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Evaluating intensified camera systems

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ABSTRACT

This paper describes image evaluation techniques used to standardize camera system characterizations. Key areas of performance include resolution, noise, and sensitivity. This team has developed a set of analysis tools, in the form of image processing software used to evaluate camera calibration data, to aid an experimenter in measuring a set of camera performance metrics. These performance metrics identify capabilities and limitations of the camera system, while establishing a means for comparing camera systems. Analysis software is used to evaluate digital camera images recorded with charge-coupled device (CCD) cameras. Several types of intensified camera systems are used in the high-speed imaging field. Electro-optical components are used to provide precise shuttering or optical gain for a camera system. These components including microchannel plate or proximity focused diode image intensifiers, electro-static image tubes, or electron-bombarded CCDs affect system performance. It is important to quantify camera system performance in order to qualify a system as meeting experimental requirements. The camera evaluation tool is designed to provide side-by-side camera comparison and system modeling information.

Keywords: image intensifier, CCD, radiography, electro-optic, imaging, camera performance, camera evaluation.

1. INTRODUCTION

Bechtel Nevada is responsible for providing electronic imaging support to the U. S. Department of Energy for a wide range of experiments. This support covers the entire life of a camera system, from design and fabrication to data acquisition and image analysis. Many of the camera systems are fast-shuttered intensified cameras, both commercial and custom-built. Due to the wide scope of imaging applications, similar types of camera systems are used by on a variety of projects. To aid these teams in evaluating and comparing their camera systems to others, we have developed a standard set of camera tests that provide essential system performance information without data overload. This streamlined camera evaluation system provides data analysis through use of an automated camera evaluation software package and requires minimal bench time to acquire calibration data. These bench top camera evaluations allow side-by-side camera comparisons. The camera evaluation process provides an experimenter with the information essential to determine whether or not they have selected the right camera system for the application. Overall system performance in an experiment is dependent on environmental conditions such as optical source characteristics, optical relay or imaging system, and background conditions. The image processing tools developed also provide an experimenter with the ability to quickly evaluate and document the performance of their imaging system in a particular experimental setup with a minimal set of calibration images. This paper describes the performance metrics and analysis approach used for camera system evaluations along with sample data evaluations and results.

2. EVALUATION PARAMETERS

The basic parameters used to compare camera systems are: resolution, sensitivity, and noise characteristics.

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A basic set of calibration data can provide a great deal of performance information on a camera system. The calibration data set includes image files of resolution and edge patterns, a series of flat fields of different intensities, and a background image.

2.1. Resolution

Resolution is a key performance parameter of any camera system. The resolution of a system determines the number of pixels (or resolution elements) per image and the field of view. Optical components may introduce a blur factor or degradation in image sharpness. Resolution parameters that describe a camera system's performance are the contrast transfer function (CTF) and modulation transfer function (MTF).

2.1.1. Contrast transfer function (CTF)

Contrast transfer function is the percent modulation detected for square wave input. The CTF at a given spatial frequency, and limiting resolution can be obtained by imaging a standard resolution bar pattern with a camera system (Figure 1). The modulation, generated by the intensity profile, is determined by,[1]

$$\text{Modulation} = m = \frac{S_{\max} - S_{\min}}{S_{\max} + S_{\min}} \,, \tag{1}$$

where,

$$\begin{aligned} S_{\max} &= \langle I_{Max} \rangle - \langle I_{Background} \rangle \\ S_{\min} &= \langle I_{Min} \rangle - \langle I_{Background} \rangle . \end{aligned} \tag{2}$$

