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Evaluation of Atmospheric (MTF) Effects on Satellite Remote Sensing Image Quality

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***Abstract*—the nature of remote sensing requires that solar radiation pass through the atmosphere before it is collected by the sensor. Because of this, remotely sensed image, beside the information about the earth's surface, it is contaminated by atmospheric effects. In general, the quality of images is degraded due to the atmospheric effects. This image degradation can be quantified by the overall atmospheric MTF, which can divide into, the aerosol MTF and the atmospheric turbulence MTF. In this paper a simulation model is created in order to study the effect of the atmosphere on the image quality. [1]**

Keywords—atmospheric MTF, aerosol MTF, turbulence MTF, remote sensing image quality.

I. INTRODUCTION

Electromagnetic fields propagating through the atmosphere are attenuated by absorption and large angle scattering by aerosols. [2]

Absorption can be viewed as a reduction in the amount of radiation that reaches a sensor while scattering and turbulence result in image blurring and loss of detail. The blurring is quantified to describe its overall degradation effect on sensor performance. This degradation is characterized in terms of an atmospheric MTF. Atmospheric MTF can roughly be described as a reduction in contrast as a function of spatial frequency. The atmospheric MTF can be divided into: an aerosol MTF and turbulence MTF [3].

The imaging systems can usually be considered linear shift invariant (LSI) systems, where the LSI is defined as having the properties

$$L\{af(x-c)+bg(x-d)\} = aL\{f(x-c)\}+bL\{g(x-d)\}$$

Where, a and b are multiplicative constants and c and d are shifting constants. f(x) and g(x) are functions of the independent variable x, and L denotes the LSI operator.

Each system contributor or component has its own impulse response and transfer function including the atmosphere, optics, detector, electronics, mechanical aspects, display, and human vision. The system impulse response can be determined by the convolution of all the component impulse response and the system transfer function can be determined by the multiplication of all the component transfer function (just like circuit analysis). In imaging systems the transfer function is described by the modulation transfer function (MTF) [3].

II. TURBULENCE MTF

Turbulence results from random fluctuations in the atmospheric refractive index, which causes the light to arrive at different angles at the receiver (sensor). This results in image dancing, distortion, and blurring. The turbulence MTF for long exposures is represented by [4]

$$\text{MTF le} = \exp\left(-57.4\, a\, v^{\frac{5}{3}}\, Cn^2\, \lambda^{-\frac{1}{3}} R\right) \qquad (1)$$

Where a is unity for a plane wave and 3/8 for a spherical wave, λ is the measured radiation wavelength, Cn^2 is the turbulence strength factor, v is angular spatial frequency and R is the distance between the object being imaged and the sensor.

For short exposures (about 1 ms or less) the turbulence MTF is

$$\text{MTFse} = \exp\left(-57.4\, a\, v^{\frac{5}{3}}\, Cn^2 \lambda^{-\frac{1}{3}} R\left[1-\mu\left(\frac{v}{D}\right)^{\frac{1}{3}}\right]\right) \qquad (2)$$

Where D is the aperture diameter of the imaging system and μ equals 0.5 in the far field and 1 in the near field.

Turbulence MTF can noticeably affect the higher spatial frequencies of thermal images, this effect are attributed either to atmospheric turbulence, which causes deflection of the radiation from its original path.

The index structure parameter ranges from $1x10^{-15}m^{-2/3}$ for weak turbulence to$5x10^{-13}m^{-2/3/}$ for strong turbulence. Factors that increase the index structure parameter are strong solar heating, very dry grounds, clear nights with little wind, low altitude, and surface roughness. Factors that provide reductions in the index structure parameter are heavy overcast, wet surfaces, high winds, and high altitude [3].

III. AEROSOL MTF

In addition to turbulence, there are scattering and absorption caused by aerosols and molecules that exist in the atmosphere. Very little of the scattered light that is dispersed by aerosols reaches the imaging system mostly because of its limited field of view (FOV). Furthermore, some of the scattered light that reaches the receiver may not be detected because of the limited dynamic range of the detector and its limited bandwidth. Part of the unscattered light can be absorbed by such particulates. The scattering and absorption of energy by the aerosols affects all spatial frequencies, therefore causing edges in the image to be blurred and the image to be smoothed.

