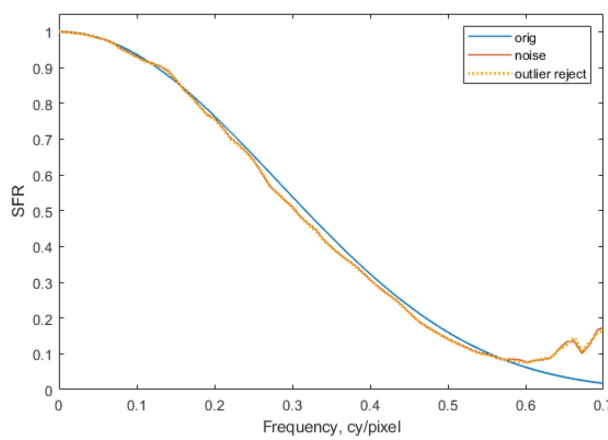

Figure 8: SFR results from the simulation experiment with only stochastic added. The noise-free input is labeled orig.

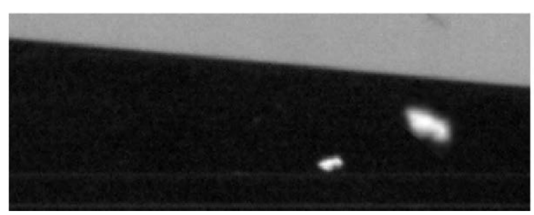

Figure 9: Example test image from high-volume document scanner (120x300)

We would expect that these defects, whether from the target or test conditions (dust) will influence both the edge angle estimation and calculation of the edge profile vector. The results of the ISO 12233 e-SFR analysis are shown in Fig. 10. For this case, the outlier rejection rate was 6%.

When we compare the results from the entire image (without outlier rejection) to those of the cropped region, two observations can be made. The first is an increased frequency-to-frequency variation, particularly at the low frequencies. The second is an apparent underestimation (negative bias) for frequencies above about 0.1 cy/pixel.

Comparing the full image (*orig*) results with those with outlier rejection, at 0.25 cy/pixel we see a 30% reduction due to the image defects. This is more evident when we show the ratio of the two SFR measurements in Fig. 11. The corresponding difference in the summary measure, SFR50, was -3.2%. SFR50 (also known as MTF50) is the lowest spatial frequency where the e-SFR has a value of 0.5 (50%). For a smaller (100x200) ROI the difference was -5%, as we might expect.

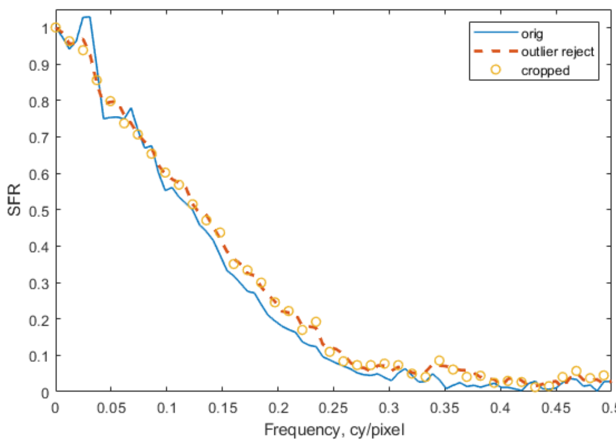

Figure 10: E-SFR results for the test image of Fig. 9.

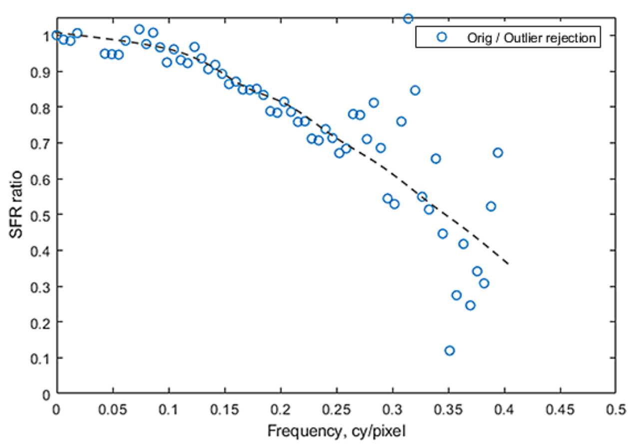

Figure 11: Ratio of e-SFR results with and without outlier-rejection

Conclusions

We have addressed the reduction of measurement error that is introduced when the analysis is applied to low-exposure (and therefore, noisy) applications, and those with small analysis regions, and evident test-target wear and dust. When considering the origins of bias errors in the resulting SFR measurement, a statistical approach was taken. The image-wise noise and distortion lead to a corresponding variation in the computed edge location. This, in turn, can propagate to bias errors (end variation) in the resulting e-SFR measurement. We introduce a simple outlier-rejection method, implemented as a masking operation. The masked locations are excluded from the edge-fitting operation. They are also omitted from the computing of the super-sampled edge profile.

The method was evaluated via a simulation that included both the addition of image noise and an edge defect. The results indicate a modest improvement in the SFR results, with no appreciable penalty for the omission of 'in-control' values.

The statistical test that was applied to the edge location is based on the simple standard deviation statistic. No account was taken of the increased variation that occurs near the ends of the edge feature. This is due to, in the current ISO 12233 method, the analysis is based on a rectangular region. When projected along the edge, this results in fewer pixel values being accumulated. For practical image testing, this results in increased variation (noise) near the ends. To some extent this is at least partially mitigated by the application of the smoothing window (third step of Fig.1). However, computing a position-varying rejection criterion may improve the results.

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Author Biography

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. Dr. Burns has authored over 80 technical publications and 23 US patents and is a fellow of IS&T.

Don Williams is the 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. He has taught short courses for many years and contributes to several imaging standards activities.