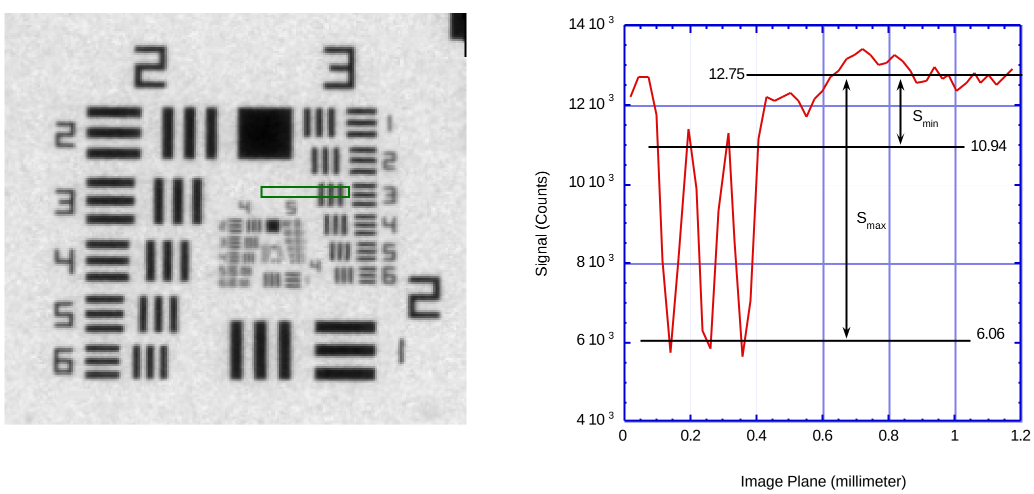

Figure 1. Resolution image with extracted profile

At a given spatial frequency CTF is the modulation in the pattern for that number of line pairs per millimeter. The limiting resolution is the spatial frequency (line pairs per millimeter) corresponding to the “smallest resolvable” bar pattern image. The “smallest resolvable” resolution is the highest spatial frequency having a modulation of approximately 5%. The corresponding number of line pairs per millimeter is called the limiting resolution (LR).

We have seen that both the CTF and LR measurements rely essentially on modulation measurements of resolution pattern images but use them in different contexts. Those contexts are determined by the user; therefore, the main functionality needed by a software tool to measure both CTF and LR is to help the user extract modulation values from bars in the test pattern images. Additionally, in both cases it is usually necessary to perform background subtraction and flat field correction of the raw images. This may improve detectable resolution in a camera system by removing fixed pattern noise.

2.1.2. Modulation transfer function (MTF)

The modulation transfer function (MTF) is calculated using edge spread functions (ESFs) from an image of a vertical knife-edge.[2,3] Since this method assumes that cuts are made perpendicular to the edge, the MTF tool automatically corrects the knife edge image for rotation. The user selects a region in the edge image to be used in the MTF calculation. This region should be horizontally as long as possible in order to completely describe low frequency components as well as produce better resolution in the MTF. The tool then takes adjacent horizontal cuts across the region, starting at the vertical center of the selected area. These cuts are edge-spread functions for the image. The user specifies the number of ESFs to be taken. More ESFs will make the final MTF less prone to some high frequency noise but will be less accurate if the image is not spatially invariant.

Each of the ESFs is differentiated to generate a line-spread function (LSF). Both the positive and negative portions of the LSFs will go to zero in ideal data. Often real data has nonzero “tails” on the LSFs. Flattening the edge image before processing may improve the tails. If necessary, future modifications of the MTF tool may include curve-fitting options to address tails in the LSFs.

The FFT is then calculated for each LSF, creating an MTF for each LSF. The ensemble of the individual MTFs is then ensemble averaged to generate a single MTF. Averaging the individual MTFs reduces noise produced in the calculation of the LSF. In addition, since averaging of the MTFs takes place in the frequency domain, perfect phase alignment of the ESFs is not essential. Setting the DC value to 1 then normalizes the final, averaged MTF.

2.2. Sensitivity

Sensitivity is a measure of the range over which the camera system is able to detect signals. These measurements may also be used to quantify the system's ability to distinguish signal from noise. Sensitivity parameters are the transfer curve, which maps a cameras signal response; detective quantum efficiency (DQE), which references signal to noise; and quantum efficiency (QE), which measures the efficiency of the photocathode.

