SOUTH DAKOTA STATE UNIVERSITY

EE 792: OPTICAL SENSORS

Modulation Transfer Function Estimation of IKONOS and QucikBird Imaging System using Edge Target

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1. Introduction

A Modulation Transfer Function (MTF) is a measure of how well an imaging system can transfer contrast from an object to its image, essentially indicating how well fine details are preserved in the image. When optical designers evaluate the performance of optical systems, they often rely on the MTF. The MTF serves as a key design specification and quality metric for imaging systems, frequently applied in remote sensing. The term "Modulation" refers to variations in the widths and spacing of the target, while "Transfer" represents the imaging system's capacity to capture and reproduce these variations in the resulting image, effectively transferring details from the target to the image. By comparing the MTF curves of different optical systems, one can determine which optical systems will best preserve fine details and produce a sharper image. A higher MTF value at a given spatial frequency means better contrast transfer, indicating better image quality. Lens aberrations, diffraction, and sensor limitations can all contribute to a decrease in MTF at higher spatial frequencies.

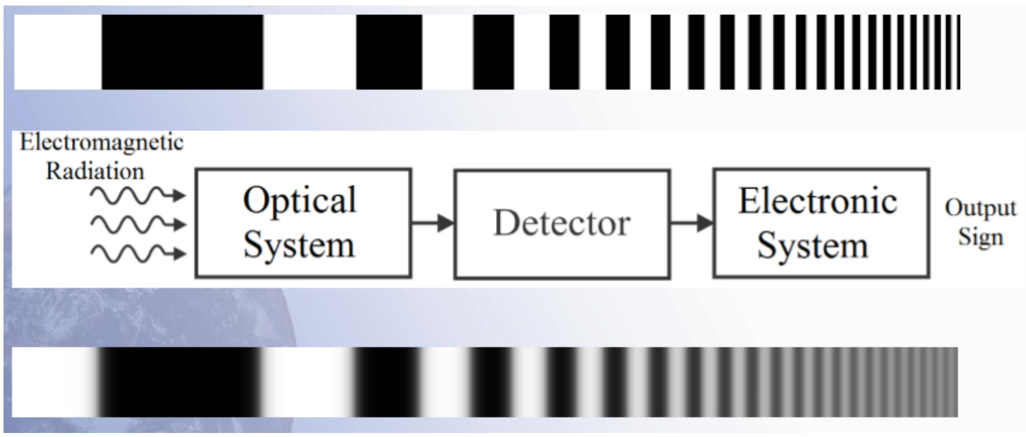
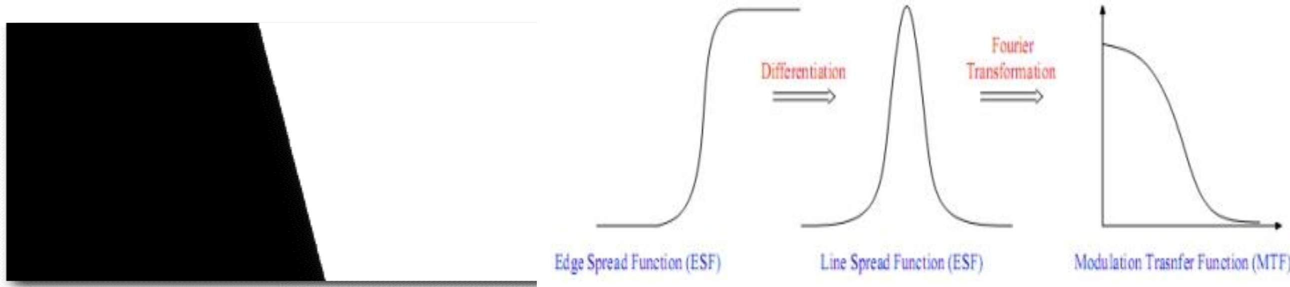


Figure 1: Modulation Transfer Function

2. MTF Estimation Using Edge Targets

Various methods have been developed to measure the spatial response of optical sensors in orbit, generally categorized based on the type of target used: Edge Targets, Point Targets, Line Targets and Pulse Targets. Among these, edge targets are the most widely utilized type of on-orbit targets, as both man-made and natural objects can be identified as suitable edge targets. The edge targets must be highly uniform on either side of the edge to minimize inherent noise within the physical edge and the target edge must also be extremely straight to ensure that the resulting ESF is indicative of the sensing system and not the physical target being imaged.



