Image Quality Improvement through MTF Compensation - A Treatment to High Resolution Data

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Abstract

The integrating effect of the Point Spread Function (PSF) of an imaging system affects the signature of a feature and also reduces the spatial resolution. Linear ground edges and other suitable features in high-resolution data can be analyzed to determine the system's line spread function (LSF). Knowledge of line spread function and hence Modulation Transfer Function (MTF) can be used in preprocessing operations to compensate for the image degradation. This results in significant improvement in image quality. The results are compared with other restoration methods like Ramp Width Reduction and De-convolution, which are also discussed. They provide satisfactory results over a wide variety of data including high-resolution imaging.

Overview

1. Introduction

Much of the information of an image resides in its edges. Therefore, the sharpness of its edges is very important to the visual quality of an image. There are a number of reasons for an edge getting wider. Sharpening of images is a classical problem in image processing. Traditional edge sharpening methods mainly increase the intensity difference across an edge. We have implemented an edge sharpening filter, which is based on a different concept to reduce the edge width (Leu, 2000) called ramp width reduction filter. Image reconstruction to compensate for signal deterioration has also been tried through deconvolution techniques with a Gaussian point spread function.

The PSF is a useful measure of how each element of an optical system spreads the image of a point, and estimating PSF is an established method for testing lens quality or overall imaging system. PSF of a sensor integrates the response from a target pixel and its surrounding pixels and is a result of the convolution of the PSF with the scene. While the recorded response derives predominantly from the target pixels it is also partially derived from the surrounding pixels. This is explained in Figure 1.

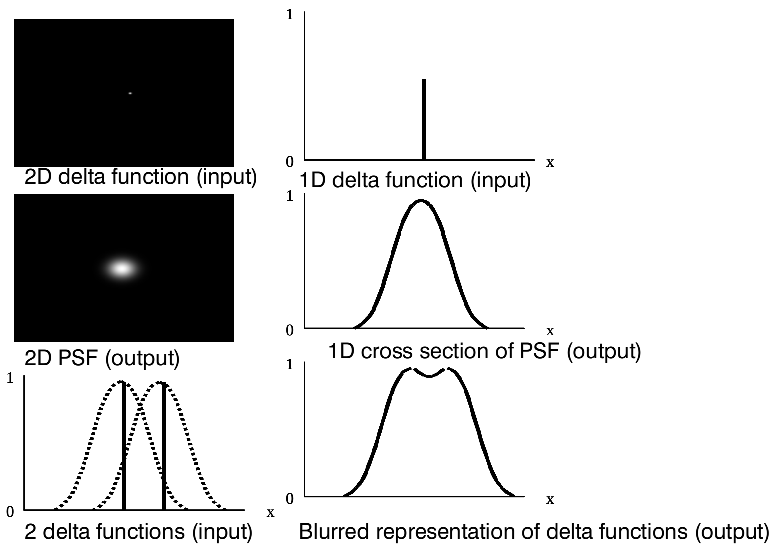


Fig.1: Point Spread function (PSF)

This effect is more pronounced when the resolution of the sensor is of the same order as the size of surface features being sensed, as can be the case of satellite imaging system.

In order to counter effect the PSF of a sensor, an estimate of its mathematical form must be determined. Ideally this would be obtained in a controlled experiment in a laboratory or by imaging linear features of different widths and orientations specifically placed in the field prior to image acquisition. This also can be measured by studying the images of the bar targets and tribar targets.

Availability of images of bar targets for a given sensor may not be feasible always, an alternative method of determining PSFs from ground features such as bridges, jetties and runways were attempted (Forster, et.al, 1994). This gives a good estimate of the point spread function. The absolute value of the Fourier transform of a point spread function is the Modulation Transfer Function (MTF). It is more common to move from spatial domain into spatial-frequency domain, which provides information concerning the behavior of an imaging system. This also can effectively be used to generate crisper images by MTF-compensation, thereby increasing the resolution of the overall imaging system, which is more systematic as compared to ramp width reduction and deconvolution.

2. High Resolution Data

Presently, many satellites are orbiting around the earth with high resolution imaging capability, with resolutions better than a meter. However, due to non-zero pitch, roll and yaw angles, at any point of time instantaneous field of view (IFOV) is greater or utmost equal to the nominal resolution. This results in MTF degradation proportional to the ratio of IFOV and GSD. These sorts of degradations can and need to be compensated (Frank, 2000).