The aerosol MTF approximated by a Gaussian form for Simplification is represented by

$$MTF(v) = \begin{cases} \exp\left[-A_a R - S_a R\left(\frac{v}{v_c}\right)^2\right] & v \le v_c \\ \exp[-(A_a + S_a)R] & v \ge v_c \end{cases} \quad (3)$$

Where A_a and S_a are the atmospheric effective absorption and scattering coefficients, respectively, and vc is the angular spatial cutoff frequency at the aerosol MTF high frequency asymptote. In clear weather, vc is determined primarily by the optical instrumentation characteristics such as FOV, dynamic range and spatial frequency bandwidth of the imaging system. [4] The cutoff spatial frequency is approximately (a/λ) where a is the particulate radius. [3]

Typical, examples of some atmospheric particles are shown in Table (I) and scattering coefficients in different conditions in table (II). [3]

IV. PROPOSED ALGORITHM

The algorithm was done using MATLAB Simulink tools as in "Fig. 1,"

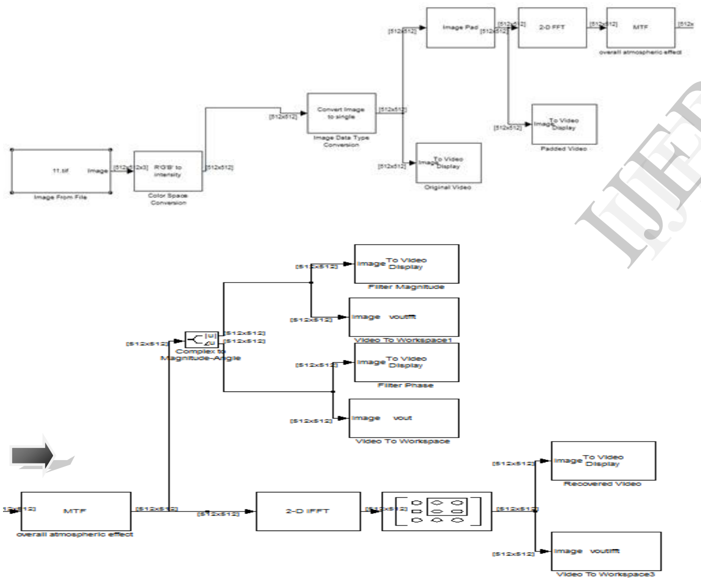

Fig (1) Algorithm of atmospheric MTF simulation

The algorithm is given below:

1. Read the Original Image
2. Convert it to RGB Image.
3. Converts and scales input image to specified output data type.
4. Pad or crop a two-dimensional input image.
5. Apply fast Fourier transform in two dimensions (2-D FFT).
6. Apply MTF equations (aerosol – turbulence – Both) to the input image.
7. Apply inverse fast Fourier transform (2-D IFFT).
8. Display the image.

V. QUALITY ASSESSMENT

Evaluation methods of the remote sensing data quality are generally classified into two types: the subjective evaluation and the objective evaluation [5].

A- Subjective fidelity criterion

RMSE is not the only measure to evaluate the reconstructed image quality. Two images could have the same RMSE but would have different visual quality. To solve this problem a subjective fidelity criterion is defined depends on the visual quality of the image evaluated by the Human Visual System (HVS). This can be accomplished by showing a typical decompressed image to an appropriate cross section of viewers and averaging their evaluations [6].

The subjective quality assessment of the image cannot be independent of the vision, but since human vision is not sensitive to the variation of image and it's partial that the image vision quality is absolutely depended on the observer, we need to synthetically evaluate the quality associating with the objective quality assessment standard. [7].

B- Objective fidelity criterion

The effect of atmosphere is expected to degrade the spatial resolution of the original images. In this paper we use Universal Image Quality Index (UIQI), Discrepancy (D), Root Mean Square Error (RMSE) and Peak Signal to Noise Ratio (PSNR) to assess the spectral quality of the degraded image. The spectral quality of the recovered images will be evaluated by comparing their spectral information with that of respective original one. This comparison is performed quantitatively using the following measures:

A) Universal Image Quality Index (UIQI) [8] The UIQI is designed by modeling image distortion as a combination of three factors; loss of correlation, radiometric distortion, and contrast distortion. It is defined by the following formula:

$$UIQI_i = \frac{4\sigma_{B_i^* F_i} \cdot \mu_{B_i^*} \cdot \mu_{F_i}}{\sigma^2_{B_i^*} + \sigma^2_{F_i} \left[\left(\mu_{B_i^*}\right)^2 + \left(\mu_{F_i}\right)^2\right]} \quad (4)$$

Where $\sigma_{B_i^* F_i}$ is the covariance between the bands of modulated images and the input (original) images, μ and σ are the mean and the standard deviation of the images. The dynamic range of UIQI is [-1, 1]. The higher UIQI the better spectral quality of the fused image.

