ON-ORBIT MTF ESTIMATION METHODS FOR SATELLITE SENSORS

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ABSTRACT:

Modulation transfer function (MTF) is a standard measurement of imaging systems' geometric performance. Prior to flight, the MTF of satellite sensors is strictly measured in laboratory through various targets. However, it is important to estimate the MTF of satellite sensors during their life cycles to determine if any system degradations occur over time. Therefore, almost all satellite management organizations put much emphasis on MTF estimation and analysis. However, remote sensing data quality analysis and control in China is not emphasized until recent years. As part of Sky-To-Earth System of Systems, we systematically research MTF estimation methods and development on-orbit payload MTF test module. This paper first reports the principle of several widely-used on-orbit MTF estimation methods (including point source/array method, knife-edge method, pulse method, and bi-resolution method), their target deployment/selection standards, data processing steps, and their advantages and drawbacks. Then, we give an example of MTF estimation result using knife-edge method and pulse method.

1 INTRODUCTION

The spatial resolution of satellite-borne sensors is usually described by the Modulation Transfer Function (MTF), i.e. the Fourier Transform (FT) of the impulse response (system's response to an ideal point source or Point Spread Function (PSF)). Prior to flight, the MTF of satellite sensors is strictly measured in laboratory through various targets. However, this important parameter for image quality has to be checked on-orbit to be sure that launch vibrations, space condition when imaging, the performance variation of detectors and other components have not spoiled the sharpness of the images. Therefore, it is important to estimate the MTF of satellite sensors during their life cycles to determine if any system degradations occur over time.

Moreover, Remote sensing is complex information acquire process, and each step will introduce some degradation to the acquired image, including ground sampling, atmosphere scatter and absorption, remote sensors' effect (diffraction, aberrations, focusing error, charge diffusion, platform motion, et al), image transmission, ground image process, and so on. All these degradations' cumulative effect during image acquisition and transmission is described by system overall Modulation Transfer Function (MTF) which can be estimated from remote sensing imagery. Therefore, MTF is useful to make a deconvolution filter whose purpose is to enhance image contrast by ground processing.

There have many on-orbit MTF estimation methods been studied and implemented. Usually, we divide those methods into point source/array method, knife-edge method; pulse method according to their targets. Furthermore, if we can acquire image couples of the same landscape in the same or similar spectral band with two different spatial resolutions, the higher resolution image can stands for the landscape so that the ratio of the image spectra gives the lower resolution sensor MTF. This is so-called bi-resolution method. Thus, this paper introduces their target deployment/selection standards, data processing steps, and their advantages and drawbacks. Then, we give an example of MTF estimation result using knife-edge method and pulse method.

2 POINT SOURCE/ARRAY METHOD

2.1 The principle of point source/array method

For line position (space) invariant system, the image produced by image system $g(x,y)$ can be represented by the convolution of system response $PSF(x,y)$ and input scene $f(x,y)$, given by:

$$g(x,y) = f(x,y) * PSF(x,y) + n(x,y)$$

Where $n(x,y)$ is system introduced noise. According to Convolution Theorem, the equation can be expressed in frequency domain as:

$$G(u.v) = F(u,v) \cdot OTF(u,v) + N(u,v)$$

Where $G(u.v)$, $F(u,v)$, $OTF(u,v)$, $N(u,v)$ are the Fourier transform of $g(x,y)$, $f(x,y)$, $PSF(x,y)$, $n(x,y)$ respectively. According to optical theory, MTF is the modulus of OTF (called Optical Transfer Function).

Therefore, if we deploy a spotlight or convex properly, the system's response to the point source can be treated as Point Spread Function (PSF). However, limited by system's spacing interval, the imaging system's response to point source is undersampled, which leads to aliasing effects on the MTF when it is computed directly using Discrete Fourier Transform. The cheapest way to overcome aliasing problem is to use a model. Another widely-used way is to properly deploy an array of point source with different sample phase, and align these system's responses to a common reference according to the sample phase to get oversampled PSF.

