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RESEARCH ARTICLE

MTF-Based Performance Comparison of Techniques for Deblurring Optical Satellite Imagery

Optik Uydu Görüntülerinde Bulanıklık Giderme Tekniklerinin MTF Tabanlı Performans Karşılaştırması

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Abstract
Blurring is a significant concern in electro-optical satellite imagery due to its negative effect on image quality, which is caused by an undesirable loss of bandwidth. Blurred images and compromised image quality may result from atmospheric distortions, camera aberrations, and relative motion during the imaging process. Deblurring is thus a process used to restore deteriorated images, reduce blur, and recover the original image. The major type of blur explored in this study is Gaussian blur, and its effects on the image are investigated by applying the blur in equal proportions. Furthermore, influence of blur on the Modulation Transfer Function (MTF) of an electro-optic satellite image as well as the impacts of deblurring techniques, namely the Richardson-Lucy Deconvolution Algorithm, the Regularization Filter, and the Blind Deconvolution Algorithm on MTF values, were explored.

Keywords: Optical Satellite Images, Deblurring, Gaussian Blur, MTF, Richardson-Lucy Deconvolution Algorithm, Regularization Filter, Blind Deconvolution Algorithm

Öz
Bulanıklık, istenmeyen bant genişliği kaybına görüntü kalitesinde düşüşe neden olduğu için elektro optik uydu görüntülerinde önemli bir sorundur. Görüntüleme işlemi sırasında atmosferik bozulmalar, kamera sapmaları ve göreceli hareketler, bulanık görüntülere neden olabilir ve görüntü kalitesini bozabilir. Bu nedenle bulanıklık giderme, bozulmuş görüntüleri düzeltmek, bulanıklığı azaltmak ve orijinal görüntüyü elde etmek için kullanılan bir işlemdir. Bu çalışmada incelenen başlıca bulanıklık türü Gauss bulanıklığıdır ve bulanıklığın eşit oranlarda elektro-optik uydudan alınmış bir görüntüye uygulanmasıyla Richardson-Lucy Ters Evrişim Algoritması, Düzenlileştirme Filtresi ve Kör Ters Evrişim Algoritması bulanıklık giderme yöntemlerinin başarımı ve etkinliği Modülasyon Aktarım Fonksiyonu (MTF) kullanılarak araştırılmıştır.

Anahtar Kelimeler: Optik Uydu Görüntüleri, Bulanıklık Giderme, Gauss Bulanıklığı, MTF, Richardson-Lucy Ters Evrişim Algoritması, Düzenlileştirme Filtresi, Kör Ters Evrişim Algoritması

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1. INTRODUCTION

The utilization of electro-optical (EO) satellites has experienced a significant rise in recent years, mostly driven by the needs of modern societies and recent advancements in technology. Satellites possess an essential role in various domains such as environmental monitoring, disaster monitoring, military intelligence, space exploration, and numerous other application fields due to their capacity to generate high-resolution images. Blurring of EO images can occur due to many causes that affect the optical capture of monitored objects. The presence of clarity concerns in these images is significant challenge in the analysis and interpretation of data, therefore rendering it a crucial matter that requires attention and resolution. The complexity of these images necessitates consideration of the criteria for their enhancement. The primary aim of this study is to thoroughly investigate the potential positive impacts of deblurring methods on the Modulation Transfer Function (MTF) value of EO satellite images.

A wide range of approaches are used in image enhancement techniques to accomplish objectives like enhancing contrast, decreasing noise, and enhancing image quality. In this paper, the EO imagine enhancement method was applied with particular filters. Care should be used while selecting filters to improve the quality of the outcomes. Using high-pass filters can be helpful, particularly when dealing with noise that contains low-frequency components. These filters are designed to block high-frequency components while passing low-frequency components through. However, low-pass filters might be more effective when dealing with high-frequency noise. These filters eliminate high-frequency components from the image, cleaning it up. As a result, selecting the appropriate filter is essential to improving images, and modifying its parameters properly for each unique application or kind of image is crucial.