B) Discrepancy (D) between the original images and the modulated images and it is defined as:

$$D = \frac{1}{M * N} \sum_{i=1}^{M} \sum_{j=1}^{N} |O(i,j) - F(i,j)| \quad (5)$$

Where $O(i,j), F(i,j)$ are the pixel values at position (i,j) in the original images and the modulated images respectively. M and N are the numbers or rows and columns of the image respectively. It is known that the spectral quality of the image increases as (D) decreases [9].

C) Root mean square error (RMSE)

It is the square root of the mean square error between the original and reconstructed image. It detects the difference between the reconstructed and the original image [10].

$$RMSE = \sqrt{\frac{1}{M \times N}\sum_{x=0}^{M-1}\sum_{y=0}^{N-1}(g(x,y)-f(x,y))^2} \quad (6)$$

Where:

- f(x,y)… The original or input image.
- g(x,y)… The output image (the reconstructed image after the compression-decompression process).
- M x N …. The image size.

D) Peak signal to noise ratio(PSNR)

Peak signal to noise ratio is defined as [10, 11]:

PSNR=

$$10\log\left[\frac{X_{max}^2}{\frac{1}{MxN}\sum_{x=0}^{M-1}\sum_{y=0}^{N-1}(g(x,y)-f(x,y))^2}\right] \quad [dB] \quad (7)$$

Where, Xmax is the maximum gray level (255 for 8-bit level) of the given input image. In case of multi-spectral satellite images the PSNR is multiplied by the number of image bands .The PSNR is more commonly used than the RMSE, because people tend to associate the quality of an image with a certain range of PSNR. Table 3 illustrates the PSNR values and its indication [12].

VI. Experimental Results and Conclusion:

1-Study of atmospheric turbulence effect

Case (1)

Range = 700 km.

Wave length = .55µm.

Index structure parameter $=10^{-15} m^{-2/3}$. (Weak turbulence))

Case (2)

Range = 700 km.

Wave length = .55µm.

Index structure parameter $=5x10^{-13} m^{-2/3}$. (Strong turbulence)

2- Study of atmospheric aerosol effect

Case (3)

Particulate radius = 10^{-2} cm^2

Wave length = .55µm.

Absorption coefficient = 1

Note that: the absorption is not a diffraction process and doesn't depend on spatial frequency .because when we set MTF (ν=0) =1 the absorption effect will be normalized out only the scattering process is important for development of an aerosol MTF. [6]

Scattering coefficient = 2 (Thin fog)

Case (4)

Particulate radius = 10^{-2} cm^2

Wave length = .55µm.

Absorption coefficient = 1.

Scattering coefficient = 78.2 (dense fog)

Here we use a data set from 5 images with different resolutions as in table (3) the results in table (4).

3-Study of the overall atmospheric MTF effect

Case (5) [weak turbulence + clear weather]

Under the following conditions

Range = 700 km.

Wave length = .55µm.

Index of refraction $=10^{-15} m^{-2/3}$. (Weak turbulence)

Particulate radius $=10^{-2}$ cm^2

Wave length = .55µm.

Absorption coefficient = 1

Scattering coefficient = .19 (clear)

Case (6) [strong turbulence + dense fog]

Under the following conditions

Range = 700 km.

Wave length = .55µm.

Index of refraction $=5x10^{-13} m^{-2/3}$. (Strong turbulence)

Particulate radius = 10^{-2} cm^2

Wave length = .55µm.

Absorption coefficient = 1

Scattering coefficient = 78.2 (dense fog)

We apply the different cases above to a different images with a different spatial resolution acquired from different sensors all with size 512x512 pixels illustrated in table 5. and Table 6 show the results of applying the spatial and the spectral quality metrics on the images.

