Deblurring of Space Targets’ Blurred Images Caused by Complex Motion of Ocean-Based Observing Platform

Xiong WANG*, Gang WANG and Ying-liang MA
China Satellite Maritime Tracking and Control Department, Jiangyin, 214431, China
*Corresponding author

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Abstract. Propagation model of space targets’ images are built up based on angular spectrum theory, and Richardson-Lucy (RL) algorithm is employed to simulate the recovery of the blurred images numerically. In the model, blurred images of space targets caused by the relative motion between the targets and the observing equipment are simulated, and degeneration of image quality due to atmospheric turbulence and noise is considered to make the simulation comprehensive. The deblurring effect using RL algorithm is investigated.

Introduction
Ocean-based TT & C platform is an important component of Chinese TT & C system. The relative motion between space target and TT & C optoelectronic equipment makes the observing image blurred [1-3]. The effect of deblurring of blurred image employing blind-deblurring method is limited because of the complexity of ocean-based platform’s motion [4-6]. Furthermore, atmospheric turbulence and noise will degrade the quality of images, and make the recovery more challenging.

Richardson-Lucy (RL) algorithm is a widely applied nonlinear iteration method of deblurring image, which employs maximum likelihood method to estimate the original image under the condition that the image pixels obey Poisson distribution [7, 8]. Even if the noise is unknown, RL algorithm can be used to deblur the blurred image as long as the point spread function (PSF) is obtained. Researchers mainly focus on deblurring of blurred images caused by uniform linear motion or central rotational motion between the target and the equipment. There is almost no demonstration on deblurring of blurred images caused by complex motion employing RL algorithm as far as we know.

In this paper, optoelectronic propagation model based on angular spectrum (AS) theory is built up to simulate blurred images of space target observed by ocean-based TT & C system with complex relative motion. The effect of deblurring using RL algorithm is investigated, and the influence of atmospheric turbulence and noise is analyzed.

Theoretical Model

In linear displacement invariant system, blurred image \( g(x, y) \) can be depicted as the sum of noise \( n(x, y) \) and the convolution of original image \( f(x, y) \) and PSF \( h(x, y) \):

\[
g(x, y) = h(x, y) * f(x, y) + n(x, y)
\]

(1)

If PSF can be obtained, one can employ RL algorithm to estimate the original image using iteration method:

\[
f_{n+1}(x, y) = \frac{g(x, y)}{h(x, y) * f_{n}(x, y)} h^*(x, y) f_{n}(x, y)
\]

(2)

where \( f_{n+1}(x, y) \) and \( f_{n}(x, y) \) are estimated images after \( n+1 \) and \( n \) iterations, respectively. It is clear that the noise \( n(x, y) \) is not necessary when estimating the original image via RL algorithm.
However, since the motion of ocean-based TT & C platform contains several degrees (such as pitch, roll and yaw), the relative motion track between space target and TT & C platform is usually a complex curve. Thus, the PSF is hardly to be estimated from the blurred image blindly. One feasible method is to measure the real-time parameters of platform’s motion, and built up a model describing the motion of line of sight (LOS) of observing equipment to calculate the accurate PSF. In this paper, the point of our investigation is the effect of deblurring when PSF is known, so the built-up of LOS model is not introduced.

AS theory is deduced from Rayleigh-Sommerfeld integral formula without any approximation, so it can be used to calculate the propagation of light accurately [9, 10]. The light field $U(x, y, z)$ at a distance of $z$ can be described as below:

$$U(x, y, z) = \int \int A_x(f_x, f_y) \exp \left( \frac{2\pi}{\lambda} \sqrt{[f_x(1-f_y^2) - (f_y^2)]} \right) \cdot \exp \left[ j2\pi(f_x x + f_y y) \right] df_x df_y \tag{3}$$

Atmospheric turbulence is indispensable when performing optoelectronic observing of space target from an ocean-based moving platform. So atmospheric turbulence phase screen is included in our model to describe the influence on observation, which makes the simulation more proximate to the practical situation. The outer scale of turbulence is 10 m, the inner scale is 0.01 m. Based on the above theory, numerical model is built up to simulate the observation of space target from an ocean-based platform, and investigation on deblurring of blurred images due to relative motion is performed.

**Results and Discussion**

Figure 1 shows the optoelectronic observing images of a space station when there is no relative motion, and the pixels of the image are 1024×1024. The amplitude of turbulence phase is 0.08. The picture in Fig. 1(a) is the observing image with no atmospheric turbulence, and that in Fig. 1(b) is the image considering atmospheric turbulence. One can find out that atmospheric turbulence blurs the image and makes the details lost clearly, which make the deblurring of blurred image more challenging. In the text follows, atmospheric turbulence is always considered in this paper if not indicated.