2.2.1. Transfer curve

A transfer curve is used to calibrate a camera systems response to input light level. This curve is used to indicate the input light level needed to exceed the noise equivalent input (NEI)[4] light level. The transfer curve will also indicate a system’s dynamic range defined as the ratio of the input light level at camera saturation to the input level needed for a signal to noise ratio of 2:1.

2.2.2. Detective quantum efficiency (DQE)

The quality prescribed to a measurement is determined by the associated signal-to-noise ratio (S/N). Introduction of noise into the measurement by the detector degrades, thereby reduces the quality of the measurement. The less noise that a detector introduces, the better the detector preserves the S/N. How well a detector preserves the S/N can be parameterized in terms of the DQE, calculated as:[5]

$$DQE = (S/N)^2_{OUTPUT} / (S/N)^2_{INPUT}, \tag{3}$$

where $(S/N)_{OUTPUT}$ is the output signal-to-noise and $(S/N)_{INPUT}$ is the input signal-to-noise.[1] The task of parameterizing the DQE becomes the task of developing and implementing procedures to compute $(S/N)_{OUTPUT}$ and $(S/N)_{INPUT}$.

2.2.2.1. Signal-to-noise output

$(S/N)_{OUTPUT}$ is estimated by separating acquired test data into the classes “signal” and “noise.” To partition the data into these classes, the signal is estimated as the averaged test data while the fluctuations about the average are interpreted as the noise. Guarding against fixed pattern noise, the approach computes the averages and fluctuations as a function of pixel location. Typical calibration data for this measurement consists of flat field illumination images of a known intensity. A number N of such data sets is acquired.

To develop the formalism for this analysis, let D(j:x,y) be the digital output for image data set j pixel location (x,y). Experience has shown that these data should be background corrected. For this purpose, a background image (B(x,y)) is acquired. The corrected data are:

$$DC(j:x,y) = D(j:x,y) - B(x,y) \ . \tag{4}$$

An averaged flat field image data set is obtained as:

$$A(x,y) = (1/N)\,\Sigma\, DC(j;x,y) \ , \tag{5}$$

where the summation is from j = 0 to j = N – 1. The averaged image intensity above background is calculated for each pixel location. The averaged flat field image retains the fixed pattern noise signature of the camera system while averaging out random noise. Removal of fixed pattern noise may further increase a detectors signal to noise characteristics. Data images are corrected for fixed pattern noise and intensity roll-off by dividing by averaged flat fields. To retain the relative signal level information in a data image the averaged flat field image must be normalized before being applied to the data. Signal levels should be measured in the linear response region of a systems dynamic range. For mean peak signal level, μ_{pk}, the normalized average flat field is given by:

$$NA(x,y) = A(x,y) / \mu_{pk} \ . \tag{6}$$

Flat field corrected images are then computed as:

$$F(j:x,y) = DC(j:x,y) / NA(x,y) \ , \tag{7}$$

where NA(x,y) > 0. The effects of repeatable, spatial variations (contributors to fixed pattern noise) in background, system gain, and illumination are removed in this set of flat field corrected image data. A central region is identified for analysis, avoiding edge affects. Width (W) and height (H) of the area are W pixels by H pixels. Typically, an area enclosing some 10,000 pixels or more is chosen. If the fixed pattern noise has truly been removed, then any flat field corrected image data could be chosen for further analysis. For flat field corrected data set FC(j:x,y), the mean within the identified region is calculated as:

$$\mu_j = (1/(W\ H))\,\Sigma\, FC(j;x,y) \ . \tag{8}$$

The standard deviation, σ, is calculated from pixel variance:

$$\sigma^2_j = (1/(W\ H))\,\Sigma\, [FC(j;x,y) - \mu_j\,]^2 \ . \tag{9}$$

Then,

$$(S/N)_{OUTPUT} = \mu_j / \sigma_j \ . \tag{10}$$

It may be instructive to compute $(S/N)_{OUTPUT}$ for a number (best all) of the flat field corrected images. Each should be calculated separately to accommodate source level fluctuations between data sets (unless a means of normalizing the data sets is addressed).