3. Ramp width reduction

This approach is a neighborhood operation. Based on the intensity of a pixel and that of its neighbors, three intensity indices and three gradient indices for a pixel are generated. The three intensity indices are used to suggest whether the pixel is on the intensity ramp. The three gradient indices further indicate the location of the pixel relative to the ramp's centerline. If it is located above the centerline on the ramp, we increase the pixel's intensity and if it is located below the centerline on the ramp, we decrease the pixel's intensity. See Figure 2.

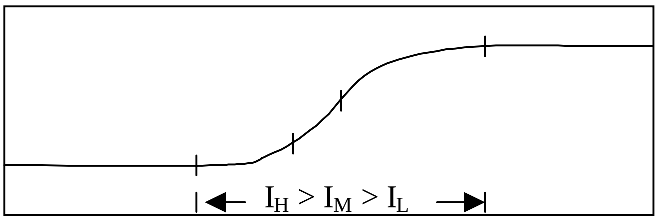


Fig.2: A typical ramp edge can be divided into three sections.

If it is located below the centerline, we reduce the intensity. If it is on or near the ramp's centerline, we have pixel's intensity unchanged. In this way the width of the ramp edge may be reduced and visually the edge becomes sharper. The result is shown in Figure 3.

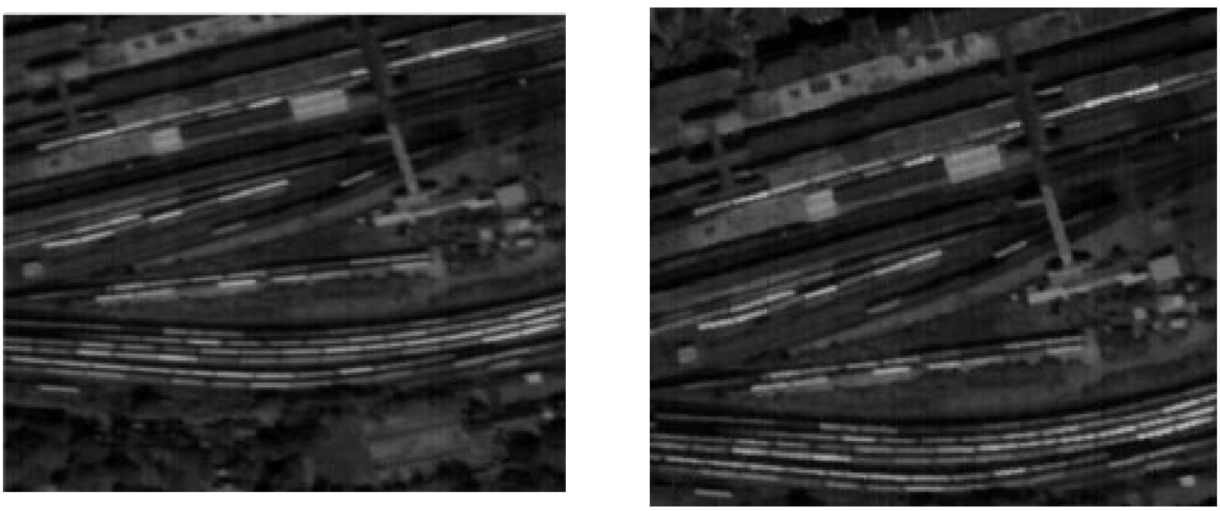


Fig.3: Original and deramped image ***Vertically scaled 1.14 times with 10% shift***

4. Deconvolution or Haze Filter

Recent work has recast linear filter operations as iterative algorithms. In this approach each estimate of the image is a linear combination of the previous and current estimates. We have adopted this as is explained below.