Blind deconvolution and non-blind deconvolution are different methodologies employed in the field of image enhancement. Blind deconvolution filters are specifically developed to address scenarios in which the Point Spread Function (PSF) is not known a priori and requires estimation. The methodology employed in this procedure entails a systematic and repetitive approach. The estimation of the PSF is achieved by a series of iterative processes and mathematical computations [1]. In contrast, non-blind deconvolution serves the same objective but relies on predetermined parameters, such as the PSF. The PSF provides a comprehensive account of the image production process, which is subsequently utilized either directly or in combination with various algorithms and mathematical procedures to enhance the accuracy of estimations. This study chosen three filters, namely the Richardson-Lucy filter, the Regularization filter, and the Blind Deconvolution filter. The Lucy-Richardson technique, also known as Richardson-Lucy deconvolution, is an iterative method used to restore the original image that has been blurred by a known PSF [2]. The utilization of regularization techniques proves to be advantageous in scenarios when there exists a scarcity of information pertaining to the characteristics of noise. The restoration of the blurred and noisy image is achieved using a constrained least squares restoration technique, which incorporates a regularization filter [3].

MTF analyses are employed during the comparison of image enhancing techniques to assess the efficacy of various filters. Resolution is a measure of the level of detail and clarity present in an image. The MTF analysis used to evaluate the quality of an image by examining its performance over various spatial frequencies, often measured in line pairs per millimeter. Higher MTF values are indicative of superior resolution in an image. By doing MTF analysis for each technique, it is feasible to determine the relative efficacy of different methods in enhancing image resolution.

The paper's structure is outlined as follows: Section 2 provides a detailed explanation of the process of extracting MTF from electro-optical satellite images. The third section of the paper examines various deblurring techniques, such as the Richardson-Lucy Algorithm, Regularization Filter, and Blind Deconvolution. The deblurring studies and their corresponding findings are presented in Section 4, while the implications drawn from these experiments are discussed in Section 5.

2. MODULATION TRANSFER FUNCTION

Electro-optical imaging systems employ the utilization of light for the purpose of capturing and presenting visual representations. The MTF is utilized to assess the effectiveness of these systems. The MTF analysis offers valuable insights on the management of image contrast and detail inside the systems, as well as the preservation of image quality. The functioning of this system is based on an examination of the transmission and alteration of light frequencies. Optical systems employ frequency analysis principles to convert complex patterns into representations comprised of sinusoidal waveforms, enabling a more sophisticated approach in contrast to basic point-object representation. The sine wave targets serve as substitutes for dispersed reflecting elements that can be observed in typical ambient lighting conditions, thereby enhancing our understanding of the system's capacity to detect and replicate detailed characteristics. MTF is a crucial parameter used to assess the optical capabilities of a system across various spatial frequencies included in sinusoidal patterns. This crucial metric holds great importance in the present assessment. The primary focus of this representation is to illustrate the complex relationship between the modulation rate of the object and the modulation rate of the generated image, which are both measured in spatial frequency units [4].

Obtaining precise and accurate MTF measurements is critical for acquiring critical insights into system performance and playing an important role in the iterative development of imaging systems. The popular technique of determining the absolute MTF involves obtaining the Edge Spread Function (ESF) from the PSF and deriving the Line Spread Function (LSF) from the ESF. The ESF illustrates how light travels through the optical system, providing information on light intensity at image borders. The LSF governs how light intensity is spread across a line segment in an image, whereas the PSF is critical for representing image blurring. The MTF is frequently seen as a symmetrical function and is used in optical analysis. It is derived from Fourier Transform analysis of the PSF and is a useful tool for examining optical system distortions and limitations. This is critical for refining and enhancing imaging systems for improved performance across a wide range of applications [5].

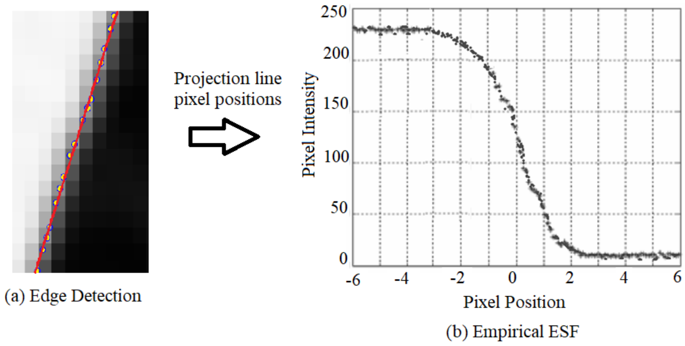


Figure 1. (a) Edge detection (b) Edge pixel projection to calculate empirical ESF.