2.2.2.2. Signal-to-noise input

The $(S/N)_{INPUT}$ is calculated more directly. The input signal is the number of quanta input, q, and the noise input is the square root, $\sqrt{q}$.[5] In "*Performance of image intensifiers in radiographic systems*" [3] the photon density, q_p, is calculated as a function of total energy input, Q_e. In practice, a simpler method is to calculate q_p as a function of energy density input, w_e, (J/cm^2). This simple measurement integrates energy density volume over time to give the energy density as a function of area. To start, the input photon density is calculated from the energy density measurement. The photon density, q_p, is calculated as follows:[6,7]

$$q_p = w_e / [(eV)\ (hc/e) / \lambda] , \tag{11}$$

where

w_e = irradiant energy density (Joules/cm^2) from measurement;

eV = 1.6022×10^{-19} J ;

(hc/e) = 1.23985×10^{-6} V m = 1240 eV nm ; and

λ = photon wavelength (nm) .

This q_p is the photon density input or photons per cm^2 (often cited as the number of input photons per resolution element). In real imaging systems, a resolution element is normally greater than one pixel. The area of a resolution element, A_{res}, in pixels, is measured as the normalized signal, or pixel count, above background generated from a point source illumination.

The acquired point source image is S(x,y) and is background corrected as,

$$SC(x,y) = S(x,y) - B(x,y) . \tag{12}$$

The peak signal level (Peak) of this image is located then the image values are normalized to a unit peak,

$$N(x,y) = SC(x,y) / Peak . \tag{13}$$

The area of illumination is then summed;

$$I = \Sigma\ N(x,y) , \tag{14}$$

where, the sum is over x and y. This sum, I, represents the area above background of the system point spread function and is called the "area of a resolution" element, typically in pixels. The pixel count, I, is multiplied by the pixel area to get A_{res} in cm^2.

$$A_{res} = I \times A_{px} ,\ A_{px} = \text{Area of a pixel in cm}^2. \tag{15}$$

The quanta input is then:

$$q = q_p\ A_{res} \tag{16}$$

$$(S/N)_{INPUT} = q / \sqrt{q} = \sqrt{q} \tag{17}$$

2.3. Noise

Noise contributions in a camera system will degrade its performance. High noise levels in an imaging system will degrade system sensitivity and limit its dynamic range. Two parameters used to evaluate a system's noise characteristics are variance and noise power spectrum (NPS).

2.3.1. Noise variance

Noise variance is a measure of the random noise characteristics of a camera system. Random noise is made apparent when two identical images are compared. Image data is normally recorded in the form of flat field illumination over a range of signal levels. The image data is background subtracted and then the difference between the two images is measured. Ideally the difference between two identical images would be zero; the departure from zero measured provides a means for camera system comparison. Before subtracting the two image files, their data type must be converted to floating point to allow negative values. Then σ^2 (Eq. 9) is calculated for the resulting data set. The calculated variance is divided by square root of two to correct for a sampling of two data sets. Variance is then plotted versus signal level.

2.3.2. Noise power spectrum (NPS)

The NPS is calculated using straightforward Fourier methods as described by Stierstorfer and Spahn.[8] Ideally a uniformly exposed image is used, but in the event that one is not available a uniformly illuminated section of one or several images of an object can be used. The processing tool sub-samples the selected image or image-portion with variably sized overlapping squares. The dimensions of the squares are a power of two, as chosen by the user. Larger squares will yield better resolution but poorer results when the user is looking for fixed pattern noise. An option to zero pad the sub-samples to increase frequency domain resolution without decreasing the possible number of sub-samples is being incorporated in the NPS tool. The user also selects the amount of sub-sample overlap. Greater overlap will provide more samples for averaging when only a limited amount of data is available for processing.