For whatever reason, if we have an image that has undergone deterioration, and we want to restore it, we will need to do the following. Let us imagine the observed image as the convolution of the initial image, f(x,y), with a point spread function, h(x,y); that is how a point would appear under identical conditions. This can be written as

$$g(x,y) = \text{observed image} = f(x,y) * h(x,y)$$

If we take the Fourier transform of this, we get

$$G(u,v) = F(u,v) \,.\, H(u,v)$$

Then, if we know the point spread function, we can restore the image by applying the equation

$$F(u,v) = G(u,v) / H(u,v)$$

So, the image in the frequency domain $G(u,v)$ is multiplied by a filter whose transfer function is $1/H(u,v)$. However, there are serious concerns here. $H(u,v)$ can have poles. This enhances noise. In practice, an additive noise, $N(u,v)$, should be added because it is present in the image. Thus our equation in frequency space looks like

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

And so now,

$$F(u,v) = \frac{G(u,v)}{H(u,v)} - \frac{N(u,v)}{H(u,v)}$$

Another criterion is well placed here, when $H(u,v)$ is small, then both the terms (including the noise term) can become large, and noise will be amplified. So, this means an initial image can only be incompletely restored. One technique to combat this problem is Wiener filtering. This technique consists of writing the image in restored form as

$$F(u,v) = [G(u,v)\, H^*(u,v)] / [H(u,v)\, H^*(u,v) + R(u,v)]$$

Where $H^*(u,v)$ is the complex conjugate of $H(u,v)$; R is the noise-to-signal power density ratio. This is a heuristic quantity, arrived at only empirically. No noise means that $R(u,v)$ equals 0, and the Wiener filter becomes the inverse filter.

Our implementation to restore the image, called 'Haze Filter', is done by iterative means; to reduce the noise typically found with Wiener filtering. Examining the following iterative equation:

$$q_{k+1}(x,y) = q_k (x,y) + [f (x,y) – q_k (x,y)*h (x,y)]$$

Where k is the iteration index, $q_{k+1}(x,y)$ is the image estimate at the k^{th} iteration, $f(x,y)$ is the original image, and $h(x,y)$ is the point spread function.

As the iteration index k increases, $[f(x,y) – q(x,y)*h(x,y)]$ approaches zero, and all that is left is $q(x,y)$, the ideal or intended image. In practice q_{k+1} is compared with q_k and if the change is minimal or below a threshold, the iteration stops. This is regularization process.

Here, we initialized $q_k(x,y)$ to $f(x,y)$. We used the Gaussian function for our point spread function $h(x,y)$:

$$h(x,y) = \exp[-(x^2 + y^2)/(2\ \text{sigma}^2)]$$

Gaussian is chosen for the following reasons:

(1) Basically, signal integration can be modeled as a rectangular function but its frequency version is a Sinc function and has poles. The main lobe is approximated as Gaussian, which avoids poles.

(2) Typically, PSF's are also modeled as Gaussian functions.

Next we calculate the next iteration $q_{k+1}(x,y)$ with negative values clipped to zero, so they have no meaning to us. This step is repeated till the intended image is got back. The result is shown in Figure 4.