![Figure 1. The effect of atmospheric turbulence on space station’s image. (a) Image without atmospheric turbulence, (b) image with atmospheric turbulence.](image)

The blurred images of satellite due to relative motion between target and observing equipment are depicted in Fig. 2. From Fig. 2(b) and Fig. 2(c) one can find out that relative motion blurs the image seriously. The image blurred by curvilinear motion shows irregular trace, which make it challenging to deblur the image based on blind deblurring method. Furthermore, noise introduced by collecting and transmitting the image degrades the quality of image further. The above study shows that the model is effective to simulate the process of image-blurring due to motion. Then deblurring of the images using RL algorithm is performed.
Figure 2. Simulation of satellite’s images observed from an ocean-based moving platform. (a) Image without relative motion, (b) image with uniform linear motion, (c) image with curvilinear motion, (d) image with curvilinear motion and noise.

Linear motion with uneven speed is investigated first. Figure 3(a) shows the image of a satellite without motion. The PSF depicts a relative motion with a direction of 135 degree and moving quantity of 99 pixels, as shown in Fig. 3(b). The sum of all the pixels of the PSF equals 1, which means the blurred image corresponding to the PSF is obtained through once exposal. The values of each pixel are different, which indicates that the linear motion’s speed is uneven. The blurred image is shown in Fig. 3(c), from which one can hardly finger out what the original image is like. RL algorithm is performed to deblur the image in Fig. 3(c), and the result after 20 iterations is depicted in Fig. 3(d). It is clear that the blur due to motion is recovered with expected outcome.

Figure 3. Recovering of blurred image due to linear motion. (a) Image of satellite without relative motion, (b) PSF of linear motion, (c) blurred image corresponding to the PSF, (d) recovered image.

Then RL algorithm is employed to recover the image blurred by complex curvilinear motion, as shown in Fig. 4. The picture in Fig. 4(a) is an image of space shuttle with influence of atmospheric turbulence, from which one can see that although some details of the shuttle are illegibility, but the profile is almost intact. Figure 4(b) depicts the PSF corresponding to complex curvilinear motion. The sum of values of each pixel is 1 to indicate that the corresponding blurred image is obtained by once exposal. This PSF depicts a rather extreme situation of relative motion, which is built up to verify the deblurring ability of the model employing RL algorithm. The corresponding blurred image is depicted in Fig. 4(c). One can find out the details of the shuttle are complete lost and the inner profile is hardly to distinguish. It is challenging to classify the shuttle from the image in Fig. 4(c). The recovered image using RL algorithm after 20 iterations is shown in Fig. 4(d). The profile of the shuttle is recovered effectively, but some details of the shuttle are still not distinguishable.
Figure 4. Recovering of blurred image due to complex curvilinear motion. (a) Image without relative motion, (b) PSF of complex curvilinear motion, (c) blurred image corresponding to the PSF, (d) recovered image.

Figure 5. Influence of atmospheric turbulence and iteration number on deblurring effect.

Since RL algorithm is an iterative method, number of iteration influences the effect of deblurring and efficiency of calculating to a large extent. Thus, deblurring effect with different iteration number is investigated employing the satellite and PSF in Fig. 3. Correlation coefficient of the recovered image and the original image is used as the standard to evaluate the deblurring effect in this paper. The bigger the coefficient is, the better the effect is. Moreover, the influence of atmospheric turbulence is also investigated. The results are shown in Fig. 5. The weak turbulence and strong turbulence in Fig. 5 are distinguished by the amplitudes of phase, which are 0.02 and 0.05, respectively. From Fig. 5 one can find out that atmospheric turbulence degrades the final recovering effect, but does not slow the convergence speed of the curve. The coefficient doesn’t increase further when the iteration number succeeds about 15.

Similarly, the integrated influence of turbulence and noise on recovering effect is investigated, as shown in Fig. 6. The results are calculated using the shuttle and PSF in Fig. 4. The amplitude of turbulence phase is increased to 0.08 to make the contrast clearer. The image noise is Gaussian noise with a variance of 0.0001. From Fig. 6 one can find out that the turbulence degrades the recovered coefficient from 0.86 to 0.78, and the noise reduces the coefficient down to 0.74. Moreover, due to the existence of noise, the further increase of iteration number degrades the effect when the iteration number succeeds about 7. So it is necessary to perform denoising and compensation of turbulence before deblurring the blurred images of space target obtained from an ocean-based moving platform.
Summary
In this paper, model based on AS theory is built up to investigate the observing of space target from an ocean-based moving platform. RL algorithm is employed to recover the blurred images caused by relative motion. The influence of turbulence and noise on the recovering effect is discussed. The results are useful for the observing of space targets from an ocean-based or land-based moving platform. Our future work will focus on improving the algorithm and optimizing the control parameters to further increase the effect and efficient of recovery.

References