MODULATION TRANSFER FUNCTION MEASUREMENT METHOD AND RESULTS FOR THE ORBVIEW-3 HIGH RESOLUTION IMAGING SATELLITE

K. Kohm

ORBIMAGE, 1835 Lackland Hill Parkway, St. Louis, MO 63146, USA – kohm.kevin@orbimage.com

KEY WORDS: Remote Sensing, High Resolution, Sensor, Quality, Metric, Analysis

ABSTRACT:

The Modulation Transfer Function (MTF) is a fundamental imaging system design specification and system quality metric often used in remote sensing. MTF is defined as the normalized magnitude of the Fourier Transform of the imaging system's point spread function. Alternatively, the MTF describes the attenuation of sinusoidal waveforms as a function of spatial frequency. Practically, MTF is a metric quantifying the sharpness of the reconstructed image. On-orbit measurement techniques are discussed to quantify the along scan and cross scan MTF profiles. While many measurement techniques exist, the technique utilized is designed to provide accurate measurements for high resolution imaging systems. Additionally, a confidence interval is assigned to the measurement as a statement of the quality of the measured value.

The classical slant-edge measurement technique for discrete sampled systems is employed. Fixed high-contrast targets are used to obtain MTF measurements in the center of the array. As access to such targets is limited, suitable edges for analysis are identified in nominal operational imagery. The measurement results from the specialized targets are used to confirm the large number of measurements from the operational imagery.

The data sets used in the analysis are from the OrbView-3 (OV-3) High Resolution Imaging Satellite, launched June 26, 2003. Results are presented for the 1 meter ground sample distance (GSD) panchromatic band of the OV-3 system.

1. INTRODUCTION

1.1 Motivation

On-orbit quantification of MTF for remote sensing systems is desirable from multiple perspectives. During sensor commissioning, the system MTF is compared against the design requirements to verify expected performance is achieved. For the end user, system MTF can be used to compare the intrinsic quality of imagery from various sources as well as analytically equalize the sharpness of multiple images from different sensors in a combined product.

This work was initiated to characterize the MTF of the OrbView-3 system during commissioning and continuing throughout the life of the program. Two specific goals for the measurement technique include determining MTF without the use of dedicated targets and providing an intrinsic quality metric of the measurement.

While dedicated targets have been shown to produce quality results, access to such targets is limited. Using features found in nominal scenes allows for many more measurement opportunities and increasing the sample size decreases the error estimate of the results. Additionally, features in nominal imagery will be positioned at various locations across the linear array. This enables MTF characterization across the extent of the linear array without the extensive specialized tasking that is required with fixed targets. MTF results from fixed targets complement the measurements from nominal scenes.

1.2 Objective

The objective of this work is to develop a robust on-orbit MTF measurement technique for remote sensing systems with GSDs on the order of 1 meter or less. One dimensional components of MTF in the along scan and cross scan directions are required. The technique must operate on both nominal image scenes as well as specialized, fixed targets. Error estimates are to be provided for each measurement.

1.3 MTF Estimation Methods

Multiple methods have been proposed for determining the MTF of remote sensing systems on-orbit. These include imaging lines or points and potentially using imagery from a system with known MTF during an underflight (Schowengerdt, 1985). In general, these measurement techniques require a particular size and orientation of targets based on the GSD and scan direction of the sensor to achieve good performance.

Another approach is to use edges to determine MTF. The edge spread function (ESF) is the system response to a high contrast edge. The derivative of the ESF produces the line spread function (LSF), which is the system response to a high contrast line. The normalized magnitude of the Fourier Transform of the LSF produces a one-dimensional slice through the two-dimensional MTF surface. Other methods exist for computing the system MTF directly from the ESF that remove the need for differentiation (Tatian, 1965).

A requirement for determining MTF from edges is to have a high fidelity representation of the ESF. The slanted edge algorithm uses the change in phase of the edge across the sampling grid to create a "super-resolved" ESF (Reichenbach, 1991). For sensors with GSDs on the order of 1 meter or less, high contrast, slanted edge targets are preferred for MTF analysis.

2. METHODS AND MATERIALS

The basis of the algorithm used in this work is the slanted edge MTF measurement technique identified above. Details of the algorithm used are described below along with image and sensor characteristics of the OV-3 system.

2.1 Algorithm

2.1.1 Edge Identification: The initial task in MTF measurement is the identification of suitable edges for analysis. Edges must be oriented near the principal along scan or cross scan axes. A minimum angle to the principal direction is required as well as sufficient length for suitable ESF construction. The candidate edge must also meet contrast and noise requirements for selection.

