Restoring Degraded Astronomy Images using a Combination of Denoising and Deblurring Techniques

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Abstract

The aim of image restoration is to restore the image affected by degradations to the most desired form. It comprises a set of techniques applied to the degraded image to remove or reduce the cause of degradations. This study focuses on Astronomy images. Astronomy images suffer from mainly two types of degradations: atmospheric turbulence blur and additive white Gaussian noise. This study presents a new method to restore astronomy images by proposing a hybrid method that combines three techniques to restore a degraded image. The first technique is phase preserving algorithm used for the denoising operation. Then a normalization operation is employed to provide the image its natural grayscale intensity. After that Richardson Lucy deblurring algorithm is used to deblur the image depending on the Point Spreading Function (PSF) determined earlier. When the deblurring process is completed, the anticipated image will be in the most desirable form.

Keywords: *Atmospheric Turbulence Blur, Additive White Gaussian Noise, Degradation, Deconvolution, Restoration, Astronomy Images, Denoising, Normalization, Deblurring*

1. Introduction

Astronomy images are captured and saved in many different environments, situations, and methods. Due to that, the chances of having errors or problems during the process of capturing the image and saving it are also increased and for that, these problems must be taken into consideration [1]. Various images illustrate captured scenes in an unacceptable situation. Since imaging systems employed to acquire images are imperfect, the surroundings under which images are gained are usually less than perfect; a captured image regularly demonstrates a corrupted edition of the original scene. The problems that occur to an image which is also called degradations consist of many kinds like noise, geometrical degradations (pin cushion distortion), illumination and color imperfections (under/overexposure, saturation), and blur [2]. Many factors lead to have degradations in an image, for instance, the surrounding atmosphere, the procedure of acquiring an image, the medium of recording an image. Due to these factors, the image that is essentially recorded often becomes unsuccessful to represent the scene sufficiently. In the case of astronomy images, many captured images suffer from two types of degradations: atmospheric turbulence blur, and additive white Gaussian noise [3]. The atmospheric turbulence blur degrades images by many ways like, images taken by cameras viewing scenes from long distances [6], The earth turbulent atmosphere [4, 5], long exposure imaging due to a low illumination environment [7], and dust particles on the surface of the lens are the main reason for the blur to happen [6, 8, 9].The additive white Gaussian noise degrades images in many ways for instance, image transmission from source to destination, the time the image is captured and generated or an error at the imaging system [10]. Also noise degrades an image because of capturing the image in a low illumination environment, errors in transmission [8], and low-contrast objects [5]. Consider the original image is (F), (H) is the blur operator who would be convolved with the original image to give the blurred image, the noise (N) will be added to the image, as in the following equation [11]:

$$G=H*F+N \quad (1)$$

Finally, the existence of these two degradations in one image can be hard to restore. However, there are certain techniques used to restore each defect with minimal effect on the other defect.

2. The Problem Statement

The restoration process in the situation of the existence of blur and noise combined together is complicated. The reason is that, the blur is a low pass signal, and the noise is a high pass signal. However, the high pass filters help to deblur the image (sharpening the image), but in this case, the noise will be amplified. Furthermore, the low pass filters help to denoise the image (Soften the image), but in this case, the blur will be amplified. Unfortunately, in this situation when trying to restore a blurry and noisy image, the effect will be adverse. Due to that reason, an alternative method has been considered to remove the noise and blur separately one after another [12]. The aim of this study is to restore an image that has an atmospheric turbulence blur and additive Gaussian noise mixed together in one image. The proposed method is trying to restore it as much as possible to look like the original one.

3. The Proposed Method

This paper focuses on image restoration. To remove the degradations from the Astronomy image, multiple filters would be used for the restoration propose. The proposed method was based on three major techniques, which is explained in detail in the following paragraphs. Those three major techniques are:

1. Phase Preserving Algorithm (Denoising)
2. Normalization Technique (Enhancing)
3. Richardson-Lucy Algorithm (Deblurring)

The main idea is to show that by combining them together, the degraded astronomy images would be restored, figure 1 illustrates the restoration process diagram.

3.1. Denoising

The denoising operation is the process that removes or reduces the noise from the degraded image. Many algorithms have been introduced. They can be applied in the spatial domain, and frequency domain. Furthermore, these denoising algorithms can be iterative or non-iterative. In spite of all the differences in the denoising algorithms, still all algorithms share one purpose that is removing or reducing the noise from the image [25].