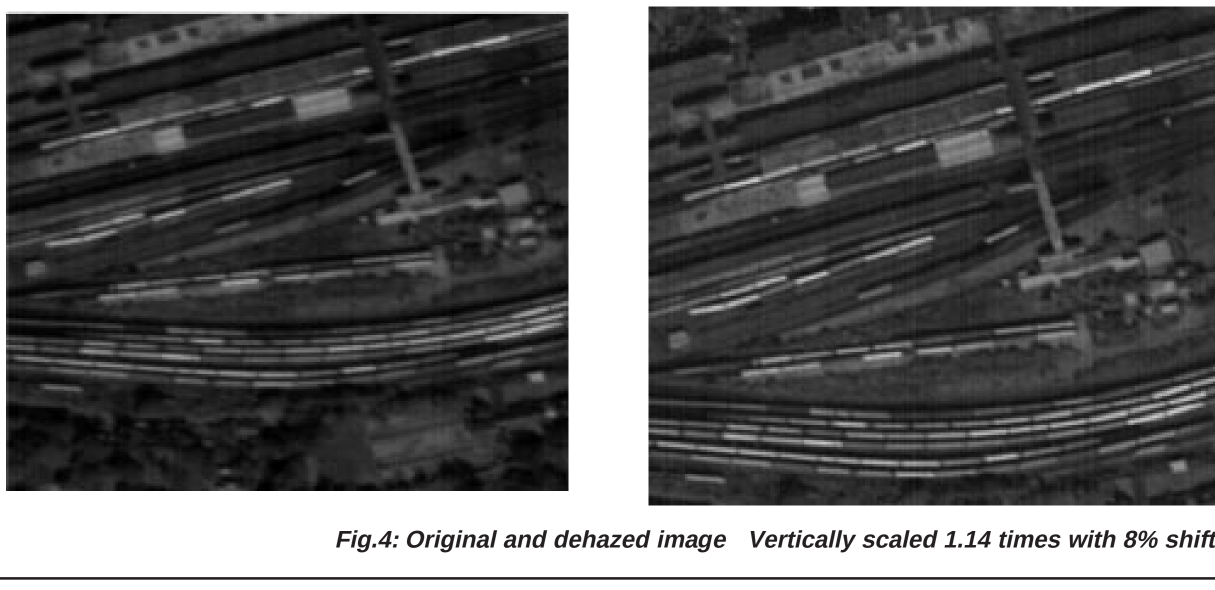


Fig.4: Original and dehazed image   Vertically scaled 1.14 times with 8% shift

5. Spread functions

The Modulation Transfer Function (MTF) tells how well a sinusoidally varying brightness of a given frequency will be reproduced by an imaging system. Again the modulation (peak minus trough divided by peak plus trough) is normalized usually by the modulation at zero frequency. The MTF carries essential information in terms of its intuitive appeal, while having a number of properties that make it easy to manipulate and solve for using linear system theory. For example, the 2-D inverse Fourier transforms of the MTF is the system impulse response or Point Spread Function (PSF). The PSF is the response of the system to a point source of radiation (mathematically the response to a delta function). Conceptually, this is the shape of the blurred image of a point source (i.e., the blur spot). The PSF is often used as a measure of resolution by measuring its full width at half maximum (FWHM). When the system's PSF is projected onto the ground, its FWHM is often referred to as the ground spot or ground sampled site.

A step function or edge can be thought of as being constructed by summing many sine waves of varying frequency and amplitude. A perfect edge contains all frequencies. If we introduce a knife-edge (i.e. a step function) as an input to an optical system, then the image along the perpendicular to the edge is the Line Spread Function (LSF). The derivative of the LSF with respect to position is Point Spread Function (PSF) in that direction as shown in Figure 5.