The calculation of the MTF is performed in a methodical manner. The identification of an edge is accomplished through the process of scanning an image. Following that, the equation of the line intersecting the mentioned edge is calculated, as illustrated in Figure 1(a). Subsequently, the pixel intensity values of the empirical ESF are subjected to fitting with a mathematical function, often a sigmoid function, in order to get the ESF. Figure 2(a) depicts the ESF. The LSF is derived from the Edge Spread Function, as depicted in Figure 2(b). The MTF is subsequently determined by applying the resultant LSF to a Fast Fourier Transform (FFT), as illustrated in Figure 2(c). The utilization of this complex methodology is of utmost importance in the examination and understanding of the performance characteristics exhibited by optical systems. It facilitates the evaluation of their capacity to efficiently acquire and convey spatial frequency data.

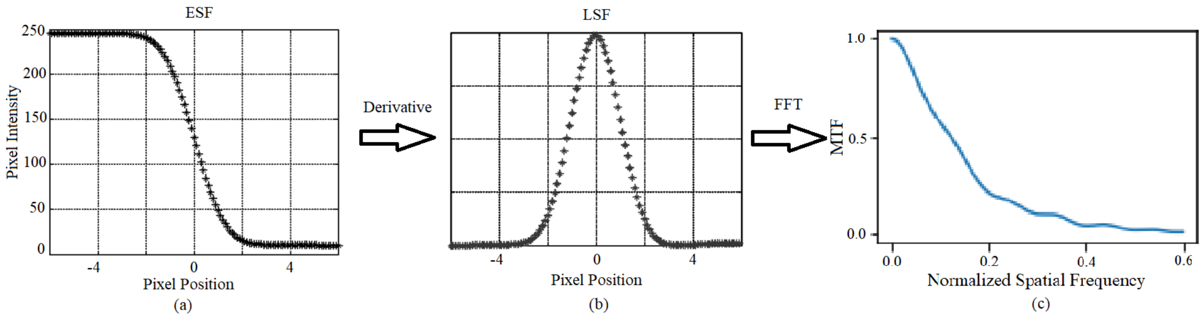


Figure 2. The entire processing chain and determination of MTF (a) ESF (b) LSF (c) MTF.

The MTF by use of the Fourier Transform of the LSF involves a series of steps depicted in Figures 1 and 2. The precision of the MTF is dependent upon various factors, including as the quality of imaging, levels of noise, and the configuration of the system. Therefore, it is essential to implement appropriate image processing techniques and calibration protocols to ensure the accuracy of the calculation of MTF [6].

The process of imagine deblurring plays a crucial role in increasing the sharpness of an image by mitigating the adverse effects of blurring, hence potentially improving the MTF.

There are several deblurring methods that have proven to be beneficial in the field. These techniques include the Richardson-Lucy algorithm, Regularization Filters, and Blind Deconvolution. Each of these algorithms plays a significant role in improving the estimation of MTF and enhancing the overall quality of images in optical systems.

3. DEBLURRING METHODS

Satellite imagery may exhibit imperfections as a result of constraints imposed by equipment and environmental factors during the acquisition process. Nevertheless, during the 1950s and 1960s, researchers made significant advancements in the field of digital image restoration to tackle these challenges and improve the overall quality of images. The primary objective of this procedure is to generate images that closely match the original. Deconvolution, a commonly employed technique, is utilized for the restoration of images afflicted with uniform spatial blurring [7]. The efficacy of image restoration is influenced by a multitude of elements, such as blur and noise, which can be mitigated through various methodologies.

Various strategies are utilized in the field of image processing to address the issue of image blurring. Among these techniques, non-blind and blind deconvolution are two distinct types of methods employed for this purpose.

3.1 Non-Blind Deconvolution

The Richardson-Lucy technique demonstrates its advantages when employed in conjunction with linear time-variant filtering. This technique facilitates the estimation of a desired stochastic process from a noisy image. However, it is imperative to have a thorough understanding of the parameters of the point-spread function before implementing this strategy. The primary focus of this function pertains to the dispersion of a point source inside an image, which can be influenced by various factors like weather conditions and optical limitations [8].