(a) (b)

Figure 2: a) A Typical Edge Target [1]. b) MTF Estimation using Edge Target [2]

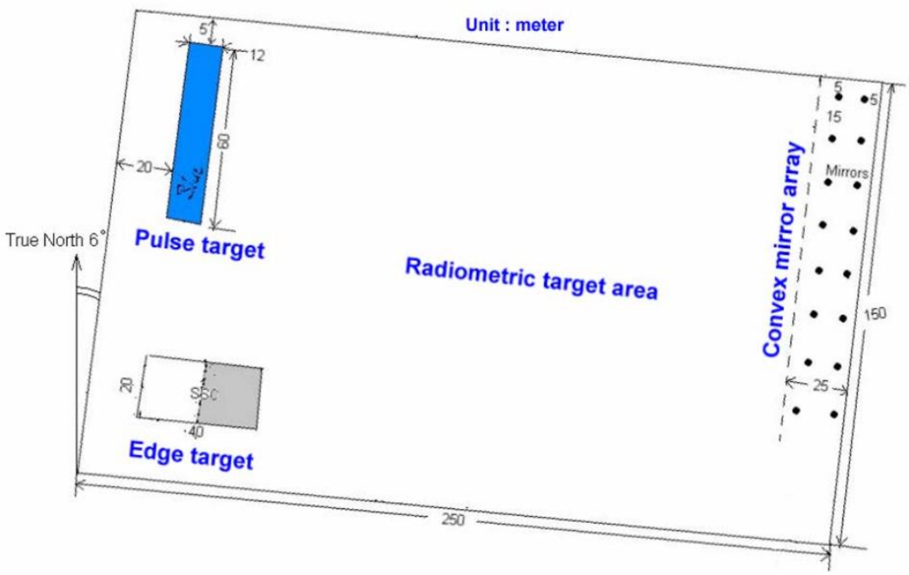


Figure 3: Field Plan of Different MTF Targets at 3M Site, Brookings, South Dakota [3]

3. Objective

The objective of this project is to use an edge target located at Brookings, South Dakota (as shown in Fig. 3) for the MTF estimation of IKONOS and QucikBird imaging systems and be familiar with different steps needed in the estimation of MTF.

4. Project Methodology

Figure 4 shows the methodology employed in the project. At first the ROI was selected, then the pixels was plotted for each rows and data was fitted using spline interpolation. After this, the column was shifted through the determination of transition point and Edge Spread Function (ESF) was generated. After this, modified Savitzky-Golay (MSG) filter was applied to ESF to differentiate it and obtain the Line Spread Function (LSF). Finally the Fast Fourier Transform (FFT) was applied to LSF to obtain the Modulation Transfer Function (MTF). Each of the steps of the methodology is described in detail in the following sections by taking IKONOS Panchromatic Band Image as a reference.

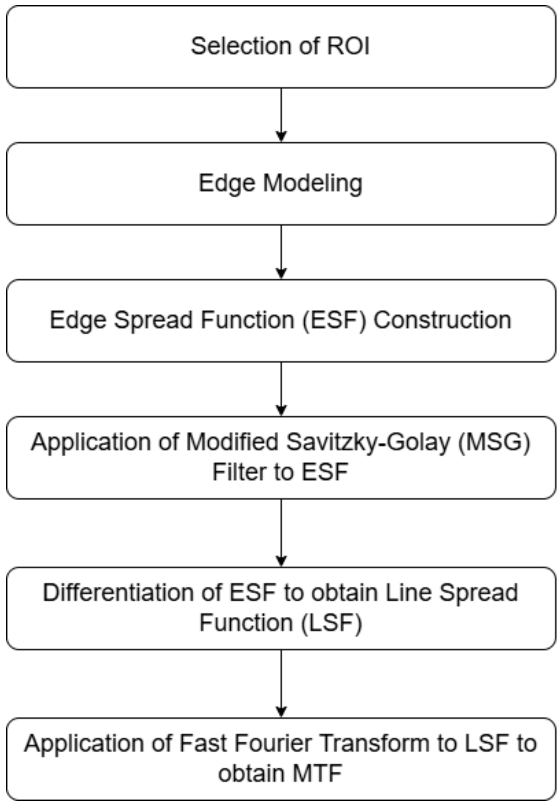


Figure 4: Project Methodology

4.1 Selection of ROI

At first, rectangular region of interest (ROI) over the edge target was selected as shown in Figure 5 and Figure 6. IKONOS Panchromatic band had 13 rows and 39 columns in its ROI.