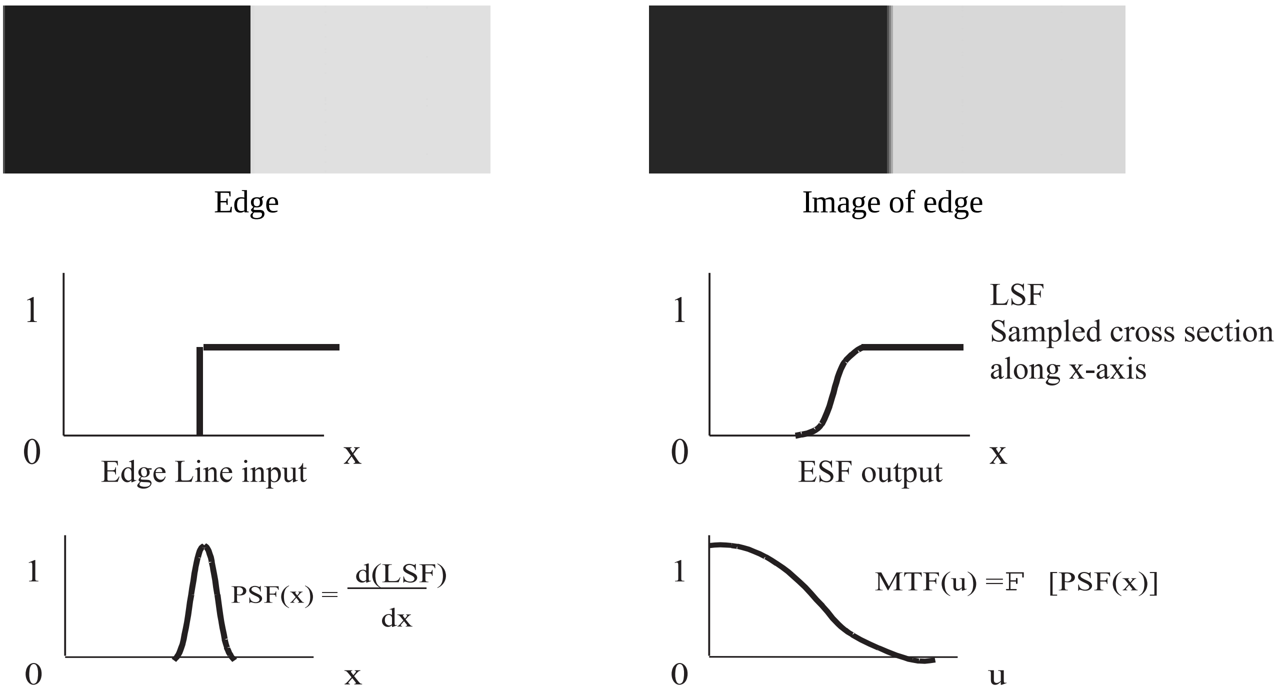


Fig.5: Relationship between the point spread function (PSF), line spread function (LSF) and the modulation transfer function (MTF) of a system.

6. MTF Compensation

6.1 Theoretical Background: The response of an individual pixel is a radiometric measurement arising from a two-dimensional spatially extended region of the field of view. The contribution from each portion of the region is proportional to the product of the PSF on the radiance, and the PSF is continually shifted relative to the scene by the forward motion of the satellite.

The Point Spread Function (PSF) of an image as already explained is the degree to which a perfect point in the object plane is blurred in the image plane. The continuous signal prior to sampling is the result of a convolution of the PSF with the scene, and after sampling is the result of a discrete convolution. Convolution can be described as "the operation whereby a structure under observation is smeared or spread out by the response or resolution of an instrument or mathematical operation". In the case of satellite imagery, the 'structure' is the radiance profile of the ground scene, and the 'instrument' is the on-board sensor.

The formula for the convolution of an object and a two-dimensional PSF is:

$$K(x,y) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} f(x-z, y-w)\, h(z,w)\, dz\, dw$$

where $K(x,y)$ is the ordinate at point x,y after convolution and f and h are two functions to be convolved.

However, for a digital image, where count values (usually with a dynamic range of 0 – 255) are measured rather than irradiance, then

$$g(x,y) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} f(x,y)\, h(z,w)\, dz\, dw \quad .... \quad (1)$$

or more simply;

$$g(x,y) = f(x,y)\, h(x,y) \quad .... \quad (2)$$

where $g(x,y)$ is the final image, $h(x,y)$ is the point spread function and $f(x,y)$ is the original image or object image.

If the point spread function is separable, i.e. $h(x,y) = h(x)h(y)$, then $h(x)$ and $h(y)$ are Line Spread Function (LSF) in the x- and y- directions, respectively, and the PSF is simply the product of the two line spread functions. For this study, this separability has been assumed. Assuming the symmetry of the PSF, a single dimensional PSF can be generated.

Three scene elements are appropriate for this exercise, which are (a) an impulse, which is narrower than the pixel size or IFOV (Instantaneous Field Of View) of the system, (b) a step or edge function, and (c) a rectangular pulse or double step function (Carnaham and Zhou, 1986; McGillem et.al.1983).

The curve derived from an edge scene element (or double step function if sufficiently wide) can be used to define PSF through the derivative method (McGillem et.al. 1983). However, as a rectangular object narrows to a spike or impulse the response would approach to that of the LSF itself. In other words, LSF is nothing but PSF when the object is very narrow like a jetty. This can be used directly without further processing.

6.2 Curve Extraction: A high-resolution image of approximately 1m ground sampling distance was used for the analysis of this work. The image showed three likely scene elements that would provide suitable data steps to develop LSF. The criteria used for choosing the scene elements are: (1) the feature must be linear; (2) the feature must have straight and sharp edges (or be less than one pixel wide); (3) the background should be of uniform reflectance; (d) the object should have uniform reflectance and have reasonable contrast to the background; and (e) the linear feature should be located at an angle sub-parallel to the satellite ground-track.

A sub-scene was chosen from the main scene that covered two test sites. These were (1) airport – referred as Hangar and is an edge feature; and (2) airport – referred to as Marker. Although, many features like jetty having double edge features can also be tried.