Figure 1 illustrates that system's response to point source with different phase get quite different response (see a-d), aligning those responses according to peak locations gets oversampled 1-D system's response (see e).

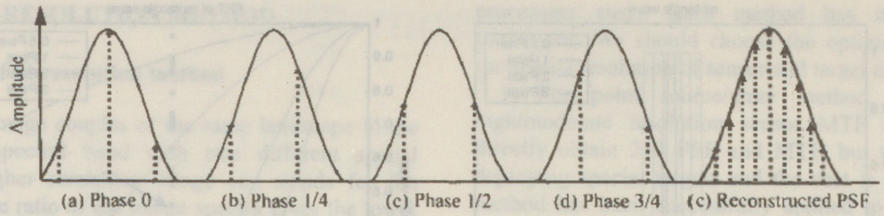

Fig 1 The reconstruction of oversampled PSF

2.2 Target deployment/selection standards for point source/array method

For point source method, the primary consideration is the at-sensor irradiance intensity. The following standards should be obeyed when deploy point source target:

1) Properly design the irradiance intensity to avoid the saturation of image system. Furthermore, to get enough contrast and SNR, the point source should be designed so that the peak sensor response is on the order of 75% of its dynamic range.

2) A complicating factor for point source method is that many high spatial resolution sensors are pointable. Therefore, it's better to use diffusion bodies or convexes as point sources.

For point array methods, besides the intensity of point sources, there are two major considerations need to be regarded:

1) The number of point sources should be as much as possible, which is restricted by the size of target, cost, etc. Experience indicates that 15-20 point sources can obtain reasonable result.

2) There must be enough distance between different point sources so that system's response to different point sources can't overlap. For many systems, the PSF does not extend over 3-GSI, thus, a minimum mirror separation of 5-GSI should be adequate.

Figure 2 gives an example of point array target. The point sources are diffusion bodies. There are total 16 point sources in a 4×4 arrange style. The distance between two nearest point sources is 5.25 pixels, and there are 0.25 pixels sample phase differences between two nearest point sources.

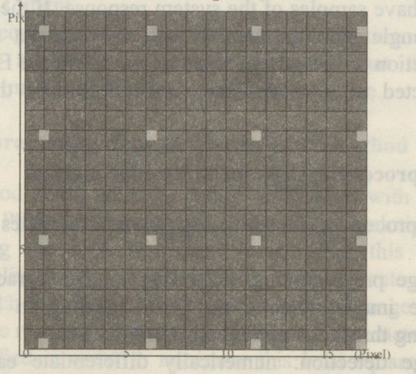

Fig 2 Point array target deploy example

2.3 Data processing steps for point array method

Usually, the data processing for point array method uses parametric approaches. The basic steps include:

1) Determines peak location of each point source data set to subpixel accuracy using a parametric two-dimensional model (Gaussian model).

2) The individual point source data sets are aligned along their model-estimated center positions to a common reference.

3) The 2-D model is applied again to estimate system's oversampled PSF.

4) A Fourier Transform is applied to the PSF and normalized to obtain the corresponding MTF.

3 PULSE METHOD

3.1 The principle of pulse method

Image system's response to ideal line is Line Spread Function (LSF), which is the integration of PSF in the direction perpendicular to the line. According to optical theory, the modulus of the Fourier Transform of LSF is corresponding 1-D MTF. However, it is impossible to get infinitely narrow line source. Thus, the Fourier Transform of LSF obtained from image should be corrected according to the width of input pulse. The approach divide the spectra of LSF obtained from image by the spectral of ideal square pulse with the same width to obtain corresponding MTF.

3.2 Target deployment/selection standards for pulse method

The target for pulse method should have the following characteristics:

1) Pulse target should consist of a uniformly bright region with two homogeneous dark regions. The boundaries between the bright and dark regions are straight edges.

2) The orientation of the pulse target must be maintained so that the oversampled pulse response can be obtained from imagery (about its principle see section 4.2).