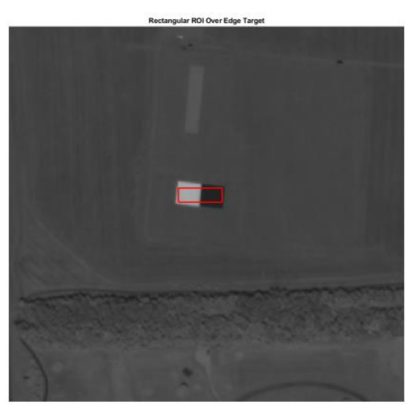


Figure 5: Rectangular ROI for IKONOS Panchromatic Band

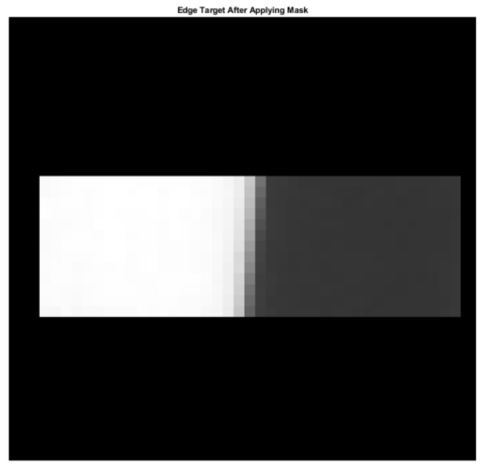


Figure 6: ROI after Applying Binary Mask to IKONOS Panchromatic Band

4.2 Edge Modeling

The digital number (DN) of each pixel for each row was plotted to generate the edge spread profile (Figure 7). The pixel values were not aligned with each other as can be seen in the plot below since the edge location in each image row were not known with the sub-pixel accuracy. In order to achieve the sub-pixel accuarcy, spline function was fitted to each row and the sub-pixel edge location in each row was determined through it.

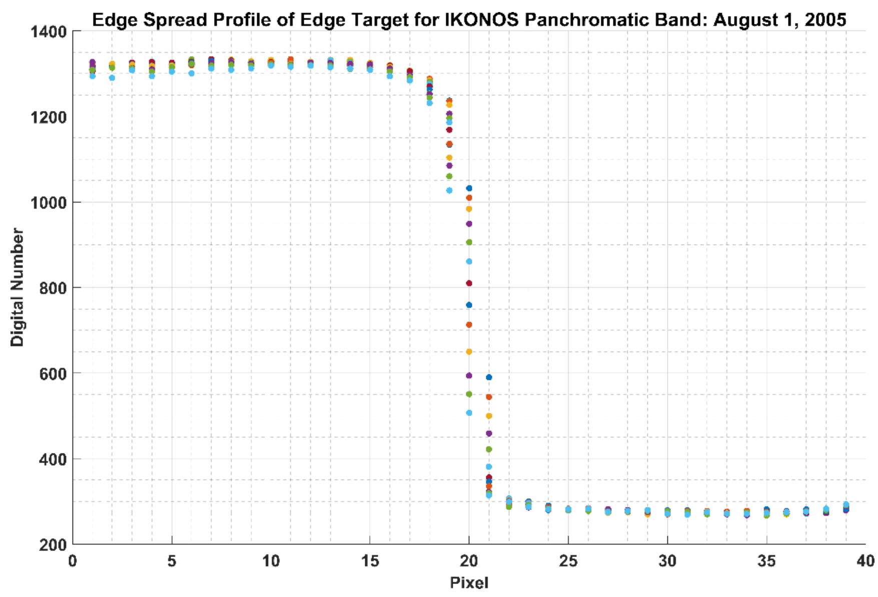


Figure 7: Edge Spread Profile of IKONOS Panchromatic Band

After determining the edge location for each row, a linear function was fitted across all the rows to obtain more accurate model describing the sub-pixel location of the edge as shown in Figure 8.