Image subsets of each of these scenes are shown in Fig.6. The marker consists of a white linear line at the middle line of the runway and the hangar has a brighter uniform foreground with a uniform darker background.

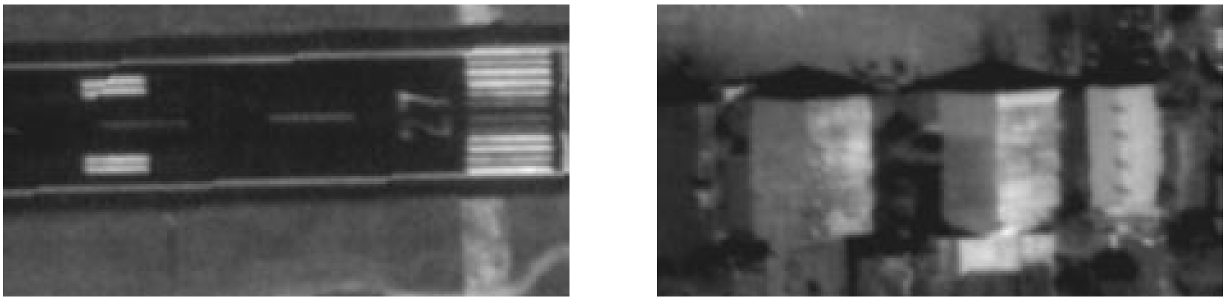


Fig.6: High resolution image (zoomed) sub-sets for (a) Marker and (b) Hangar

A sub-set of 20 image rows was examined for location of the peak brightness values, which occurred over the runway marker compared to the darker surrounding values. The method used was to find the line; pixel coordinates for the peak value of each row and then fit a least squares line to these values. This equation defines for each row the exact location of the peak value for that line. The image peak is located at a certain distance from the calculated peak value, and the set of values for the row are then shifted by the amount that the peak value was offset from the calculated peak value. Therefore for each row the brightness values are shifted to sub-pixel accuracy.

A set of similar arrays were combined and sorted to create a single array of brightness values at approximately 0.1 m sampling intervals. The shifted values for the marker and the hanger array are shown in Fig.7, where the values are plotted as a scatter plots around the central zero axis. The profile across the marker shows excellent definition of the reflectance curve.

The continuity of the data points shows the accuracy of the shifting technique. The sorted array can be used as an input data for curve fitting and further calculations.

Hangar was the second scene for which a shifted array of brightness values was derived. The method provides a high-frequency definition of the edge curve. The most significant feature is the resolution of the sharp peaks and low at both edges. This feature has a good foreground and background contrast.

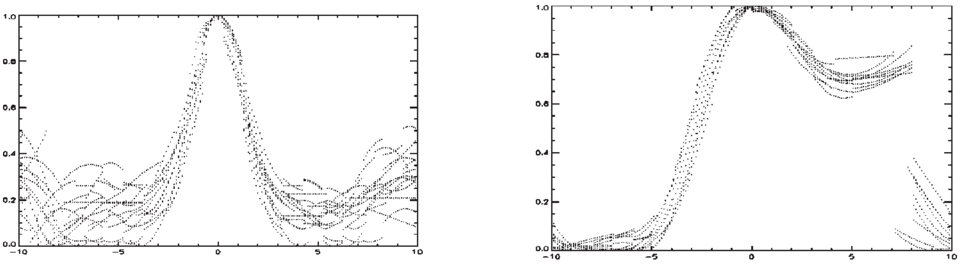


Fig. 7: Shifted brightness values verses distance for the (a) Marker and (b) Hangar array, around a central zero axis.

6.3 Derivation of PSF: The first step required was to fit curves to the image reflectance arrays. Once the edge response is defined as a polynomial function or equivalent vector of calculate points, then the line spread function can be derived through the derivative of this curve. As described previously, the line spread function is the first derivative of an edge exposure trace. Taking the first derivative of the fitted curve vector gives a line spread function vector. This approach can be applied to any edge scene such as APRON. The marker is too narrow, and this LSF itself is a PSF. The normalized amplitude of the Fourier transfer of the PSF results in Modulation Transfer Function (MTF).