A Sobel edge detection operator followed by thresholding and binary morphological processing is used to identify edges with the proper orientation and minimum magnitude (Jain, 1989). An initial estimate of the location and angle of the edge is then determined by performing a least squares regression of selected points along the edge. For each identified edge, metrics are acquired such as the magnitude of the edge, noise level and length. These metrics are used in a voting process for edge selection and retained for later use in determining bias and precision estimates.

2.1.2 Edge Spread Function Construction: The ESF is the system response to the input of an ideal edge. As the output of the system is a sampled image, the fidelity of the edge spread function using a single line of image data is insufficient for MTF analysis. Aliasing due to undersampling in the camera, along with phase effects and the angle of the actual edge with respect to the sampling grid will cause variable results for a single line. The phase effects and edge angle may be exploited, however to provide a high fidelity measurement of the ESF.

Construction of the ESF is graphically represented in Figure 1 (Schott, 1997). The edge (1) is identified in the image as described above. A line is then constructed perpendicular to the edge (2). For a given line of image data, each point (3) around the edge transition is projected onto the perpendicular line (4). This process is then repeated for each subsequent line of image data along the edge. The difference in sub-pixel location of the edge with respect to the sampling grid for different lines in the image results in differences in the location of the projected data point onto the perpendicular. This yields a high fidelity representation of the system response to an edge.

Small changes in the edge angle used during construction of the super-sampled edge affect the quality of the resulting ESF. The angle is systematically adjusted by small increments around the initial estimate. The quality of the resulting curve fit is used to refine the edge angle estimate for the final ESF construction.

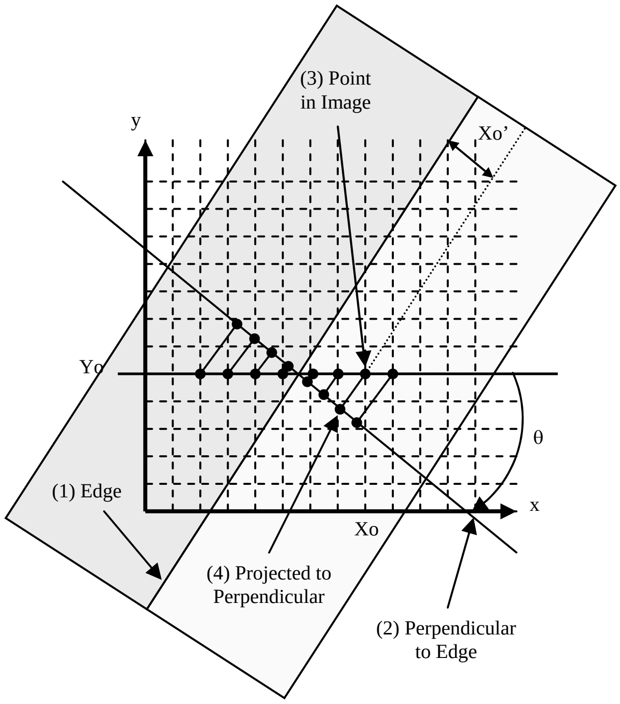

Figure 1. ESF Projection Technique

After the individual ESF data points have been determined, the data must be conditioned and resampled to a fixed interval. In general, the angle of the edge with respect to the sampling grid does not produce uniformly distributed data points along the perpendicular to the edge. Also, with longer edges, many data points may be located in close proximity to one another. The LOESS curve fitting algorithm is used to resample the data to uniformly spaced sample points (Cleveland, 1985). In order to obtain the desired number of samples in the MTF result, thirty-two uniformly spaced ESF samples are calculated for each pixel pitch in the image through the LOESS fit. An example ESF from an OV-3 image is shown in Figure 2. Data points used in the curve fit are shown in black. The resulting curve fit to the ESF is shown in red.