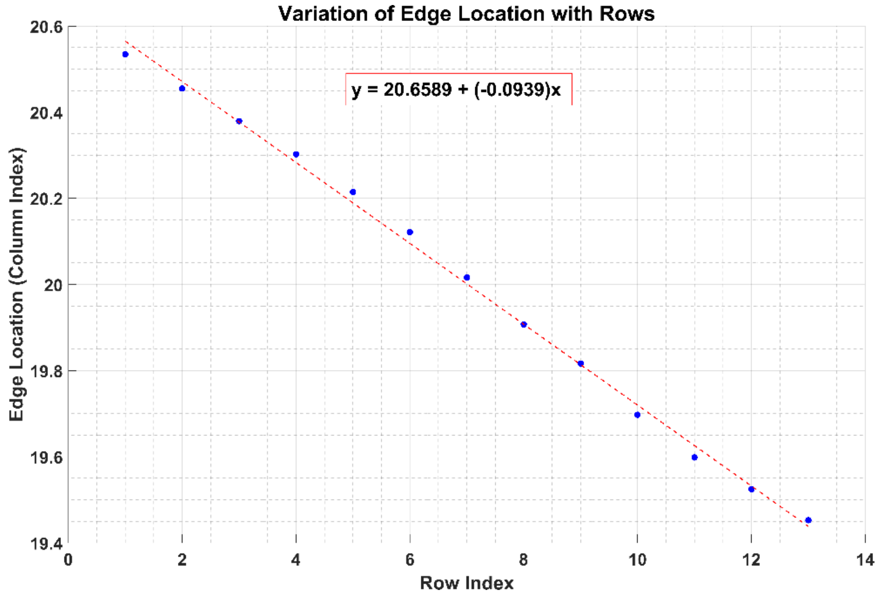


Figure 8: Edge Modeling using Linear Function for IKONOS Panchromatic Band

4.3 Edge Spread Function (ESF) Construction

Constructing the ESF involves mapping the 2-D image intensity values i(x,y) onto a 1-D representation i(z). The magnitude of z represents the shortest distance from a pixel at coordinates (x,y) to the slanted edge. For each pixel the value z is calculated as:

$$z = [x - e(y)] \times cos\theta \ldots\ldots\ldots (1)$$

Where e(y) denotes the location of the edge in row y, as predicted by the edge model, and θ denotes the relative edge angle. The cosine factor transforms a distance measured along a row into a distance measured perpendicularly to the edge. Here, the value is θ was taken as 6 degree as can be seen in Figure 3. Thus, an oversampled ESF and non-uniform (irregularly spaced) ESF was constructed using equation (1) and shown in Figure 9.

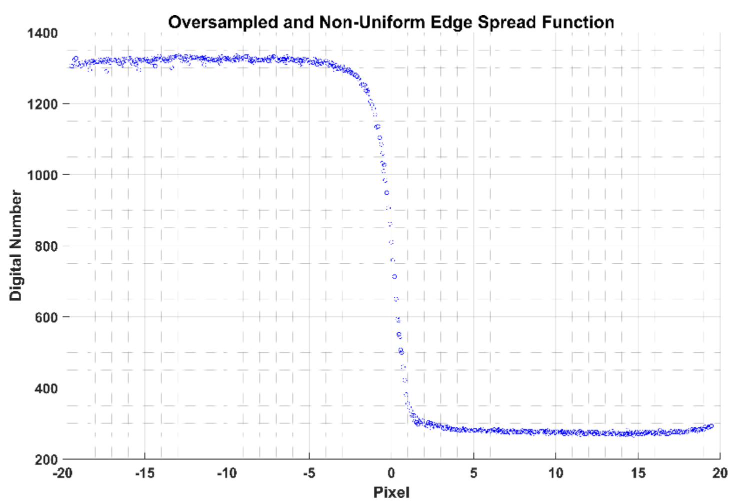


Figure 9: Oversampled and Non-Uniform ESF of IKONOS Panchromatic Band

4.4 Application of Modified Savitzky-Golay (MSG) to ESF

The oversampled ESF filtered to reduce high frequency noise and resampled to obtain the uniformly spaced samples using a modified Savitzky-Golay filter. The window was set to 2 pixels and the fourth-order polynomial was fitted to the data. Similarly, signal to noise ratio (SNR) was calculated by the ratio the edge height to the average of the standard deviations of the region on either side of the edge [4].