The Richardson-Lucy approach has demonstrated significant effectiveness in scenarios characterized by the presence of image blurring and noise, particularly in the context of image improvement within domains such as astronomy. One notable benefit of this technique is its ability to effectively enhance deteriorated images caused by several sources, employing an iterative approach that progressively refines the estimation of the original image. The methodology is especially suitable for the analysis of satellite imagery [9].

While this approach proves to be advantageous, it is important to acknowledge its inherent limits. These factors are primarily associated with the frequency of successful execution. Determining the optimal termination point for image processing poses a significant challenge in achieving the desired outcomes. Insufficient processing poses the risk of losing crucial details, while excessive processing might lead to visual inaccuracies.

The Richardson-Lucy deconvolution method is a widely used and effective technique that is frequently deployed in the field of image restoration. In comparison to linear inverse filtering methods, the utilization of a nonlinear iterative approach frequently yields more favorable results, rendering it particularly advantageous in the context of image quality enhancement. The operation of this system involves the maximization of the probability of observing a noisy image, $Pr\ (g|f)$, where g represents the observed image and f represents the estimation of the true underlying image [10]. The application of the Richardson-Lucy technique regularly improves the quality of the recovered image.

The iterative Richardson-Lucy deconvolution method uses a filter to estimate the true image, *f*. The efficacy of the method is dependent upon the number of iterations, *k*. The iterative procedure concludes when the algorithm achieves a desirable result. The task of determining the most suitable number of iterations might present difficulties and consume a significant amount of time, primarily due to the distinct attributes of the image and the extent of degradation it has undergone. The task of establishing a balance between preserving crucial image data and reducing image noise is a complex optimization problem that often requires expertise in the field and an iterative methodology [11].

One of the aims of this study is to provide a thorough examination of the Richardson-Lucy algorithm and its utilization in the context of image restoration. The study also aims to evaluate the MTF results of filtered and unfiltered images, specifically focusing on determining the effectiveness of the Richardson-Lucy method in restoring images suffering by various types of distortion and its impact on MTF.

Regularization is a well-known non-blind imagine restoration deconvolution method. It entails adding restrictions to a minimization problem to improve the quality of the restored image. This method is especially beneficial when working with transformed images, as the inverse transform frequently offers an ill-posed problem that requires the usage of additional information to solve. Regularization filtering used in deconvolution requires less prior knowledge, making it a more effective technique.

A viable strategy for regularization involves integrating pre-existing image knowledge into the process of restoration. For example, natural images commonly demonstrate specific statistical characteristics, such as sparsity or homogeneity. By utilizing these properties as constraints to regularize the problem, the quality of the recovered image can be enhanced. As an illustration, these constraints may suppress noise or distortions or prevent negative values. Deconvolution [12] is the result of regularization employing the decay model as a function, referred to as the PSF, in combination with the convolution of the source image and random noise.

Preliminary data based on natural image statistics should be used to simplify the problem and improve the blur's quality. This could contain edge information, pixel intensity distribution data, or other characteristics that are typical of real images. More accurate and visually acceptable outcomes can be obtained by adding this extra information to the deconvolution process [13]. Furthermore, it is important to remember that regularization is not a magic bullet, even though it can greatly enhance imagine restoration outcomes. Regularization and deconvolutional approaches' efficacy can differ based on a number of parameters, including the type and degree of blur, the image's noise level, and the image's unique properties. As a result, it is critical to give these aspects serious thought while selecting and utilizing image restoration procedures [14].

3.2 Blind Deconvolution

Restoring the original image from a degraded image that has been blurred by a degradation process—usually brought on by a PSF—is the main goal of image restoration [15]. The blind deblurring algorithm is another technique for image restoration that has been investigated. Precise information about the blurring filter's impulse response, also known as the PSF, is frequently unavailable in real-world situations [16].

The task of blind image deblurring (BID) is characterized by a hard situation in which the degradation operator is not well-conditioned, and the problem itself is very ill-posed. The assurance of the solution's uniqueness and stability is not possible due to the existence of an infinite range of alternatives. These solutions, when paired with the original image and blurring filter, are compatible with the observed degraded image [17].