The procedure followed was to fit a 15-term polynomial to the array of raw data to obtain as a close fit to the data as possible, and then to take the derivative of this function over the same range. The derivative calculation gives the LSF as a vector. The accuracy of this method is dependent on the accuracy and frequency content of the fitted curve. As we worked on the natural data, obtaining a symmetric PSF was almost impossible. To obtain a symmetric PSF, the best half of the fitted PSF (here, steepest slope was considered) was taken and mirrored to the other half replacing the unsuitable portion of the PSF. Modulation transfer function is nothing but the amplitude of the Fourier transform of the PSF, which showed an expected result.

6.4 Compensation: The intuitive approach is to invert the PSF matrix or compensate for the MTF. Here also, we adopted the iterative method as explained in section 2. In the deconvolution method the PSF was assumed to be Gaussian but here we generated the MTF from the data itself and inverted for its cause. Figure 8 shows the compensated image of Figure 6 in their zoomed forms.

7. Results

The approach described above to generate PSF as MTF was applied to the TES data. MTF compensation was applied on high resolution data at many locations. It can be seen that substantial image quality improvement in the image quality has resulted from the application MTF-compensation approach. To demonstrate quantitatively, we plotted a gray profile along a line before and after compensation as shown in left Figure 9. This clearly shows the improvement in contrast. The power spectrum also showed a boost in frequencies indicating overall image quality improvement as depicted in the right half of Figure 9. Figure 10 shows a result of MTF compensation.

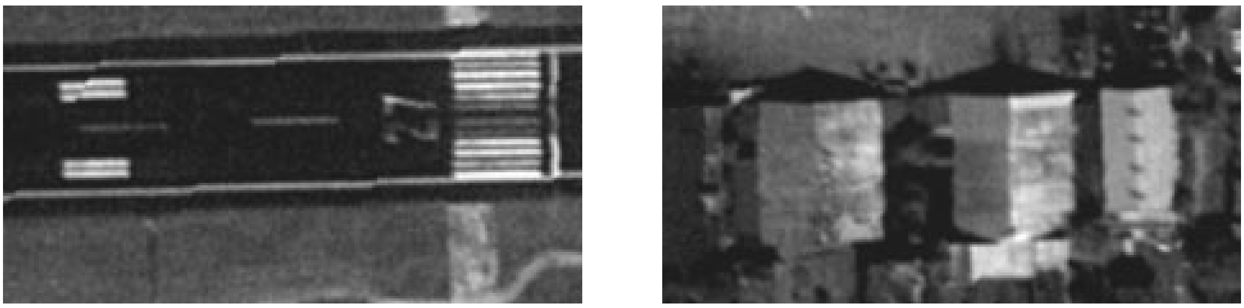


Fig.8: MTF-compensated images of fig 6.

8. Conclusions

The point spread function of high resolution image was determined using linear and edge features. The line spread function of the marker, possibly that of jetty or bridge can give the most accurate definition of the PSF. The MTF was calculated from the PSF. When the images were compensated for the MTF, the results provided greatly enhanced images when compared to original raw ones.

Because of non-nadir viewing nature and larger coverage, one needs to apply a range of filters for different parts of image and for different acquisition times. We propose to maintain look up tables of PSFs and MTFs to generate crisper and presentable quality of images operationally and automatically.