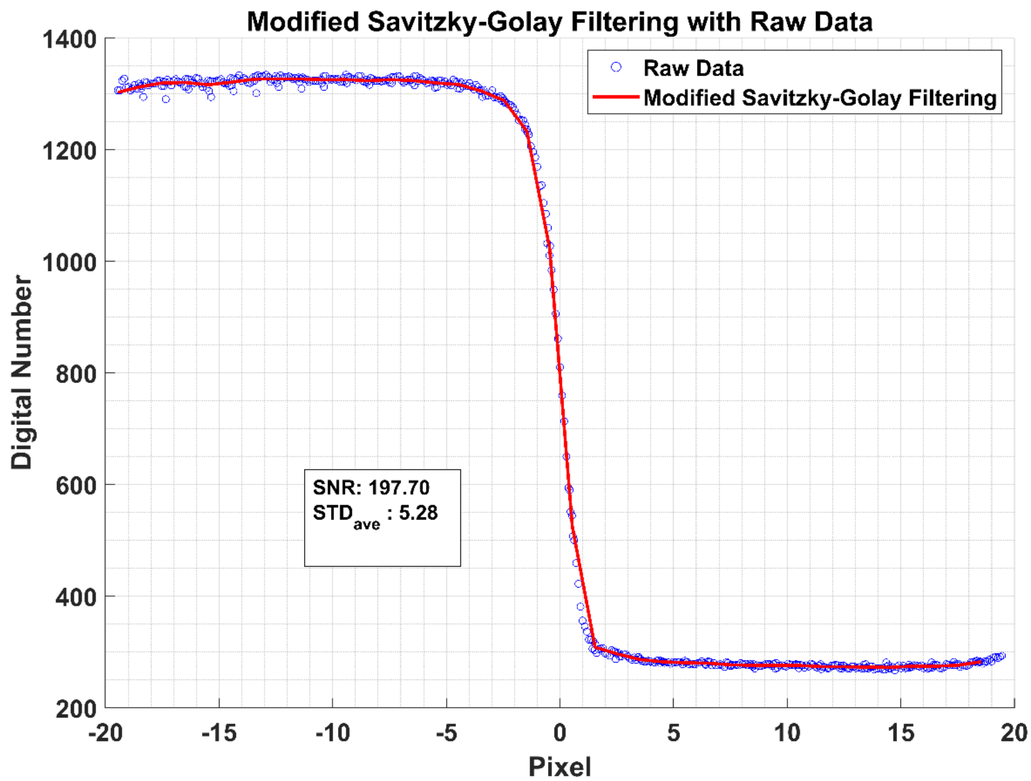


Figure 10: Modified Savitzky Golay Filtering of ESF for IKONOS Panchromatic Band

Figure 10 shows the plot of the raw (oversampled and irregular spaced) data and the data after application of MSG filter (uniformly spaced data).

4.5 Differentiation of ESF to Obtain Line Spread Function

The uniformly spaced ESF was converted to Line Spread Function (LSF) by computing the first order differencing approach. LSF was normalized using the min-max normalization which made the scaled value to range from 0 to 1. Figure 11 shows the normalized LSF of IKONOS Panchromatic Band with full width half maximum (FWHM) value of 1.745 pixels.