3) The length of pulse target should be as long as possible, at least obtain several 'slices' of the PSF in the orthogonal direction.

4) The pulse target width must be designed carefully to place the zero-crossings at locations where the value of the MTF is not critical to evaluating system performance (especially not at Nyquist frequency).

When calculating system MTF, a Fourier Transform of the pulse response and ideal squre pulse function is required. Since the well-known Fourier Transform of a square pulse function is a sinc function, it is necessary to deal with zero-crossings. It is apparent that the width of pulse target should be as narrow as possible to avoid zero-crossings, say one GSI or less. However, the difficulty is that the strength of the signal received by the sensor from the narrow pulse width decreases linearly as the width of the pulse. As a result, the SNR is compromised and a good estimate can not be obtained. Practice has shown that a pulse width of 3-GSI is optimal for this type of target. With this width, a good tradeoff is reached between obtaining a strong signal and maintaining ample distance from placing a zero-crossing at the Nyquist frequency (see figure 3).

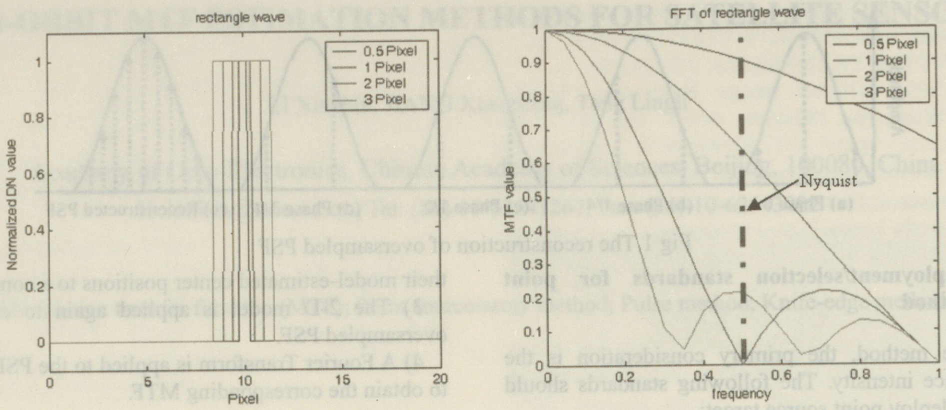

Fig 3 The relationship between the location of Nyquist frequency and pulse width

3.3 Data processing steps for pulse method

The data processing for pulse method includes following steps:

1) Image preprocessing: according to the characteristic of pulse image, remove the noise existing in pulse image using threshold method and median filter.

2) Edge detection: numerically differentiate each image profile to detect the location of maximum slope.

3) Least-square error fitting line for subpixel edge locations: It has been assumed that the subpixel edge locations should lie along a straight line. Therefore, all edge cross sections were forced to a straight line by perform a least squares fit.

4) Edge alignment: first interpolates the edge profiles to a subpixel interval, and then averages these image profiles after alignment according to edge location to obtain LSF.

5) Fourier Transform: calculates the Fourier Transform of trimmed LSF and generated ideal square pulse function.

6) MTF estimation: divide the Fourier Transform spectra of LSF by the Fourier Transform spectra of ideal square pulse function and normalized to obtain the corresponding MTF.

4 KNIFE-EDGE METHOD

4.1 The principle of knife-edge method

The response of system to ideal knife-edge is called Edge Response Function (ERF), which is the signal spreading along the direction perpendicular to the edge. The theory basis of knife-edge method is that the differentiation of ERF is LSF.