The square sub-samples are then windowed using a Hanning window. The square of the complex FFT of each sub-sample is calculated, and the frequency domain power spectra sub-samples are combined in an ensemble average. This average of the power spectra is the noise power spectrum. The NPS tool generates two products: the two-dimensional NPS and cuts along the x and y axes for the vertical and horizontal noise power spectra.

3. DATA ACQUSITION

3.1. Laboratory Setup

The laboratory setup for these calibration measurements does require a small investment but proves to be invaluable in the operational checkout of a high-speed imaging system. The desired equipment includes a strobe lamp, light source, a set of test targets, optical projector lens, a spectral filter, neutral density attenuation filters, and energy meter, mechanical positioning and electronic timing equipment. The strobe lamp is in an integrating sphere to provide flat illumination to test targets. Test targets consist of various types of resolution patterns and a point source target. A single mode, 6 micron, fiber is often used for a point source target. The optical projector lens is used to image test patterns onto the camera system. The spectral filter is normally a narrow band-pass filter to make optical energy calibrations at a wavelength of interest. Neutral density filters are used to adjust the light level.

Most laboratory camera checkouts are done with no camera lens involved. For camera systems incorporating a lens optical relay system, the lens system is removed if possible. This process removes the lens from the calibration process. The lens itself can be a strong contributor to the system performance and should also be evaluated.

4. DATA PROCESSING

The software package being developed by Bechtel Nevada will be a stand-alone package, allowing an experimenter to evaluate parameters in a straightforward manner using tailored image processing tools. The software package is a Research Systems Interactive Data Language (IDL) 'Widget' type platform called Image Tool that automates many routine image processing functions. Because it employs standard techniques and the user does not need to be an IDL programmer to use it, the time it takes to perform the evaluation process is greatly reduced.

4.1. Data loading, pre-processing

Image Tool pre-processes data as it loads. This capability allows the option of performing background subtraction and flat field correction as an image file is loaded. The pre-processing step eliminates the need to manually process the data type manipulation and image arithmetic functions (16-bit integer or 32-bit floating point). Some image arithmetic operations require floating point data to allow fractional or negative values. This feature saves time when evaluating several data images, as it allows you to go directly into the evaluation tools.

4.2. Resolution

4.2.1 CTF measurement process

The following general measurement procedure is given from the *user's* perspective, treating the software functionality as a black box (Figure 2). The user selects a subset of consecutive bars from the image that corresponds to a particular number of line pairs per millimeter (spatial frequency), and extracts an intensity profile, which cuts orthogonal across the bars.

1.) Load resolution pattern image with pre-processing.
2.) Rotate image (if resolution bars are not square with image frame).
3.) Define region of interest (ROI) corresponding to desired spatial frequency.
4.) Generate a pixel-averaged intensity profile of the modulation.
5.) Identify I_{max}, I_{min}, and I_{bkgnd}, with the cursor. The CTF modulation is automatically computed.