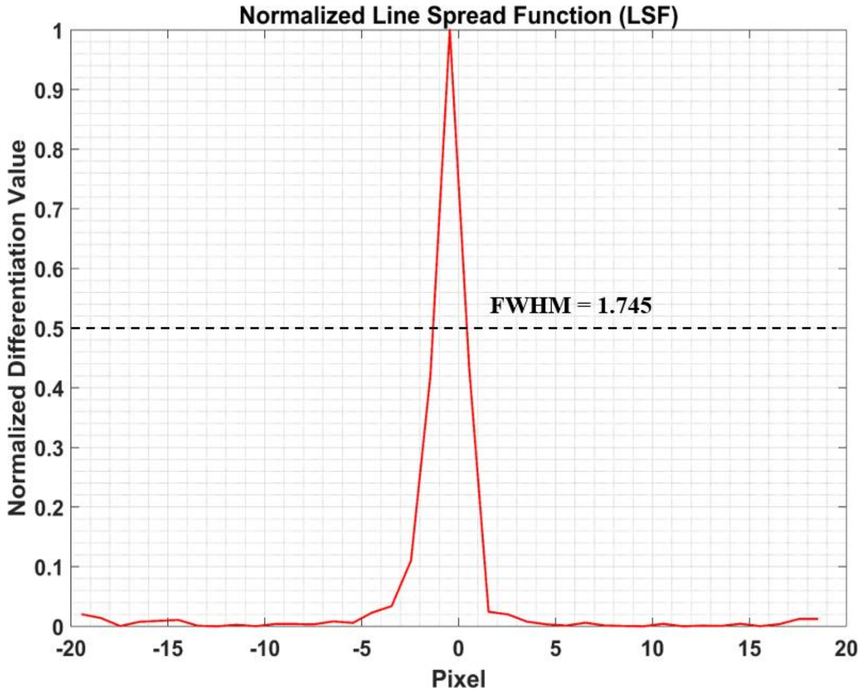


Figure 11: Normalized LSF of IKONOS Panchromatic Band

4.6 Application of Fast Fourier Transform to LSF to obtain MTF

Fast Fourier Transform (FFT) was applied to normalized LSF to obtain MTF. The MTF was normalized to the zeroth value which provided a relative measure of contrast transfer across frequencies. The frequency axis was also normalized based on the number of points in FFT and oversampling factor (which was set to 1 in our case). The corresponding MTF values at Nyquist frequency (the frequency after which aliasing occurs) was also calculated.

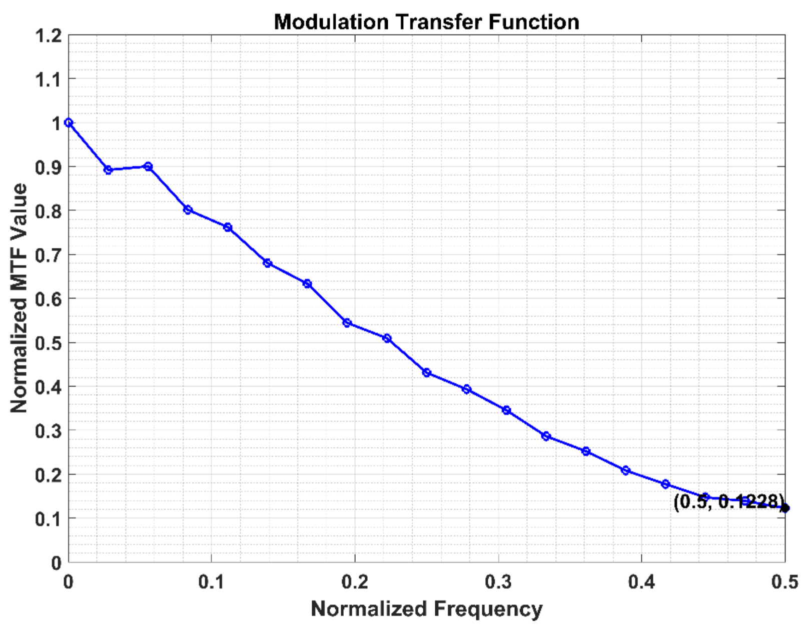


Figure 12: MTF of IKONOS Panchromatic Band

Figure 12 shows the plot of the resulting MTF at Nyquist frequency (or 0.5 cycle/pixel) for IKONOS Panchromatic band using the edge target, MTF_{50} = 0.1228. It means the imaging system transfers only 12.28% of the original contrast at the Nyquist frequency—the highest spatial frequency it can sample—so fine details at that limit are reproduced with significantly reduced contrast in the image.

5. Results and Discussion

Each of the steps described above were implemented for panchromatic as well as multispectral bands (blue, green, red, and NIR) of IKONOS and QucikBird satellite. The plots and graphs for each satellite image bands are attached as a separate file along with this report as an APPENDIX. In this section, a summary of the obtained results is presented and discussed.