Suppose knife-edge can be express as:

$$f(x) = \begin{cases} 0 & \forall x < 0 \\ 1 & \forall x \geq 0 \end{cases}$$

Then, the output of system is:

$$g(x) = f(x) * LSF(x) = \int_{-\infty}^{+\infty} f(\tau) \cdot LSF(x-\tau) d\tau$$

Thus: $g(x) = \int_{0}^{+\infty} LSF(x-\tau) d\tau$

Assuming $t = x - \tau$, then $\tau = x - t$. Therefore:

$$g(x) = \int_{x}^{+\infty} LSF(t) d(x-\tau) = \int_{-\infty}^{x} LSF(t) dt$$

Where $g(x)$ is so-called $ERF(x)$. Thus:

$$ERF(x) = \int_{-\infty}^{x} LSF(t) dt$$

Equivalently:

$$LSF(x) = \frac{d[ERF(x)]}{dx}$$

In conclusion, the differentiation of ERF is LSF.

4.2 Target deployment/selection standards for knife-edge method

The target for knife-edge method should have the following characteristics:

1) A good edge target consists of a 'dark' or low-reflectance side, and a 'bright' or high-reflectance side. The high-reflectance side ideally has a reflectance level that provides a sensor response near the high end of its dynamic range; a rule of thumb is >75% of the dynamic range of the sensor. The dark side of the edge should be a reflectance level as low as possible, say less than 5%.

2) Because most high quality will not have a PSF that extends beyond a distance of a few GSI, a reasonable rule of thumb is that the target should extend 7-10GSI beyond the edge.

3) Edge target need to be well controlled in terms of homogeneity and contrast. The homogeneous regions should be uniform and isotropic, and the contrast across the edge must as large as possible. Simulations have shown that an SNR>50 is a reasonable lower threshold.

4) Often orientation becomes critical due to the imaging system being discrete. If the edge is parallel with the sample grid, no matter how long the edge is, only on a regular grid of locations have samples of the system response. If the target has a slight angle with the sample grid, we can get subsample reconstruction of the system response, and then the ERF can be reconstructed at a much finer resolution than the sample distance

4.3 Data processing steps for knife-edge method

The data processing for knife-edge method includes following steps:

1) Image preprocessing: according to the characteristic of knife-edge image, remove the noise existing in knife-edge image using threshold method and median filter.

2) Edge detection: numerically differentiate each image profile to detect the location of maximum slope.

3) Least-square error fitting line for subpixel edge locations: It has been assumed that the subpixel edge locations lie along a straight line. Therefore, all edge cross sections were forced to a straight line by perform a least squares fit.

4) Edge alignment: first interpolates the edge profiles to a subpixel interval, and then averages these image profiles after alignment according to edge location to obtain ERF.

5) LSF derivation: numerically differentiate ERF to obtain system's LSF.

6) MTF estimation: calculates the Fourier Transform of trimmed LSF and normalized to obtain the corresponding MTF.

5 BI-RESOLUTION METHOD

5.1 The principle of bi-resolution method

If we can acquire image couples of the same landscape in the same or similar spectral band with two different spatial resolutions, the higher resolution image can stands for the landscape so that the ratio of the image spectra gives the lower resolution sensor's MTF. Its theory basis is that the MTF of reference image is nearly 1 at the frequency of interest in low spatial resolution image and therefore is negligible.

$$estMTF_{Low}(u,v)=\frac{|image_{Low}(u,v)|}{|image_{Ref}(u,v)|}$$

$$=\frac{|scene(u,v)|MTF_{Low}(u,v)}{|scene(u,v)|MTF_{Ref}(u,v)} \quad (a)$$

$$=\frac{MTF_{Low}(u,v)}{MTF_{Ref}(u,v)} \quad (b)$$

$$\cong MTF_{Low}(u,v)$$

Where (u,v) are spatial frequency coordinates in units of cycles per pixel, $MTF_{Low}(u,v)$、$MTF_{Ref}(u,v)$ are MTF of low spatial resolution image and reference image respectively. $image_{Low}(u,v)$ is the spectra image of low spatial resolution image, which is the multiplication of the observed scene spectrum and MTF, $image_{Ref}(u,v)$ is the spectra image of reference image. Cancellation of term $|scene(u,v)|$ in equation (a) leads to equation (b). Because $MTF_{Ref}(u,v)$ is nearly 1, the ratio of the image spectra gives the lower resolution sensor MTF.

