Effects of slant angle and illumination angle on MTF estimations

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Abstract. Modulation Transfer Function (MTF) is a measure of the spatial resolution of an optical imaging system. For Earth Observation (EO) imaging systems in space, continuous MTF assessment is crucial for data quality. Several techniques of measuring MTF exist and some are still in development. MTF assessment techniques include the use of slanted knife-edge targets, point source techniques that make use of convex mirrors or xenon lamps and pulse methods that use linear features such as bridges. All these techniques have been successfully used to assess the MTF of imaging systems aboard the Ikonos, Landsat and QuickBird satellites. Laboratory experiments were conducted to evaluate the effect of slant angle of the knife-edge target and the effect of light illumination angle on the MTF result. MTF results were computed using a standard method according to ISO 12233. This paper will report the results of these laboratory experiments.

1. Introduction

The image quality of earth observation satellites strongly depends on the Modulation Transfer Function (MTF) of the system. Practically, MTF is a metric quantifying the sharpness of the reconstructed image. By definition, MTF is the normalized magnitude of the Fourier Transform of the system Point Spread Function (PSF) [1] as shown in Equation (1). PSF is the system response to a point source. In order to comply with the (ISO) standard, MTF is measured at Nyquist frequency [3]. Nyquist frequency is half of the sampling rate of a signal.

$$MTF = \left| \mathcal{F}\{PSF(x,y)\} \right| \tag{1}$$

The development process of a satellite system incorporates testing and calibration before the satellite is launched into space. The Modulation Transfer Function (MTF) of an imaging system of a satellite is one of the characteristics that are assessed before the satellite is launched into orbit. However, the vigorous nature of launch and the effects of space such as high radiation and extreme temperatures may alter the characteristics of the imaging system including MTF. Hence the MTF of an imaging system must be continuously characterized on-orbit [2].

Multiple methods have been used to determine the MTF of earth observation satellite imagers. These include the use of knife-edge (shown in Figure 1 and Figure 2) [3], pulse (lines) and point source (spot lights and convex mirrors) targets [4]. The use of knife-edge targets is one the most commonly used methods [5]. When using the knife-edge approach, the first step is to determine the required geometry (size and orientation) of the knife-edge target. This is highly dependent on the spatial resolution and orbit of the satellite. The second step is to image the target on a clear day free of clouds. The third step is image processing.

Figure 1. A knife-edge target for measuring the MTF of satellite imaging systems.

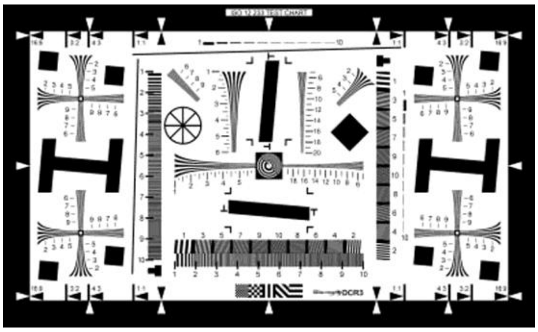

Figure 2. ISO 12233 chart for measuring the MTF of imaging systems.

Image processing steps involve detecting the edge in order to compute the Edge Spread Function (ESF). The ESF is the system response to a high contrast edge. The first derivative of the ESF generates the Line Spread Function (LSF), which is the system response to a high contrast line as shown in Figure 3. Quantitatively, the LSF is the 2-dimensional PSF integrated over one dimension and thereby reduced to a function of a single dimension [5]. The normalized magnitude of the Fourier Transform of the LSF produces the MTF of the imaging system.