Deconvolution requires two steps: system identification and signal restoration. We estimate the parameters of the system model in the first step, system identification, which is a difficult process that involves correct evaluation of both amplitude and phase. The next stage, signal restoration, is designing an inverse filter to recover the input signal using the given system model parameters. The transition between these processes may be unclear, depending on the system model. Deconvolution is essentially the process of finding the system's impulsive response and restoring the input signal in both amplitude and phase [18].

4. EXPERIMENTS AND RESULTS

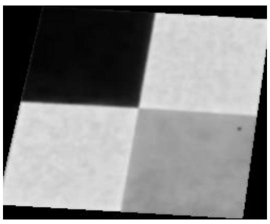
In this section, the findings of our conducted experiments are shown, wherein three various deblurring procedures were applied to the cropped images of the Baotou Region. The MTF values of these images were subsequently measured. In our study, we employed a specific portion of a Google Earth image obtained from the Baotou test site located in Inner Mongolia, China. The approximate geographical coordinates of this site are situated at N 40.854 latitude and E 109.628 longitude. The designated area for testing consists of two distinct square targets, each measuring 48x48 meters, which are clearly delineated. In order to further investigate the subject, we conducted an additional experiment utilizing a synthetic image that incorporated diverse edge angles. This was done to illustrate the influence of these angles on the observed value of the MTF. The MTF values were calculated using open-source code obtained from a GitHub repository [19]. Additionally, deblurring techniques were built and validated in the GNU Octave environment [20].

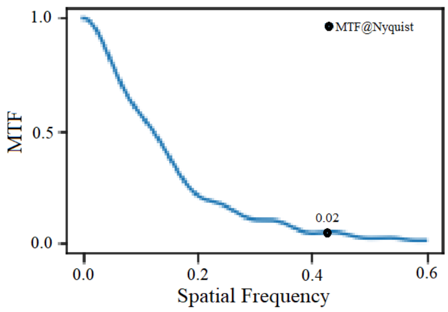
The MTF values were precisely determined through the implementation of a Python program that was developed with this objective in mind. The primary objective of our research was to perform an exhaustive assessment of these MTF values. This methodology involved conducting direct comparisons with the original image in addition to evaluating the MTF values of the deblurred images. By employing this methodology, a comprehensive evaluation could be conducted to determine the impact of every deblurring technique on crucial image attributes, such as contrast and resolution. In conjunction with the quantitative measurements, MTF curves were generated for every processed image. The graphical depictions in these curves illustrated the impact of the deblurring procedure on the spatial frequency components of the images. They furnished significant observations regarding the ways in which various frequency components contributed to the overall quality and severity of the image. The main emphasis of our comprehensive analysis was on the attributes exhibited by these MTF curves. An examination of the peak MTF frequency, a crucial indicator of the maximum achievable image sharpness, was incorporated into this analysis. In addition, we conducted a thorough examination of any anomalies or deviations present in the MTF curves, which enabled us to acquire a more profound comprehension of the merits and drawbacks intrinsic in every deblurring technique.

Our study aimed to assess the effectiveness of several deblurring methods in enhancing contrast and resolution. The findings of our investigation demonstrated that each technique has the ability to improve image quality, while also exposing variations in performance. Furthermore, we investigated the effects of Gaussian blur and examined the potential of deblurring techniques in mitigating this degradation.

4.1 MTF Values of Blurred Image

The MTF value of the blurred image is determined to be 0.171 at a spatial frequency of MTF30, representing 30% of its maximum value at 0 spatial frequency. Similarly, the MTF value is measured to be 0.123 at MTF50, which corresponds to 50% of its highest value in terms of bandwidth and sharpness. Furthermore, the MTF value at Nyquist is found to be 0.019, indicating that the imaging equipment fails to adequately transfer the contrast of the object, resulting in a blurred image.





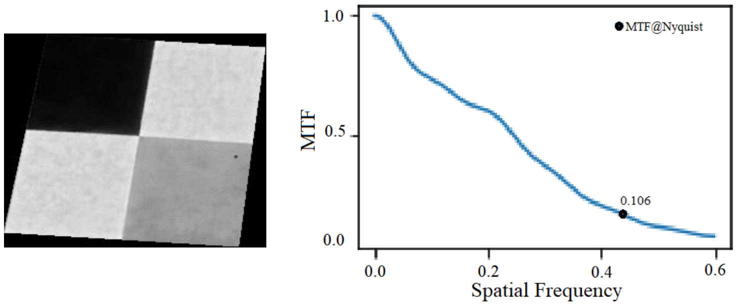
(a) (b)

Figure 3. (a) The blurred image (b) MTF vs. blurred image spatial frequency.