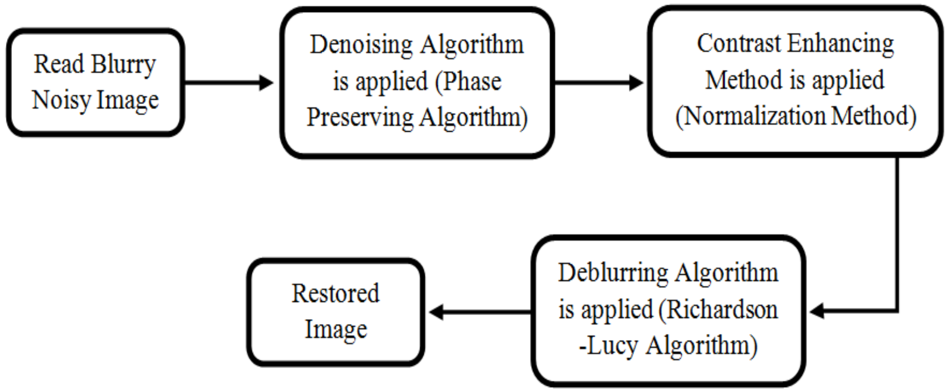


Figure 1. The Restoration Diagram

3.1.1. Phase Preserving Algorithm: The phase preserving algorithm presented by Peter Kovesi in 1999, states that each pixel value in the frequency domain has a real part which represents the phase and an imaginary part which represents the amplitude. The main idea of this algorithm is to keep the phase unchanged and change the amplitude by shrinking it. The amplitude shrinking is done when the amplitude exceeds a known value called the threshold. The phase preserving algorithm uses a discrete wavelet transform and using wavelets that are in symmetric/anti symmetric pairs by following the approach of Morlet, which uses wavelets based on complex values and log Gabor functions. The phase preserving algorithm works simply in the following course, First a log Gabor function is needed to extract the local amplitude of the image and also a Gaussian spreading function is needed to extract the local phase of the image. Before the construction of these two functions, a 2D filter must be created to control the radial component which represents the amplitude of the signal and an angular component which represent the phase of the signal. Two matrices (X and Y) must be created to form the 2D filter, each of these matrices has the same size of the image but the values of these matrices are normalized radius from the matrix center. The range of the values is 0 in the middle and increases to 1 in the boundaries. After creating the 2D filter, the radial component can be calculated by using this equation:

$$Radius = \sqrt{x^2 + y^2} \quad (2)$$

After that, the resulted radius matrix may contain (zero) values, which should be eliminated from the radius matrix to avoid its problems when creating the log Gabor function. Then, the log Gabor function can be applied to build a filter that would be used later to extract the local amplitude, the log Gabor equation is:

$$G(f) = \exp\left(\frac{-(\log(f/f_0))^2}{2(\log(\sigma/f_0))^2}\right) \quad (3)$$

Where (f) is the radius calculated earlier in equation2, (σ/f_0) is a pre-calculated value that equal to 0.55 and (f_0) can be calculated using the following equation:

$$f_0 = \frac{(1/wavelength)}{0.5} \quad (4)$$

Where the initial value of wavelength is two, then the value will be reduced using the above equation depending on the number of scales used. Currently, the filter for extracting the local amplitude is ready, now a second filter must be created to calculate the angular component to manage the orientation. This can be done by first calculating theta value by the following equation:

$$\Phi = atan2\ (y, x) \tag{5}$$

After the calculation of the angular component, the problem of the angular twist must be corrected. The difference of sine (DOS) and cosine (DOC) must be taken to the values of theta (Φ) and angle that represents the angle of the Gaussian center. The absolute angular distance (AAD) must be calculated for the difference of sine (DOS) and cosine (DOC), the following equations used to calculate the absolute angular distance (AAD):

$$DOS = [(\sin(\Phi) * \cos(angle)) - (\cos(\Phi) * \sin(angle))] \tag{6}$$

$$DOC = [(\cos(\Phi) * \cos(angle)) + (\sin(\Phi) * \sin(angle))] \tag{7}$$

$$AAD = |atan2\ (DOS, DOC)| \tag{8}$$

After that, the Gaussian spreading function (ψ) can be applied to build a filter that would be used later to extract the local phase, where (r) represents the absolute angular distance and (b) represents the standard deviation of the angular Gaussian filter multiplied by two, the Gaussian spreading function (ψ) equation is[21]:

$$\psi(r) = (\pi b^2)^{-1} \exp(\frac{-r^2}{b^2}) \tag{9}$$

After calculating the Gaussian spreading function and log Gabor function, the two functions must be convolved together to form the overall filter, another operation must be applied to the overall filter before convolving it with the image, a Fourier shifting operation is applied to shift all zero values to the corners and the high and low values to the center. By now the overall filter is done and ready to be convolved with the noisy image. Then, the filter is convolved with the image which has been transformed to the frequency domain. Every pixel value of the image has two parts in the frequency domain; real part and imaginary part, by convolving the image to the filter, there will be a 90 degree phase difference between the real numbers and the imaginary numbers of the same image and by that Morlet approach is applied. By taking the inverse Fourier Transform of the result after the convolution of the image with the created filter, even-symmetric element will be in the real part of the result, and the odd-symmetric elements will be in the imaginary part of the result. Morlet approach depends on the signal analysis as a significant issue. According to the Morlet approach, the analysis of the signal is done by convolving the signal with each of the quadrature pairs of wavelets. Quadrature is defined as a phase difference of 90 degrees between two waves of the same frequency. Morlet method can be applied using the following equation**:**

$$[e_n(x), o_n(x)] = [I(x) * M_n^e, I(x) * M_n^o] \tag{10}$$

Where (e_n, o_n) are the real and imaginary parts of complex valued frequency, (I) is the signal, (M^e and M^o) are the even-symmetric and odd-symmetric wavelets, (n) is the scale. An array of response vectors will be available at each point (x) in a signal. These vectors represent the value of (x) in each scale of the filter, see figure (2). In this figure the amplitude is the length of the vector, and the phase is the angle of the vector.

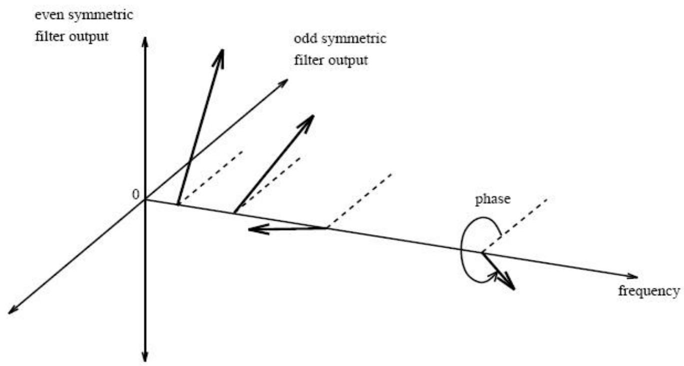


Figure 2: Phase and Amplitude of the Response Vector at Different Scales [13].

Currently, the denoising process will start by estimating the noise threshold at the smallest scale. The thresholding operation would be applied at the smallest scale to shrink the amplitude of the vectors properly, but the phases of the vectors must remain untouched.

3.1.1.1. Establishing the Threshold Creating an automatic threshold for the denoising operation is essential for successful denoising. Many techniques used manual thresholding but the phase preserving algorithm used an automatic thresholding, which probably makes it one of the finest algorithms in denoising. In this case, the noise is additive white Gaussian noise so the distribution of the noise would be Rayleigh's distribution. The interesting thing in the distribution is the response vector magnitude. By knowing the type of distribution, the thresholding process calculation would be much easier. The Rayleigh distribution equation is:

$$R(x) = \frac{x}{\sigma_g^2} \exp \frac{-x^2}{2\sigma_g^2} \tag{11}$$

Where (σ_g) is the variance of the 2D Gaussian distribution describing the position of the filter response vectors, the strongest noise response can be found in the smallest scale filter; here the regions responding to features are small regions. Therefore, the smallest scale wavelet will respond mostly to the noise. Here in this point the estimation of the threshold is easier and the process of estimation can work properly. The first step in the creation of the automatic thresholding is to find the median of the Rayleigh distribution; this can be done by using the following equation**:**

$$median = \sigma_g \sqrt{-2ln(1/2)} \tag{12}$$

Then, find the mean of Rayleigh distribution; this can be done by the following equation:

$$E(A_N) = \frac{1}{2} \sqrt{-\pi/\ln(1/2)} \; .median \tag{13}$$

Then, find the variance of Rayleigh distribution; this can be done by the following equation:

$$\sigma_r^2 = \frac{4-\pi}{2} \sigma_g^2 \tag{14}$$

Finally, the threshold is ready to be calculated after finding the variables of the thresholding equation. The threshold equation is:

$$T = E(A_N) + K \sqrt{\sigma_r^2} \tag{15}$$

Where K is a constant, after determining the threshold (T), a noise vector (NV) must be constructed to store the pixels that exceed the threshold and subtract them from the image; the noise vector (NV) can be created using the following equation where (SI) denotes as symmetric image and (ASI) denotes as absolute symmetric image:

$$NV = (T * SI) / (ASI) \quad (16)$$

The amplitude vector will be shrunken by this value; the shrinking of the amplitude is done by subtracting the noise vector from the image that Morlet approach has been applied to it. This operation would be applied to all the vectors that exceed the threshold in the smallest scale filter. The result will be reducing the noise for the entire image because the amplitude vectors that exceed the threshold value considered as the noise of the image. By getting the threshold in the small scale filter, it can be applied to the other scales and reduce the amplitudes that exceed the threshold, and by that the noise reduction will involve the entire image. After finishing the thresholding, the image now is expected to be a noise free image, still after the denoising the image would appear darker and a normalization process is needed to enhance the brightness of the image [13].

3.2. Normalization

Normalization is the technique that would give the image a typical gray level intensity, so if the image is too dark, it would be less dark and if the image is too white, it would be less white. The following equation illustrates the normalization operation [14]:

$$N_{ij} = \frac{A_{ij} - min}{\max - min} * 255 \quad (17)$$

Where (N_{ij}) is the normalized value; (A_{ij}) is the current pixel value; (min) is the minimum pixel value in the image, (max) is the maximum pixel value in the image.

3.3. Deblurring

The deblurring operation is the process that removes or reduces the blur from the image. The Point Spreading Function (PSF) is used to determine the distortion factor. Richardson Lucy algorithm with pre-determined PSF value is used to deblur the image depending on the PSF value.

3.3.1. The Point Spreading Function (PSF): The PSF illustrates the degree to which a device or a method blurs (spreads) a point of light. The PSF is an important variable that needed to be calculated before the beginning of the deblurring process. The PSF simply is an estimation of the blur filter or (distortion operator) that convolved with the original image to form the blurry image [15]. To restore the blurry image, a deblurring or deconvolution operation is applied. Most of the deblurring algorithms demand the PSF as one of its variables to restore an image [15], such as Richardson Lucy algorithms, Weiner algorithms, Van Cittert Algorithm, Poisson MAP Algorithm. So for these algorithms, estimating the value of (H) or the PSF is critical. However, some of the blur properties must be known before the estimation occurs [16]. The type of PSF used is the Gaussian PSF because Gaussian PSF used in the case of astronomy images. The Gaussian PSF has one variable that must be identified in order to work properly that is the blur parameter (σ) [17], the Gaussian PSF equation is [18]:

$$v_{\sigma_{blur}}(m,n) = \frac{1}{2\pi(\sigma_{blur})^2}\ exp(-\frac{m^2+n^2}{2(\sigma_{blur})^2}) \quad (18)$$

After that, the PSF must be transformed to optical transfer function (OTF) by applying the Fourier transformation on the PSF, the OTF is used inside the deblurring algorithm to restore the image corrupted with blur. The PSF is vital in the restoration process since the quality of the image depends on it [17] [19].

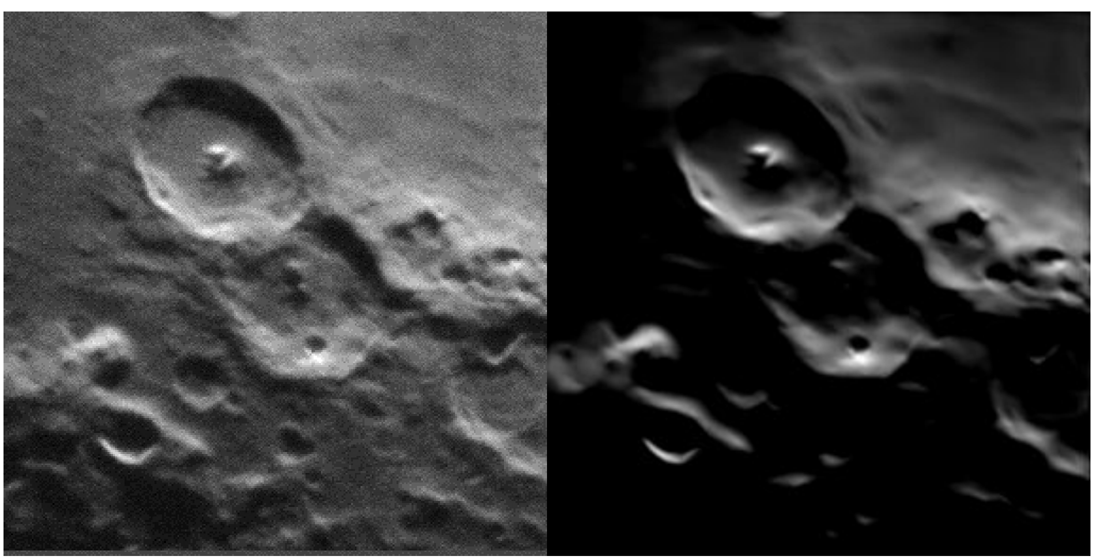
3.3.2. Iterative Richardson – Lucy Algorithm: Richardson-Lucy algorithm considered as one of the finest deblurring algorithms in the image processing field; in this algorithm, no exact noise form is assumed. One of the best features of this algorithm is that it doesn't need information from the previous original image. This algorithm is an iterative algorithm. In addition, this algorithm work in case of noise existence but the noise would be amplified during the increased number of iterations [19, 20]. The equation of the Richardson-Lucy algorithm is [22]:

$$f^{n+1} = f^n H\left(\frac{g}{Hf^n}\right) \tag{19}$$

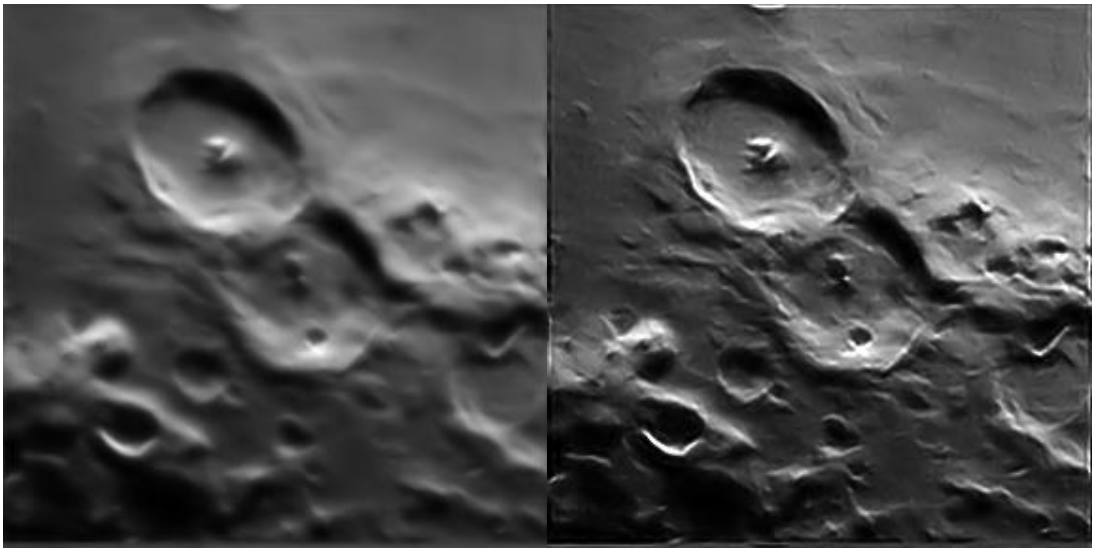
Where $f^{(n+1)}$ is the new estimate from the previous one $f^{(n)}$ to the original image, $f^{(0)} = g$, (g) is the blurred image, (n) is the number of the step in the iteration, (H) is the blur filter (PSF) [22, 15].

4. Experimental Results and Discussion

Several restoration techniques were applied to the degraded image in order to restore it; firstly, a denoising algorithm is applied to remove the noise from the image, this step is very important to avoid noise amplification in the deblurring period, next a normalization technique is applied to provide the image in its normal gray intensity, finally a deblurring algorithm is applied to remove the blur from the image. In this paper, two images were employed to illustrate the restoration process. Figures 2 and 3 illustrate the restoration process. The degraded image in figure 3 was taken from [24]. The degraded image in figure 4 was taken from [23].