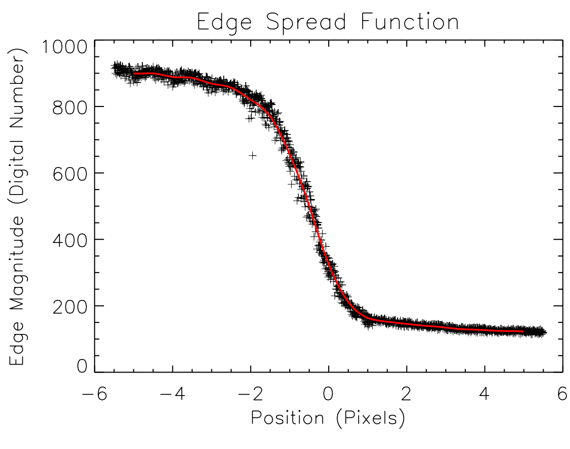

Figure 2. Example ESF from OV-3

2.1.3 Modulation Transfer Function Calculation: Once the edge spread function has been determined, the MTF can be calculated as follows. The line spread function of the system is calculated by taking the numerical derivative of the equally spaced ESF samples. A Fast Fourier Transform is performed on the resulting LSF, the normalized magnitude of which yields MTF. Care must be taken in selecting the number of points calculated along the ESF with respect to the sampling rate in order to obtain the desired number of points in the resulting MTF. Appropriate scaling of the frequency axis of the MTF must also be performed to represent the calculated MTF in terms of the Nyquist frequency of the imaging system. The Nyquist frequency is defined as the highest sinusoidal frequency that can be represented by a sampled signal and is equal to one half the sampling rate of the system.

2.2 Algorithm Calibration

2.2.1 Calibration Approach: Once the algorithm has been developed, it is important to determine the accuracy and precision of the measurement tool. Identification of systematic errors can improve the overall accuracy of the measurement and quantification of precision allows error estimates to be associated with individual measurements.

In order to characterize performance, images of synthetic edges were generated with varying edge characteristics such as edge magnitude, length, noise, angle and sharpness. As the edges are computer generated, the actual value of each parameter is known by construction. The MTF measurement algorithm is then run on each edge and results compared to the actual values. Surfaces are then fit to the measured bias and standard deviation as a function of edge characteristics.

Subsequently, when an edge is analyzed from an operational image, the edge characteristics are also measured. Prior to reporting results from the algorithm, the measurement values are corrected for bias and an error estimate is assigned based on the fits obtained from the synthetic edges.

2.2.2 Test Suite: In generating the test set, a preliminary experiment was performed to determine the edge characteristics that impact the bias and standard deviation of the results from the synthetic edges. The values of the parameters spanned the range expected to be obtained operationally from 1 meter GSD imagery. From the list of characteristics above, it was determined that the measurement bias and standard deviation was invariant to edge angle and edge sharpness. Note that while the edge measurement technique is invariant to edge angle, operationally, the edge angle is limited to small angles around the along scan and cross scan principal directions.

A full scale experiment was then performed using eight values of edge magnitude, five values of noise standard deviation and eight levels of edge length. This results in 320 test cases. One hundred edges for each test case were then generated and analyzed, bringing the total experiment sample size to 32,000 edges. For each edge constructed, the edge angle and sub-pixel edge location were randomized over small ranges. These variations, along with the actual Gaussian noise sequence, characterized by the noise standard deviation parameter, provided the various instances of edges used in the calibration experiment.

2.2.3 Calibration Results: For each test case, consisting of a common edge magnitude, noise standard deviation and edge length, the mean and standard deviation of the MTF measurement at eight spatial frequency points were tabulated. A multiple parameter least squares regression was performed on the standard deviations with 93 degrees of freedom (Mandel, 1964). The correlation coefficient of the regression for the Nyquist frequency is 0.92. Surface plots for the fit of the standard deviation of MTF measurements at the Nyquist frequency as a function of edge magnitude and noise standard deviation for two edge lengths are shown in Figure 3.

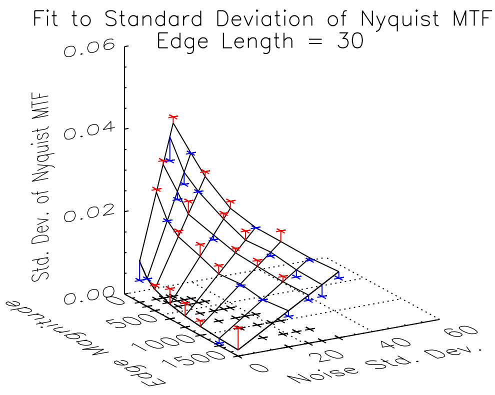

Figure 3a. Surface fit for standard deviation of Nyquist MTF for edge length = 30