Figures 3(a) and (b) depict the original blurred image and its corresponding MTF function, respectively. In order to demonstrate the enhancement, a comparison was conducted between the MTF values of the initial blurred image and the MTF values obtained from the deblurring methods.

4.2 Richardson-Lucy Algorithm MTF Values for De-blurred Images

The statistical analysis conducted after using the Richardson-Lucy approach for image deblurring reveals that the MTF30 value is 0.336, the MTF50 value is 0.243, and the Nyquist value is 0.107. Notably, all these values exhibit a substantial increase compared to the MTF value observed in the original blurred image. Figures 4 (a) and (b) depict the resultant deblurred picture and MTF respectively.

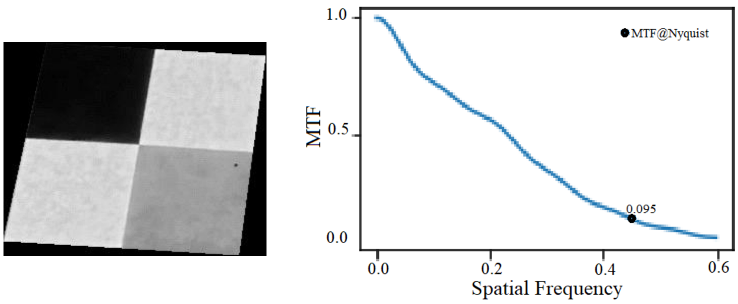


(a) (b)

Figure 4. (a) The regularized filter-deblurred image (b) MTF vs. deblurred image spatial frequency.

4.3 MTF Values of a De-blurred Image Determined Using a Regularized Filter

Metrics obtained after applying the regularization filter revealed that the MTF30 value is 0.326, the MTF50 value is 0.231, and the Nyquist value is 0.096, which are all much higher than the MTF value of the blurred image. The final deblurred image and its matching MTF function are shown in Figures 5 (a) and (b), respectively.

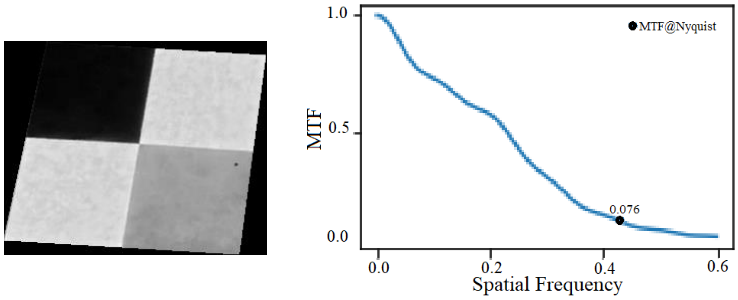


(a) (b)

Figure 5. (a) The regularized filter-deblurred image (b) MTF vs. deblurred image spatial frequency.

4.4 MTF Values of De-blurred Image Calculated with Blind Deconvolution Filter

The use of the Blind Deconvolution Filter resulted in the acquisition of data indicating that the MTF30 was measured at 0.3, the MTF50 at 0.229, and the Nyquist at 0.077. These values were found to be considerably greater than the MTF value observed in the original blurred image. Figures 6 (a) and (b) depict the deblurred image and the MTF respectively.



(a) (b)

Figure 6. (a) The Blind Deconvolution Filter- deblurred image (b) MTF vs. deblurred image spatial frequency.

Table I presents the MTF values acquired for the initial blurred image and the deblurred images using the three different deblurring techniques. The Richardson-Lucy method demonstrates superior performance compared to the other two approaches, whereas the Regularization Filter exhibits almost similar performance to the Richardson-Lucy algorithm. The performance of the Blind Deconvolution Filter is comparatively poor. Figure 7 illustrates the representation of frequency-based changes in MTFs.