Table 1: Summary Results of IKONOS Imaging System

Band	FWHM	SNR	STD_{avg}	MTF at Nyquist
Panchromatic	1.745	197.70	5.28	0.1228
Blue	1.668	197.91	4.42	0.5351
Green	1.769	284.99	4.22	0.5085
Red	1.875	300.18	3.90	0.4643
NIR	1.948	337.22	3.07	0.4371

The blue band exhibits the highest spatial resolution with the lowest Full Width at Half Maximum (FWHM) of 1.668 and the highest Modulation Transfer Function (MTF) at Nyquist frequency of 0.5351, indicating superior detail preservation. However, it has a lower Signal-to-Noise Ratio (SNR) of 197.91 compared to longer wavelengths. As we move from blue to NIR bands, the FWHM increases to 1.948, indicating a decrease in spatial resolution, but the SNR significantly improves to 337.22, and the average standard deviation (STD_{avg}), representing noise levels, decreases to 3.07, enhancing image clarity. The panchromatic band strikes a balance with moderate spatial resolution (FWHM of 1.745) and SNR (197.70) but has higher noise levels (STD_{avg} of 5.28) and the lowest MTF at Nyquist (0.1228), suggesting reduced ability to transfer fine detail contrast. Overall, a trade-off between spatial resolution and signal quality across different spectral bands is illustrated in the above data: shorter wavelengths offer higher resolution and detail preservation but lower SNR, while longer wavelengths provide better signal quality and lower noise at the expense of spatial resolution.

Table 2: Summary Results of QuickBird Imaging System

Band	FWHM	SNR	STD_{avg}	MTF at Nyquist
Panchromatic	1.505	175.59	3.26	0.1828
Blue	1.500	96.70	3.94	0.2236
Green	1.380	89.22	7.18	0.2948
Red	1.357	81.02	6.23	0.3093
NIR	1.267	86.56	6.09	0.4215

The QuickBird imaging system's summary results indicate that the near-infrared (NIR) band offers the highest spatial resolution with the lowest Full Width at Half Maximum (FWHM) of 1.267 and the highest Modulation Transfer Function (MTF) at Nyquist frequency of 0.4215, signifying superior detail preservation. The panchromatic band, while having a slightly higher FWHM of 1.505, provides the highest Signal-to-Noise Ratio (SNR) of 175.59 and the lowest noise level (STD_{avg} of 3.26), reflecting excellent signal quality. The multispectral bands (blue, green, red) exhibit decreasing FWHM values from blue (1.500) to red (1.357), indicating improved spatial resolution across these bands, but they have lower SNRs and higher noise levels compared to the panchromatic band. Overall, the data reveal a trade-off between spatial resolution and signal quality: the NIR band excels in resolving fine details and preserving image sharpness, while the panchromatic band offers superior signal quality with minimal noise.

6. Conclusion

The project successfully demonstrated the estimation of the Modulation Transfer Function (MTF) for the IKONOS and QuickBird imaging systems using edge target at Brookings, South Dakota. By employing a systematic approach—spanning ROI selection, edge modeling, Edge Spread Function (ESF) construction, Line Spread Function (LSF) differentiation, and Fast Fourier Transform (FFT)—it quantified the imaging systems' ability to preserve detail and contrast. The results provided critical insights into the performance of different spectral bands, highlighting the trade-offs between FWHM and SNR. This project underscores the significance of MTF as a reliable metric for assessing and comparing imaging system capabilities.

References:

[1] Mitja, C., Escofet, J., Tacho, A., & Revuelta, R. (2011, November 31). Slanted Edge MTF Plugin. ImageJ. Retrieved November 18, 2024, from https://imagej.net/ij/plugins/se-mtf/index.html

[2] Crespi, Mattia & De Vendictis, Laura. (2009). A Procedure for High Resolution Satellite Imagery Quality Assessment. Sensors (Basel, Switzerland). 9. 3289-313. 10.3390/s90503289.

[3] Helder, D., Choi, J., & Anderson, C. (2006, March 15). On-orbit Modulation Transfer Function (MTF) Measurements for IKONOS and QuickBird. Civil Commercial Imagery Evaluation Workshop. Image Processing Laboratory, Electrical Engineering and Computer Science Department, South Dakota State University. Retrieved November 15, 2024, from https://core.ac.uk/reader/42754680

[4] Françoise Viallefont-Robinet, Dennis Helder, Renaud Fraisse, Amy Newbury, Frans van den Bergh, DongHan Lee, and Sébastien Saunier, "Comparison of MTF measurements using edge method: towards reference data set," Opt. Express 26, 33625-33648 (2018)