5.2 Target deployment/selection standards for bi-resolution method

There is no special requirement for bi-resolution MTF estimation method targets. However, to get ideal result, it's better to choose an image contain a variety of features, such as roads, shorelines, buildings, etc. that exhibit high spatial frequency content.

Another requirement is that the spatial resolution difference should be as much as possible to insure that the higher resolution image can stands for the true landscape.

5.3 Data processing steps for bi-resolution method

This method starts with the image simulation with an initial PSF, This PSF is to be sampled as the high resolution image. Convolving the high resolution image with this PSF and undersampling at the low resolution sampling rate yields an image which is compared to the low resolution image through a least square residual computation. The initial parameter value is then modified in order to minimize this least square residual, according to a classical least square minimization algorithm. The iterative process will end when the relative residual change between two iterations goes below a threshold level to be fixed by the user. Then, the PSF can be treated as the PSF of low resolution sensor. A Fourier Transform is applied to the PSF and normalized to obtain corresponding MTF.

6 ANALYSIS AND COMPARISON

We have introduced the principle of several widely-used on-orbit MTF estimation methods (including point source/array method, knife-edge method; pulse method, and bi-resolution method), their target deployment/selection standards, data processing steps. Each method has its applicability and limitations. We should choose the optimal method according the spatial resolution of sensor and target condition.

1) For point source/array method, it is suitable for high/moderate resolution sensor MTF estimation. We can directly obtain 2-D PSF and MTF, but this method requires deploying special targets and the cost is relatively high. This method has been successfully applied to MTF estimation of Landsat/TM、SPOT、Quickbird.

2) The target for knife-edge method is relatively easy to deploy or select. Very high SNR can be obtained leading to accurate MTF estimation. But for low resolution sensors, it is difficult to find a large enough target.

3) For low resolution sensors, pulse method is a good choice. While good results can be obtained, limiting factors including controlling background regions on either side of the pulse, avoiding zero-crossing when designing the target, and directly deriving the PSF.

4）Bi-resolution method requires acquiring image couples of the same landscape in the same or similar spectral band with two different spatial resolutions simultaneously. The data processing of this method is relatively complex, and it is sensitive to noise and aliasing.

7 EXAMPLE

In on-orbit MTF estimation module, knife-edge method and pulse method is the .primary MTF estimation methods. There we give an example of MTF estimation result of SPOT/Pan image using knife-edge method and pulse method.

7.1 Knife-edge method target and result

The targets used for knife-edge method is runway in Dalian airport. Three different targets are given in figure 4 and the MTF estimation results are shown in figure5.

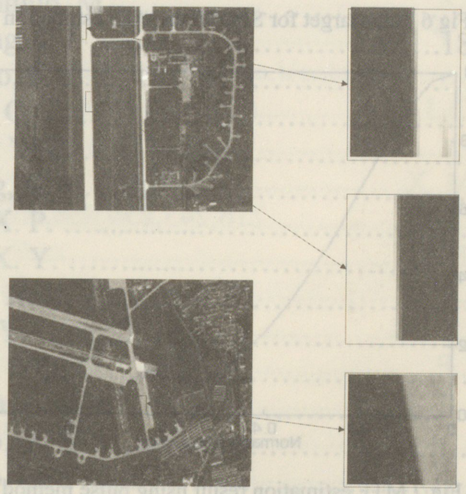

Fig 4 Three knife- edge targets for SPOT/Pan MTF estimation

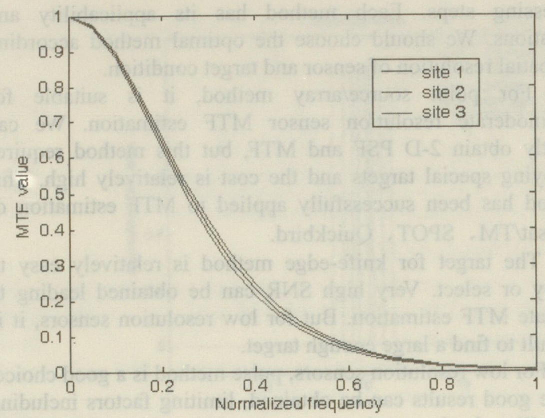

Fig 5 MTF estimation results using knife-edge method

It is clear that MTF estimation from three different targets obtain relatively consistent results. However, site 3 obtains lower MTF and the most error at Nyquist frequency is about 0.018, which may result from lower contrast and bigger slope.