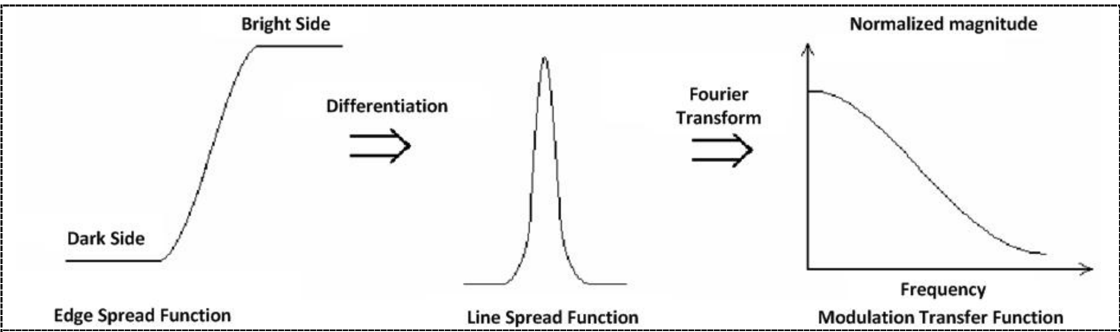

Figure 3. Computation of the Modulation Transfer Function using the knife-edge target.

2. Methodology

The objective of this study is to assess the effects of edge slant angle and illumination angle on the estimated MTF. To achieve this objective, two laboratory experiments were set up and these are explained in detail in the following subsections.

2.1. Effects of slant angle

A knife-edge test target was used to test the effects of varying edge slant angle on the estimated MTF. The laboratory arrangement of the knife-edge and camera is shown in Figure 4. The standard laboratory (fixed) fluorescent lamps were used as light sources. Images of the knife-edge target were captured while varying the inclination angle of the knife-edge target by rotating the target about an axis perpendicular to the target surface. Results of this experiment are shown in Figure 6 and Figure 7.

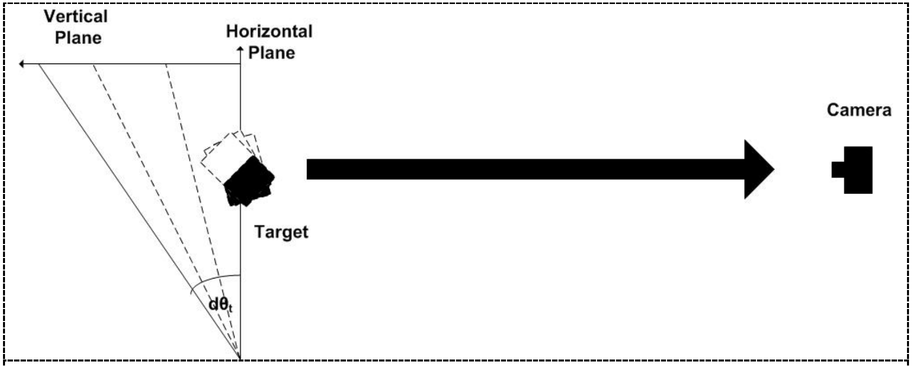

Figure 4. Setup for the experiment for evaluating the effect of varying the slant angle of the knife-edge target on estimated MTF.

The challenge of this experiment was that the operator manually changed the inclination angle. This may not introduce an uncertainty, but the change in slant angle d(θ) was not constant. It was also noted that the iris of the imaging system was in most cases adjusted during initial setup of each measurement. After each measurement, the knife-edge target was replaced with the ISO 12233 MTF target (shown in Figure 2) and its image was captured using the same camera and same laboratory settings.

2.2. Effects of illumination angle

In this setup, instead of fixed fluorescent lamps, a moveable lamp was used as a light source. Images of the fixed inclined knife-edge target were captured while varying the illumination angle of the light source. Figure 5 below, gives an illustration of the arrangement of the slanted knife-edge target, lamp and the camera. The results of this experiment are shown in Figure 7.