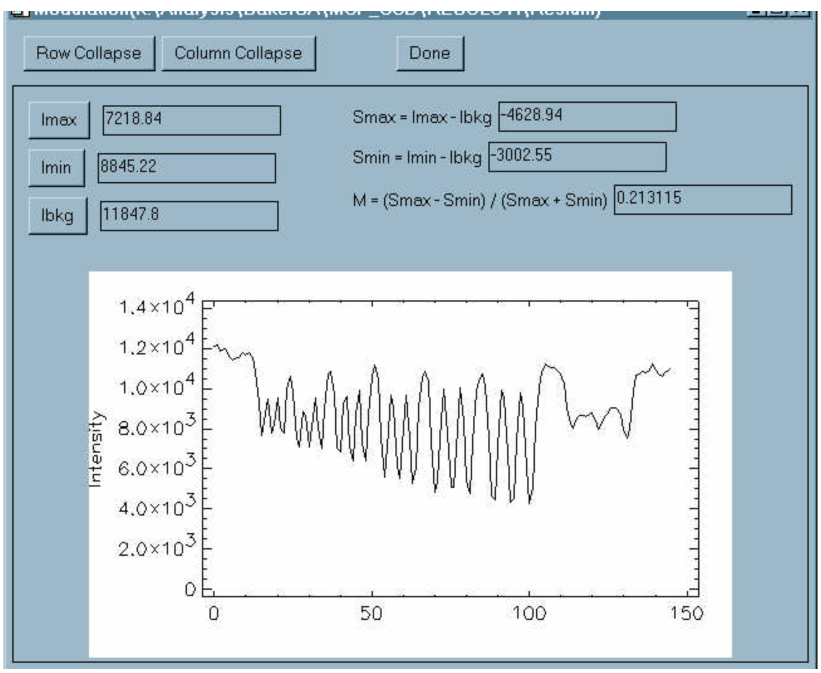

Figure 2. CTF panel

4.2.2. MTF process

MTF processing involves loading and pre-processing an edge image, then defining the ROI from which to extract an edge profile. The edge profile is used as an ESF to compute an LSF and an MTF. Both LSF and MTF are saved to a file. The MTF is plotted with an active cursor to identify particular locations on the plot (Figure 3). The 50 percent modulation point is identified as the cut-off frequency (f_c), and it is used for performance comparisons.

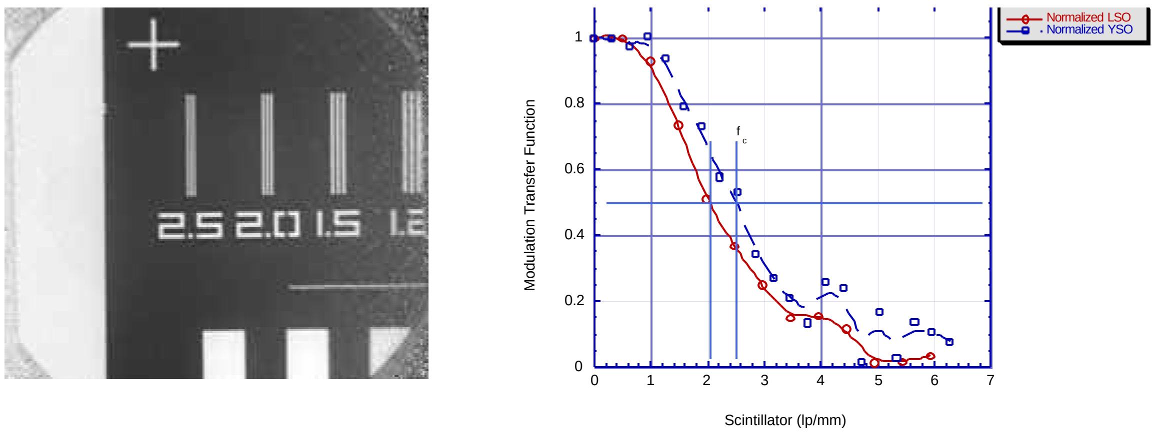

Figure 3. Pre-processed edge image, MTF curve

4.3. Sensitivity

4.3.1. Transfer curve

Transfer curve data is processed by pre-processing data files when loaded with background subtraction. Statistical measurements are computed to determine the average signal and noise level over a range of input light levels from noise to saturation. Then, average signal above background versus input light level is plotted. The NEI level is noted on the plot (Figure 4). This indicates the threshold input energy needed to have signal above the system noise. System dynamic range is also taken from this plot, as the ratio of input energy from saturation to a signal to noise ratio of 2:1.