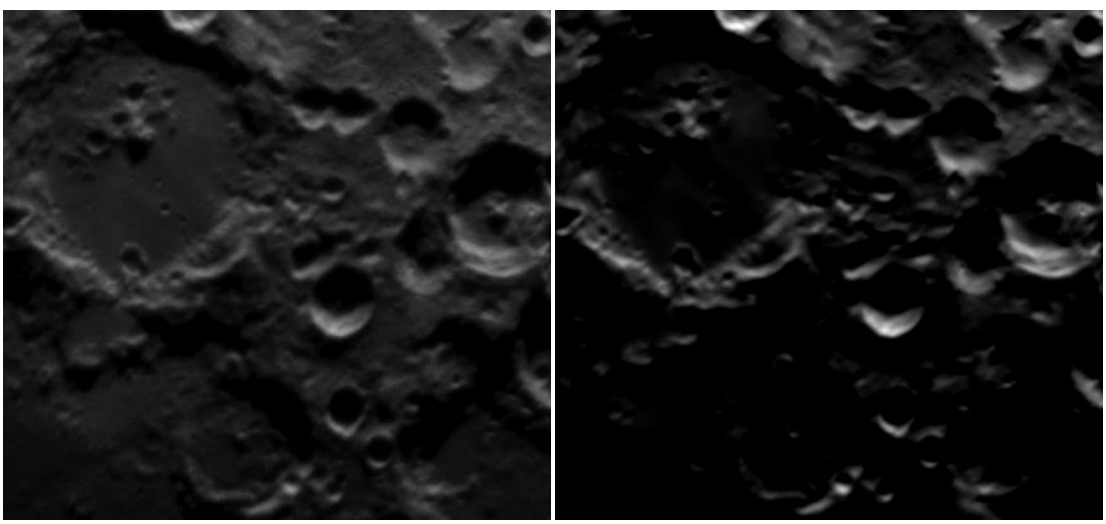


a) Degraded Image **b) Denoised Image**

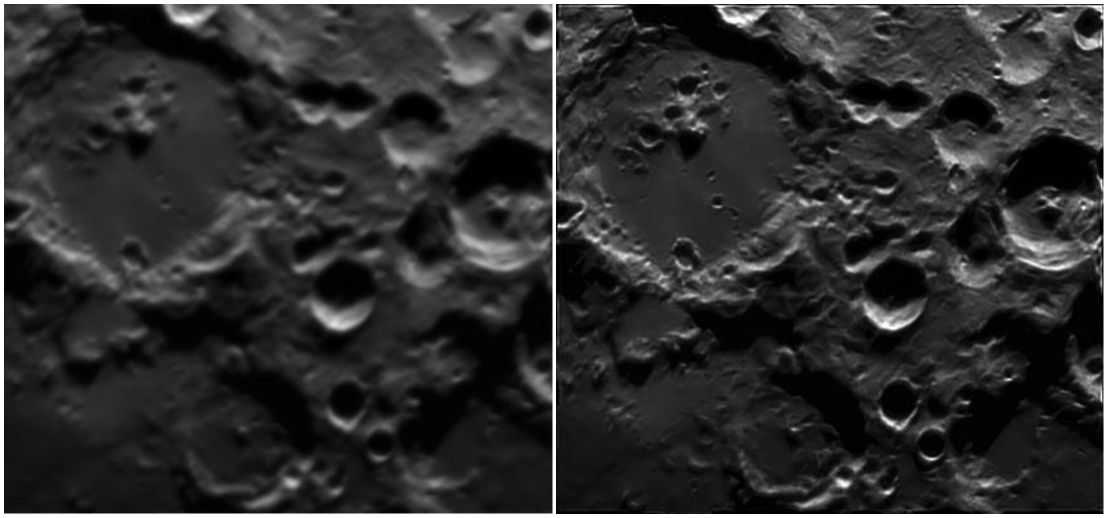


c) Normalized Image **d) Deblurred Image**

Figure 3: Restoration process from (a) to (d): degraded image, denoised image with phase preserving algorithm, enhanced image by using normalization, deblurred image by using Richardson Lucy algorithm.



a) Degraded Image **b) Denoised Image**



c) Normalized Image **d) Deblurred Image**

Figure 4: Restoration process from (a) to (d): degraded image, denoised image with phase preserving algorithm, enhanced image by using normalization, deblurred image by using Richardson Lucy algorithm.

5. Conclusion

This study focuses on Astronomy images. Several problems have been identified in the captured images, but the focus of this research is mainly on two types of degradations: the atmospheric turbulence blur and additive white Gaussian noise. The use of multiple techniques in the restoration operation is very important. This is due to the specific characteristic of each technique in its own domain of problems. Thus, the combination of series of techniques is thought and proven to deliver a better result in image quality. As a future work, the current method can be improved by applying more enhancement techniques in the restoration operation to obtain better results, also employing more than one deblurring algorithm would lead to more precise results, furthermore, Utilizing a fine algorithm to estimate the point spreading function (PSF) will result in more accurate outcome in the deblurring process.

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