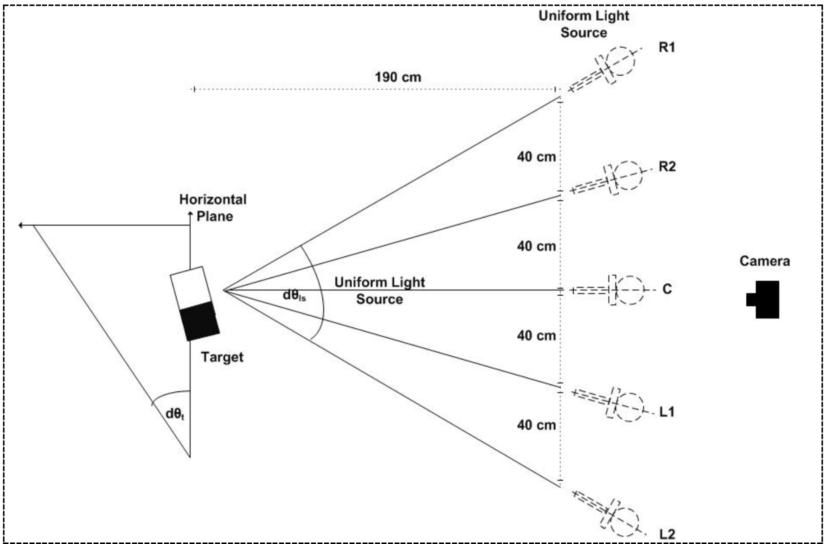

Figure 5. Setup for the experiment for evaluating the effects illumination angle on estimated MTF

The challenge for this laboratory set-up was the limitation of space, which limited the extent to which the illumination angle could be varied. The lamp was also moved manually and this might introduce an uncertainty since the pointing direction towards the target will be different each time the lamp is moved. Nonetheless, the distance between the light source and the target was considered small and therefore the effects of pointing were assumed negligible.

3. Results and discussions

This section gives a summary discussion of results. Plots shown in Figure 3 and Figure 4 below illustrate the relationship between the inclination angle the resulting MTF at Nyquist frequency. These plots illustrate that there is relationship between the inclination angle of the knife-edge target and the resulting MTF estimate at Nyquist frequency.

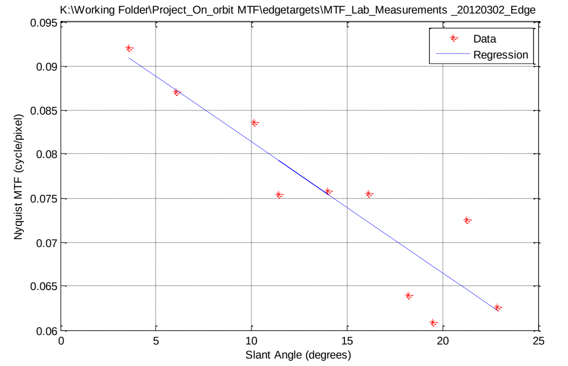

Figure 6. Regression of positive slant angle and MTF at Nyquist Frequency.

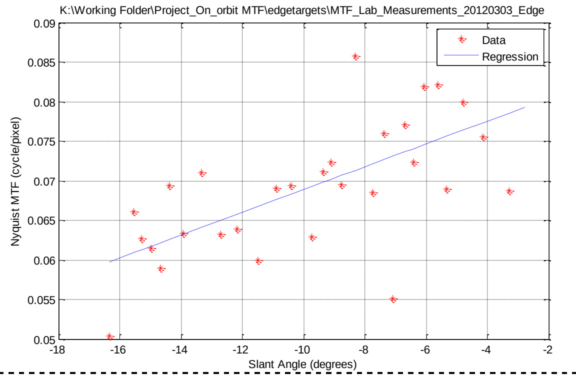

Figure 7. Regression of negative slant angle and MTF at Nyquist Frequency.