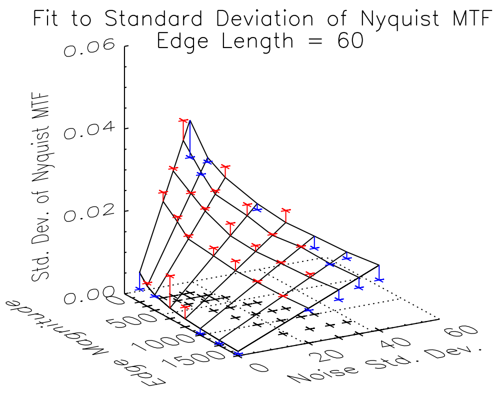

Figure 3b. Surface fit for standard deviation of Nyquist MTF for edge length = 60

Observe that the results of the regression follow intuition. For example, as the noise increases, the standard deviation of MTF increases or alternatively, confidence decreases. As edge magnitude increases, confidence increases and as edge length increases, confidence increases.

The bias for each point is determined by subtracting the true value used to construct the edge from the mean value measured by the algorithm. Again, a multiple parameter least squares regression was performed on the measurement bias with 93 degrees of freedom. The correlation coefficient of the regression for the Nyquist frequency is 0.63. A plot of the MTF bias at the Nyquist frequency as a function of test case number and the residual error after bias correction is shown in Figure 4.

Measurement bias is denoted in blue and the residual error is shown in red. Test case number zero denotes the minimum values for all parameters. Increasing test case number first increases in edge length, then noise standard deviation and finally edge magnitude.

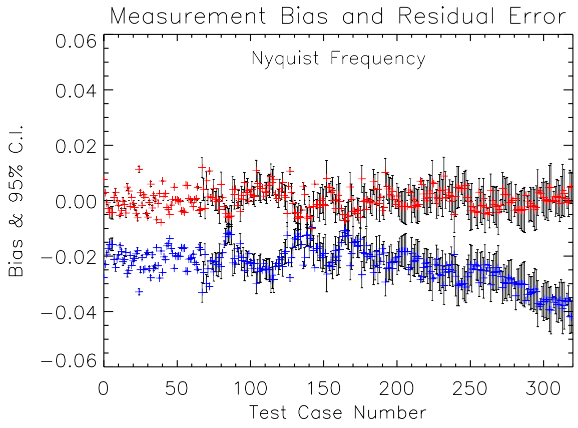

Figure 4. Bias and residual error for Nyquist MTF

2.3 Imagery

2.3.1 Sensor: The OV-3 High Resolution Imaging Satellite acquires one-meter GSD panchromatic and four-meter GSD multispectral imagery from an orbital altitude of 470 km. The nominal ground sample distance values reported are for nadir acquisitions. OV-3 maintains a sun-synchronous orbit with an inclination angle of 97.25^o. The telescope is a 3-mirror anastigmat design with a 45 cm aperture. This paper focuses on the analysis of the panchromatic band as it is the more stressful case for MTF; the panchromatic focal plane is described below. The panchromatic detectors are 6.0 µm by 5.4 µm in the cross scan and along scan directions respectively. Even and odd parity detectors are offset in the along scan direction by approximately 4 pixels or 24 µm. The offset pixels are subsequently aligned during the image reconstruction process. Imagery is acquired at 11 bits per pixel (bpp) and is compressed for downlink to 2 bpp.

Exposure is control is provided by 16 panchromatic imaging modes. The camera may be commanded to image at line rates of 5000 lines per second (lps), 2500 lps, 1000 lps or 500 lps. Additionally, the integration fraction or duty cycle for each line rate may be selected from full, one half, one quarter or one eighth of a sample period. These modes provide broad control over dynamic range, signal to noise ratio and detector smear.

The nominal revisit period for any point on the earth is 3 days within a 50^o field of regard (FOR). The FOR may be reduced, however depending on product requirements. For this work, the look angle was restricted to 15^o.

2.3.2 Fixed Targets: Edges targets that are constructed specifically for MTF measurements are generally preferred for analysis. One such target has been constructed at the John C. Stennis Space Center. The target is of sufficient size to measure MTF of imaging systems with GSDs of 1 meter or less. Each painted edge is 20 m long by 20 m wide. An OV-3 image of the MTF target range is shown in Figure 5. Observe that two targets are available for along scan and cross scan measurements in a single acquisition.