7.2 Pulse method target and result

The target used for pulse method is a dam between different fish ponds in the same scene as knife-edge method. it is shown in figure 6 and MTF estimation result is shown in figure 7.

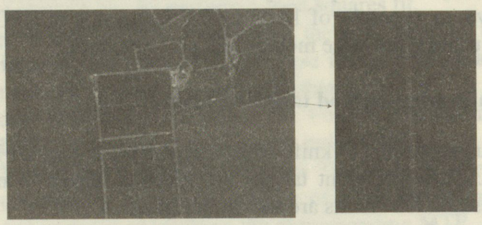

Fig 6 Pulse target for SPOT/Pan MTF estimation

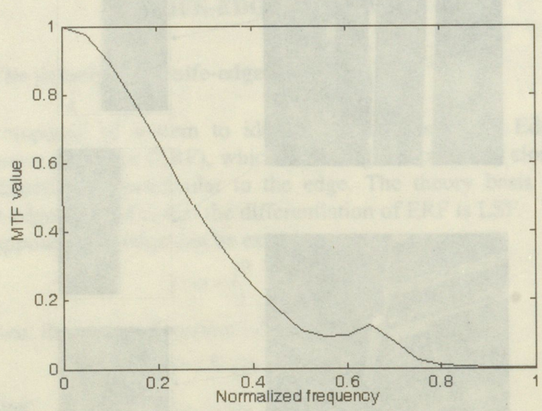

Fig 7 MTF estimation result using pulse method

Because the input pulse is about 1.5 pixels, the first zero-crossing is located at normalized frequency of 0.6, which leads to the bad result at $f_N = 0.6$.

7.3 Analysis

Figure 8 shows the relative difference between knife-edge and pulse method. The biggest error reaches to 0.085, but it is cause by zero-crossing. In other frequency domain, the biggest error is about 0.04, which indicate that the accuracy of MTF estimation methods is quite reasonable.

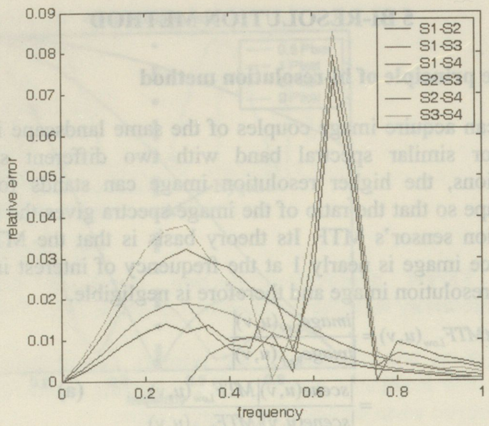

Fig 8 Error analysis result

8 CONCLUSION

Modulation transfer function (MTF) is a key measurement of imaging systems' geometric performance. It is not only an indicate the performance of imaging system, but also make a deconvolution filter whose purpose is to enhance image contrast by ground processing.

This paper systematically introduces the principle of several widely-used on-orbit MTF estimation methods (including point source/array method, knife-edge method; pulse method, and bi-resolution method), their target deployment/selection standards, data processing steps, and their advantages and drawbacks. We should choose the optimal method according the spatial resolution of sensor and target condition. We hope to accelerate the construction of remote sensing data quality analysis and assessment system with self-dominated intellectual property right through the studies and implementation of on-orbit MTF estimation.

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