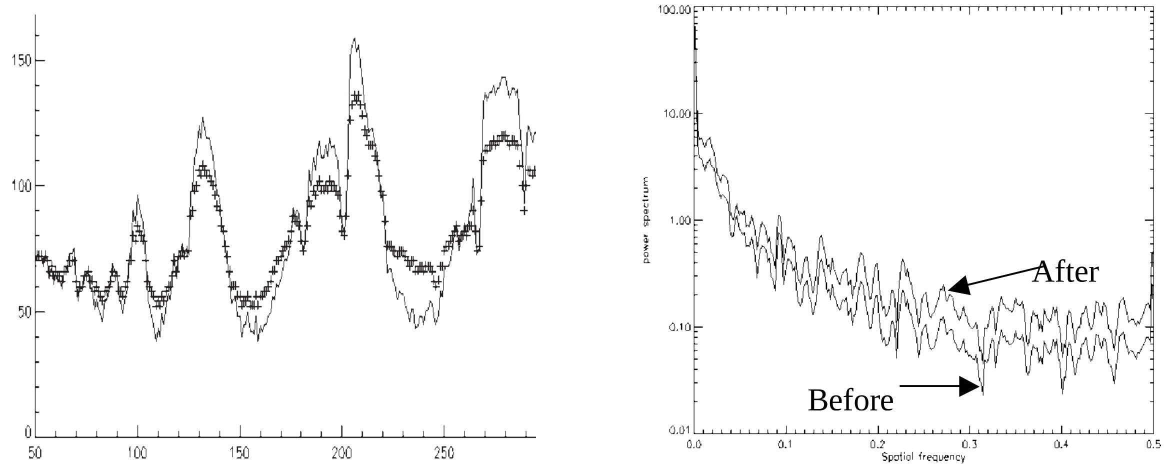
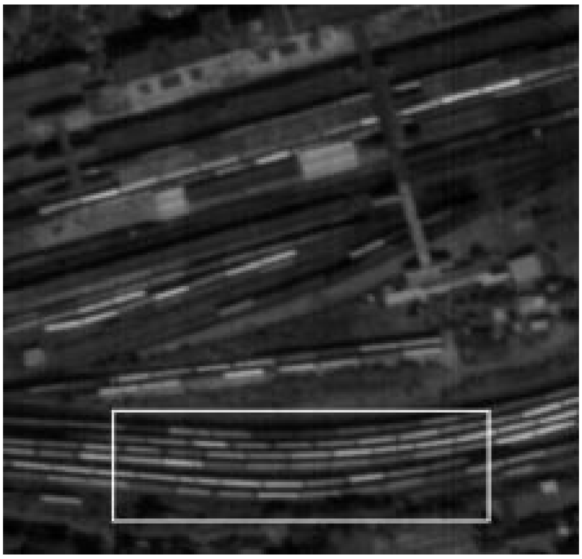
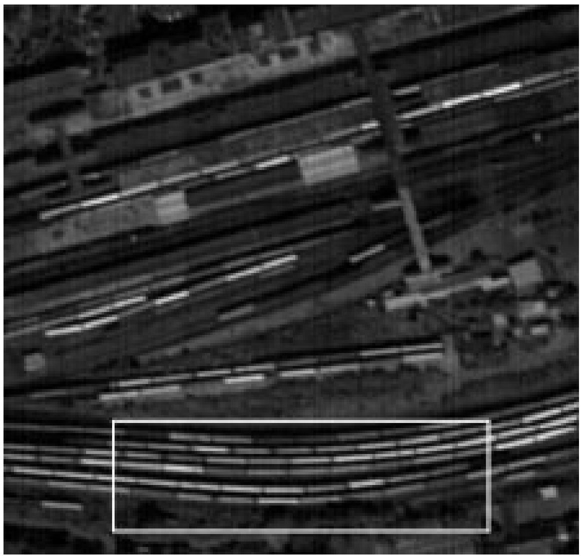


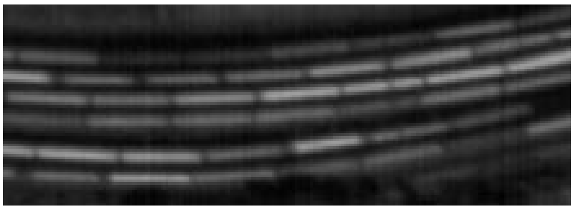
Fig.9: A gray level profile along a line: before (+) and after (-) in left. Power spectrum of the same is on the right.



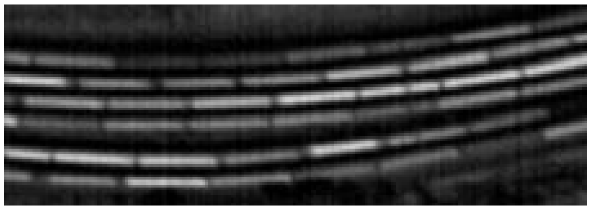
(a)



(b)



(c)



(d)

Fig.10: Original (a) and MTF-compensated (b) and their zoomed versions in (c) and (d) respectively.

9. Acknowledgement

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