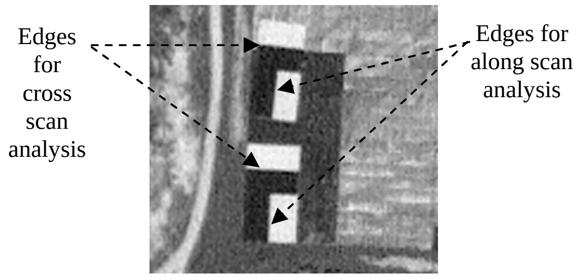

Figure 5. Edge targets at Stennis Space Center

2.3.3 Urban Edges: Imaging opportunities for fixed targets are limited, particularly as near-nadir acquisitions are desired to reduce atmospheric effects. With careful selection, suitable edges can be found in urban areas. This allows many more edge samples to be used in the analysis. Measurements from individual edges are combined using a weighted least squares approach. This provides a straightforward way of including measurements from different target types. An OV-3 image of a building edge used for MTF measurement is shown in Figure 6. The ESF from this edge is presented in Figure 2.

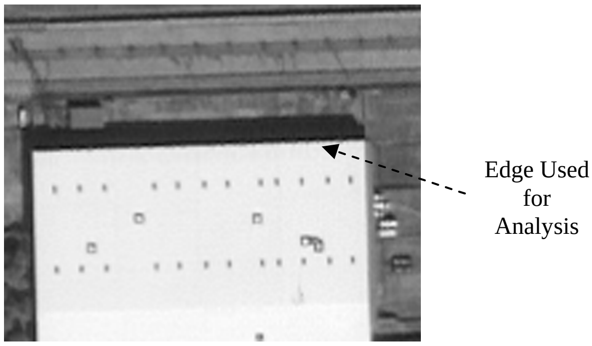

Figure 6. Building edge for MTF analysis

3. RESULTS

One dimensional MTF estimates are provided for the panchromatic band in the along scan and cross scan directions. MTF was calculated on the Basic image product, which is an 11 bit, satellite geometry image. In general, a nominal sharpening or Modulation Transfer Function Compensation (MTFC) is applied to the image data prior to delivery. Results are presented both with and without sharpening applied for more direct comparisons to other imaging systems.

A total of 36 edges were used for the MTF analysis presented here. Eighteen edges were used for cross scan measurement, with 6 edges being fixed, painted targets and 12 edges from urban scenes. Eighteen edges were used for along scan measurements as well with 6 edges from painted targets and 12 edges from urban scenes. The 18 MTF estimates were combined into an overall estimate for the cross scan or along scan component via a weighted least squares with the weights being set to the reciprocal of the variance estimate for each individual measurements. All error estimates presented in this section are 1σ values. Along scan MTF results are presented in Figure 7; cross scan MTF results are presented in Figure 8.

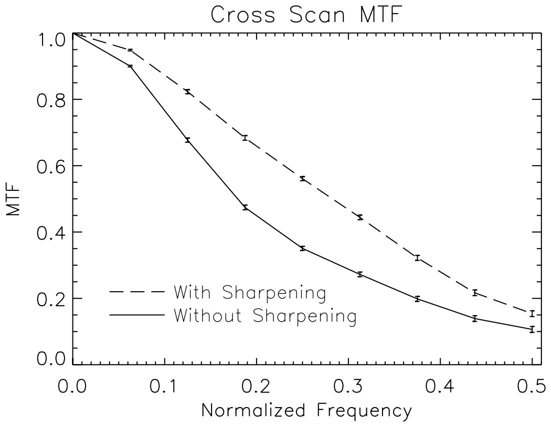

Figure 7. OV-3 panchromatic cross scan MTF estimate

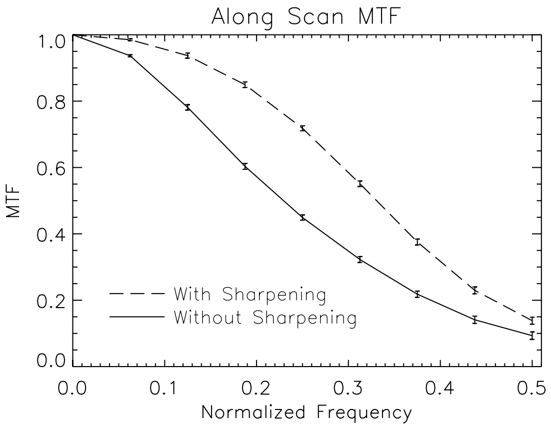

Figure 8. OV-3 panchromatic along scan MTF estimate

The MTF of imaging systems are frequently specified by the MTF value at the Nyquist frequency, where the along scan and cross scan components are averaged. For OV-3 imagery without sharpening, the overall Nyquist MTF was measured as 0.10 ± 0.01. With the nominal sharpening applied to the imagery, the overall Nyquist NTF was measured as 0.15 ± 0.01.