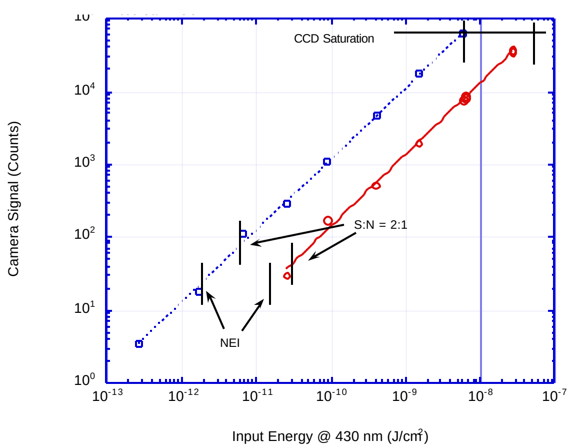

Figure 4. Transfer curve

4.3.2. Detective quantum efficiency (DQE)

This process is not fully automated at the time of this proceeding, but the manual processing is as follows:

The required data set includes ten or more flat field exposures at a fixed signal level, a background image, a point source measurement, and the input energy density measurement. The flat field exposures are background subtracted and averaged. The averaged flat field is then normalized to its mean peak level to produce a fixed pattern noise correction file. The normalized average flat field is then divided into a single flat field image. Signal and noise output are measured on this flat field corrected image. Signal to noise input is calculated from the input energy density and point source measurements. Input energy density is used to calculate the photon density input. The point source measurement is used to calculate the area of a resolution element, or the area of the point spread function above background. Signal-to-noise input is then calculated as the number of photons per resolution element.

The Image Tool interface steps involve providing the input energy density and wavelength of light used, then identifying the flat field, background, and point source images. The user defines a region of interest to be used for the signal to noise measurements and the program runs through the processing steps of background subtraction, averaging (if needed), and normalizing to produce a correction file which can be saved and applied to any data file. A single data image is then identified, and the correction file is applied to remove fixed pattern noise. Signal-to-noise statistics are then computed on the selected region of the corrected image. The user then identifies the point source image from which the signal is background subtracted and normalized. The number of signal pixels is summed above the dark level to give the number of pixels per resolution element. The input energy density and pixel size is then used to calculate the signal to noise input squared as the number of photons per resolution element input. DQE is then calculated as signal-to-noise input squared divided by the signal-to-noise output squared.

4.4. Noise

4.4.1. Variance processing

Flat field, noise variance data is processed from the transfer curve data set (Figure 5). Pairs of images at each intensity level are pre-processed for background subtraction, then one is subtracted from the other. The resultant image is statistically analyzed for variance, Eq. 9. Variance is then plotted versus signal level.

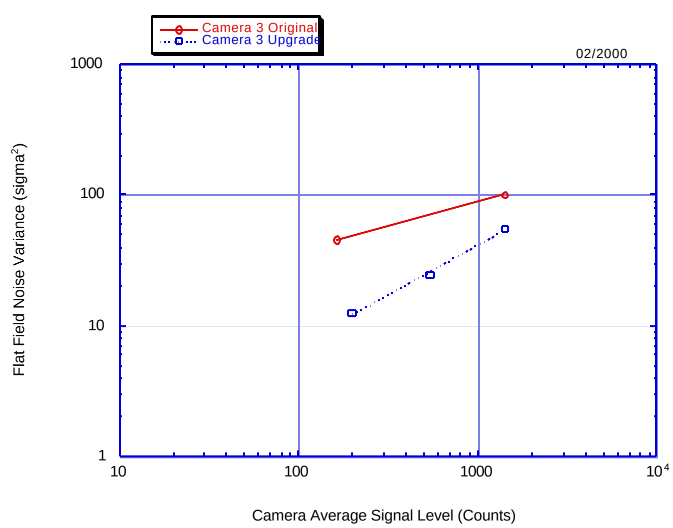

Figure 5. Variance plot

4.4.2. NPS processing

NPS processing may be run on raw data files or on processed data (Figure 6). Flat field corrections with fixed pattern noise removal will improve the results of this analysis. Noisy imaging systems will have more area under the NPS curve than less noisy systems (the area under the curve or the 50 % modulation point).