The relationship between the edge slant angle and MTF estimate was assumed linear and the derived regression equations from the plots in Figure 6 and Figure 7 are shown in equation(2) and equation(3) respectively. The reason for different regression equations could be attributed to different settings of the imaging system's iris. These plots show that as the slant angle moves away from perfect alignment with the pixel array, the estimated MTF at Nyquist frequency is reduced. Table 1 shows the MTF results of the ISO target that were used to verify the regression equations. The predicted Nyquist MTF values are within 5 % of the Nyquist MTF results yielded using ISO targets as shown in Table 1.

$$y = -0.0015x + 0.0962 \tag{2}$$

$$y = 0.0014x + 0.0833 \tag{3}$$

Table 1. ISO target Nyquist Frequency MTF.

Regression Equation	Correlation Coefficient	ISO Image Angle	ISO Image MTF at Nyquist Frequency	Predicted MTF at Nyquist Frequency	Percentage Error (%)
2	-0.914	-5.6625	0.0885	0.0878	0.7956
3	0.668	-4.8562	0.0794	0.0763	3.982

The plot shown in Figure 8 below displays the average Nyquist frequency MTF corresponding to different illumination angles. As illustrated in Figure 5, 'C' is the illumination at nadir (centre), 'L2' and 'R1' represent the illumination from the extremes (Left and Right) of the target. These results indicate that the estimated MTF at Nyquist frequency is highest when the illumination direction is orthogonal to the target and decreases as the light source is moved away from orthogonality.

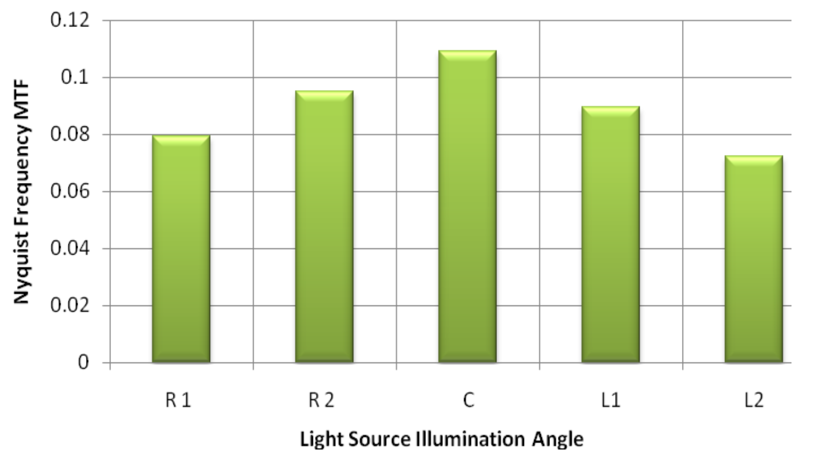

Figure 8. Light Source Angle and Average MTF at Nyquist Frequency.

Results obtained in both experiments are important for the study of system MTF. These results indicate that the estimated MTF of the same imaging system will be different when measured under different conditions.

4. Conclusions and recommendations

After analyzing the data, it was observed that lower absolute edge slant angles relative to the satellite cross-track direction tend to increase the estimate of the MTF at Nyquist and higher angles tend to decrease the estimate of the MTF at Nyquist. It was also observed that the MTF at Nyquist frequency is high (maximum) when the illumination angle is orthogonal. This means that the MTF at Nyquist frequency decreases as the angle of illumination diverges from orthogonality.

With reference to these observations it can be concluded that the angle of inclination and the illumination angle may add an uncertainty to the estimated MTF. The uncertainty was not quantified. However, the derived regression equations demonstrate this argument.

The recommendations are that the uncertainty due to the light source illumination angle imply that on-orbit MTF estimations must be done at consistent acquisition solar and sensor geometry and that any estimated MTF must be accompanied with information on the sun illumination angle and the inclination angle of the knife-edge target with respect system's sample grid.

The underlying mechanism resulting in these variations in the MTF estimate should also be investigated. Another effect worthy of investigation is the variation in the MTF estimate caused by edge targets that deviate from straightness.

References

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