Individual MTF measurements at the Nyquist frequency for the cross scan and along scan components are presented in Figure 9. The Nyquist MTF measurement samples are ordered such that the fixed target edges and urban edges are grouped together. The overall data point on the graph is the weighted least squares of all the fixed target and urban edge measurements, with the dashed horizontal line indicating the overall mean value for reference.

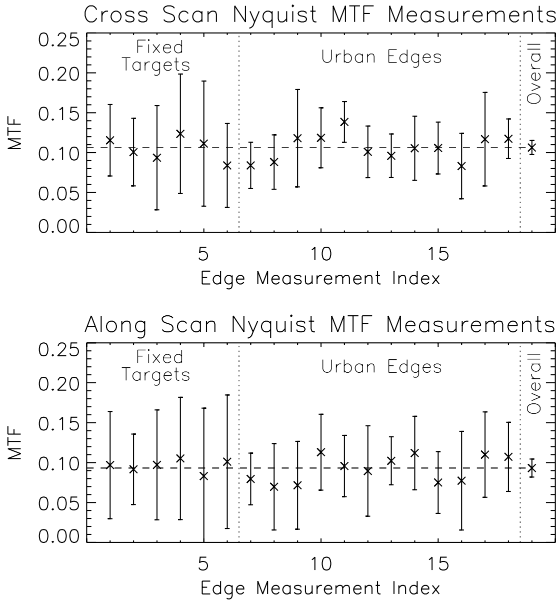

Figure 9. OV-3 cross scan and along scan Nyquist MTF measurement samples

4. DISCUSSION

Consistent results were obtained across the range of edges used for analysis. This is demonstrated by the Nyquist MTF values presented in Figure 9. Significant overlap in the 1σ confidence intervals is observed. Note also that the confidence in the urban edges, as derived from the simulated edge experiment, is higher than for the fixed targets. This is primarily driven by the line length of the edges used. Even though the edge contrast was typically less for the urban edges used in this analysis compared to the fixed targets, the urban edges were much longer, which decreased the error estimate.

The Nyquist MTF for the unsharpened panchromatic band of 0.10 ± 0.01 provides a balance between aliasing in the imagery due to high MTF and poor image sharpness due to low MTF. The sharpening processing that is applied to the imagery provides a modest boost in sharpness while not introducing objectionable artifacts.

Ultimately, MTF is one component in characterizing the overall image quality performance of an imaging system. Other components include signal to noise ratio and radiometric accuracy. These parameters for the OV-3 sensor are published in the literature (Kohm, 2004) and must be considered in determining overall image quality and comparing quality metrics between different sensors.

5. CONCLUSIONS

A robust method for estimating the MTF of high resolution remote sensing systems is presented. Error estimates for each measurement point are determined using simulations of edges with a wide range of characteristics. Along scan and cross scan MTF results for the OrbView-3 panchromatic sensor are provided for both unsharpened and sharpened image products.

REFERENCES

Cleveland, W., 1985. *The Elements of Graphing Data*. Wadsworth, Belmont, CA, USA.

Jain, A., 1989. *Fundamentals of Digital Image Processing*. Prentice Hall, Englewood Cliffs, NJ, USA.

Kohm, K. and Tira, N. (2004). On-orbit image quality and radiometric accuracy characterization of the OrbView-3 High Resolution Imaging Satellite. Accepted for publication in *Proceedings of the ASPRS 2004 Annual Conference*, May 23-28, 2004.

Mandel, J., 1964. *The Statistical Analysis of Experimental Data*. Interscience, New York.

Reichenbach, S., Park, S. and Narayanswamy, R., 1991. Characterizing digital image acquisition devices. *Optical Engineering*. 30(2), pp 170- 177.

Schott, J., 1997. *Remote Sensing: The Image Chain Approach*. Oxford University Press, New York.

Schowengerdt, R., Archwamety, C. and Wrigley, R., Landsat Thematic Mapper image-derived MTF. *Photogrammetric Engineering and Remote Sensing,* 51(9), pp 1395-1406.

Tatian, B., 1965. Method for obtaining the transfer function from the edge response function. *Journal of the Optical Society of America*. 55(8), pp 1014-1019.

ACKNOWLEDGEMENTS

The author would like to thank Vicki Zanoni of NASA Earth Science Applications Directorate at John C. Stennis Space Center for coordination of the use of the high contrast edge targets.