Table 1. Blurred and de-blurred image MTF values

		MTF		
		MTF30	**MTF50**	**MTF Nyquist**
Blurred Original Image		0.171	0.123	0.019
Deblurring Methods	**Richardson – Lucy Algorithm**	0.336	0.244	0.107
	Regularization Filter	0.326	0.231	0.096
	Blind Deconvolution Filter	0.31	0.229	0.077

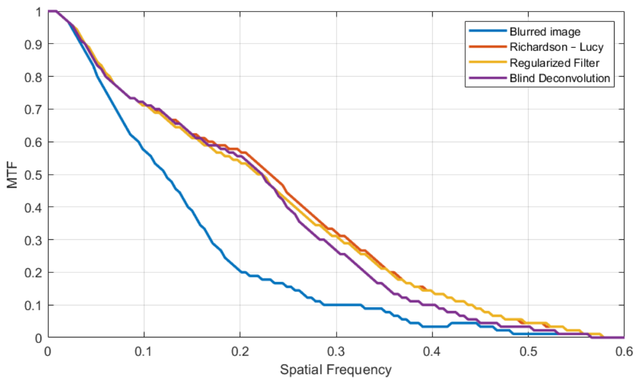


Figure7. MTF Values of Blurred and Deblurred Images.

The variation in the angles at which images are collected, relative to the target edge and the direction of satellite scanning, has an impact on the measured value of the MTF. In order to demonstrate the correlation, we utilized a synthetic image featuring varying edge angles, including 45°, 30°, and 11°. Figure 8(a), (b), and (c) illustrate synthetic images featuring varying edge angles of 45º, 30º, and 11º, respectively. Figure 9 illustrates the MTF of a synthetic image that has undergone Gaussian blurring with a kernel size of 5x5 and $\sigma = 1$.

(a) (b) (c)

Figure 8. Synthetic images with (a) 45º, (b) 30º and (c) 11º edge angles with scanning direction.

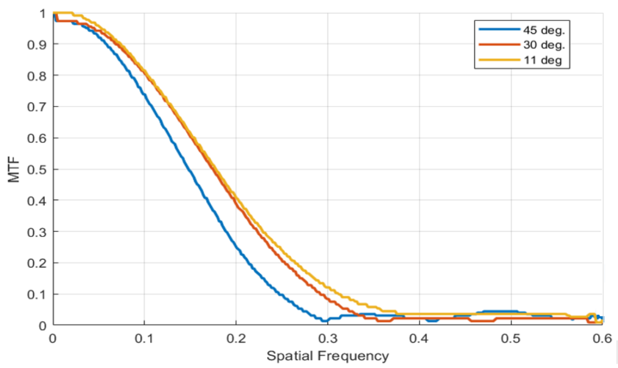


Figure 9. MTF Values for 45º,30º and 11º edge angles.

5. CONCLUSION

This study employed three distinct filters to examine the impact of deblurring on the MTF value of electro-optical satellite images. The filters utilized were the Richardson-Lucy method, the Regularization Filter, and the Blind Deconvolution Filter (see Figure 7). The Richardson-Lucy technique demonstrates superior performance compared to the other two filters in relation to MTF values over nearly all spatial frequencies. Nevertheless, it is important to note that the Regularization Filter has comparable MTF values to those of the Richardson-Lucy method, specifically for spatial frequencies that exceed 0.37. These results emphasize the importance of implementing an effective deblurring technique to enhance the MTF values of satellite images. However, similar to the Regularization Filter and the Blind Deconvolution Filter, the Richardson-Lucy technique does include certain drawbacks. The sensitivity of the Richardson-Lucy algorithm to noise in the input image is significant, as even minor levels of noise can lead to the generation of inaccurate outcomes by the algorithm. Determining the optimal number of iterations for convergence in the Richardson-Lucy algorithm poses a challenge, as selecting an insufficient number of iterations can result in poor image quality, while an excessive number of iterations can lead to overfitting and the degradation of image details. In addition, it is imperative to possess a precise comprehension of the PSF in order to effectively employ the approach, as the PSF characterizes the extent to which the imaging device introduces blurring to the image. Insufficient knowledge of the PSF may lead to suboptimal outcomes in the procedure. In considering the drawbacks associated with the Richardson-Lucy algorithm, it is advisable to use precautionary measures to mitigate these limitations and so enhance the efficacy of the algorithm in various applications. In addition, it is important to consider the impact of the angle between the target edge and the satellite scanning direction on the MTF values.

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