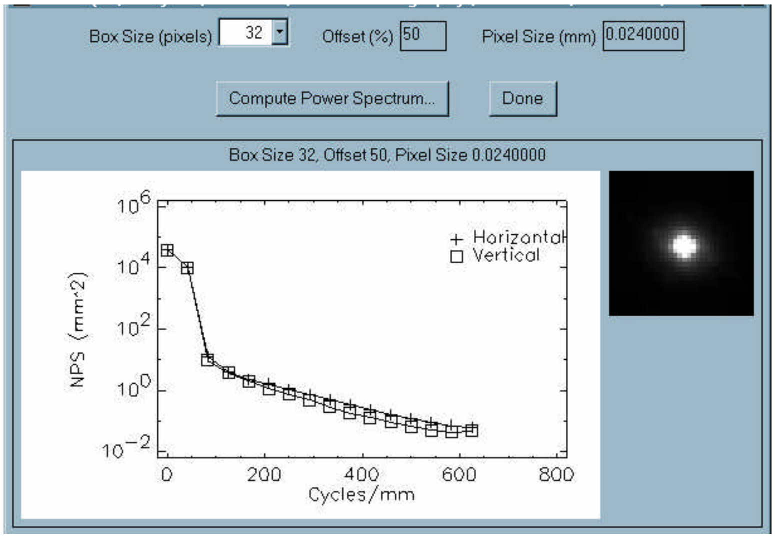

Figure 6. NPS panel

CONCLUSION

Image Tool is a single, stand-alone package capable of processing and documenting a camera system's calibration data with straightforward, consistent techniques. The software tool is an excellent means of evaluating a large amount of information in a short amount of time. Image Tool provides valuable camera comparison and performance information as well as system modeling information used in predicting experimental results. Evaluation techniques are being streamlined to provide essential performance information on a camera system in a simplified manner. The effort to improve camera evaluation techniques and capabilities continues to evolve as new evaluation techniques are developed and process modifications are implemented. Software development is being used to blend traditional spatial domain analysis with frequency domain analysis. Image Tool is designed to be a multi user program available to several teams of people working with similar types of camera systems. By acquiring the appropriate calibration data set, one can generate comparable calibration data through the consistency of data processing techniques. As camera systems are evaluated, their performance information is stored in a data base for performance records and comparisons. The MTF and NPS curves generated by Image Tool may also be used for system modeling. Future versions of Image Tool will incorporate improved automated processing functions with user-selected optional parameters as well as upgrades to data presentation.

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REFERENCES

1. I. P. Csorba, *Image Tubes*, Howard W. Sams & Co., Inc. Publishing, 1985.

2. G. D. Boreman, "MTF in optical and electro-optical systems." SPIE, CREOL, University of Central Florida, 1997.

3. S. A. Baker, N. S. P. King, S. S. Lutz, D. V. Morgan, T. Schaefer, M. D. Wilke, "Performance of image intensifiers in radiographic systems," in *High-Speed Imaging,* SPIE Vol. 3968, 2000.

4. G. C. Holst, *CCD Arrays, Cameras, and Displays*, SPIE Optical Engineering Press, 1995.

5. J. C. Dainty, and R. Shaw, *Image Science,* Academic Press, 1974.

6. RCA, *Electro-Optics Handbook,* 1974.

7. W. L. Wolfe and G. J. Zissis, *The Infrared Handbook*, IRIA, Environmental Research Institute of Michigan, 1978.

8. Karl Stierstorfer and Martin Spahn, "Self-normalizing method to measure the detective quantum efficiency of a wide range of x-ray detectors," *Med. Phys.* **26 (7),** July 1999.

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