VII. CONCLUSION

The aerosol MTF is dependent on the aerosol size distribution, absorption and scattering coefficients. Furthermore, the aerosol MTF actually recorded in the image is usually affected also by the optical and photoelectronic instrumentation, the aerosol MTF prediction is concentrated on predicting the aerosol size distribution that often performed by LOWTRAN and its successor MODTRAN which give very good results in the prediction of absorption attenuation according to the weather The distribution of coarse particles changes very sharply with weather. They give rise to small-angle forward light scattering and cause image blur.

The turbulence MTF is dependent on the index structure parameter Cn2 to predict it, notable computer programs such as IMTURB and PROTURB have been developed by scientists at the U.S. Army Atmospheric Sciences Laboratory. [13]

Aerosol blur, often referred to as the adjacency effect, is well-established as the primary and perhaps only source of atmospheric blur in remote sensing imaging from satellites. However, much of the propagation community considers turbulence blur only in interpreting experiments, and then notes discrepancies with turbulence theory without considering how broad system engineering approach is called for, which includes aerosols, turbulence and many other atmospheric effects. In general, turbulence is most significant at low elevations up to a few meters above earth's surface, and aerosol blur is most significant at higher elevations. [14]

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TABLE I. ATMOSPHERIC PARTICLES

Atmospheric particles		
Particle type	***Radius (µm)***	***Density (per cm^2)***
Air molecules		
Haze particles		
Fog droplet(mie)	1-10	10-100
Raindrops (Geometric)		

TABLE II. SCATTERING COEFFICIENT (FROM HOLST)

Scattering coefficient (from Holst)	
Condition	***Scattering coefficient***
Dense fog	78.2
Moderate fog	7.82-19.6
Thin fog	1.96-3.92
Haze	.98-1.96
Clear	.19-.39
Very clear	.078-.19

TABLE III. STANDARD EVALUATION OF SUBJECTIVE METRICS

Standard evaluation of subjective metrics		
Scores	Quality scale	Obstruction scale
5	Very good	Audiences can seldom find the image quality deterioration
4	Good	Audiences can find the image quality deterioration, but it doesn't impede watching
3	Ordinary	Audiences can clearly find the image quality deterioration, and it impedes watching slightly
2	Bad	It impedes watching
1	Very bad	It impedes watching very seriously

TABLE IV. THE PEAK SIGNAL TO NOISE RATIO AND ITS DESCRIPTION

The Peak Signal to Noise Ratio and its description	
PSNR	***Radius (µm) Density (per cm^2)***
Over 40 dB	Excellent image (i.e., being very close to the original image).
Between 30 to 40 Db	Good image (i.e., the distortion is visible but acceptable).
Between 20 and 30 dB	Acceptable.
Lower than 20 dB	Unacceptable.

TABLE V. DATA SET USED

Atmospheric particles		
Sensor	***Resolution***	***Place***
GeoEye-1	.5M	Arizona-USA
Ikonos	1M	Vancouver-Canada
Spot 5	2.5M	Shanghai-China
RapidEye	5M	Hawaii
COUNS	10M	Hawaii

TABLE VI. RESULTS

Atmospheric Effect	***Resolution***	**Objective fidelity criterion**			
		UIQI	***D***	***MSE***	***PSNR***
Case (1)	.5M	1	0	0	99
	1M	1	0	0	99
	2.5M	1	0	0	99
	5M	1	0	0	99
	10M	1	0	0	99
Case (2)	.5M	1	0	02	99
	1M	1	0	0	99
	2.5M	1	0	0	99
	5M	1	0	0	99
	10M	1	0	0	99
Case (3)	.5M	0.999987	0.06418	0.0991	8.17
	1M	0.99998025	0.112545	0.1983	55.15
	2.5M	0.99996915	0.124302	0.2616	53.95
	5M	0.999986	0.01667	0.0828	58.94
	10M	0.999993	0.00509	0.0334	62.88
Case (4)	.5M	0.989148	3.68901	141.4748	26.62
	1M	0.98802657	6.71129	299.9488	23.360
	2.5M	0.981576	7.39157	344.2767	22.76
	5M	0.977649	4.96517	180.7632	25.55
	10M	0.991651	3.48528	99.6658	28.14
Case (5)	.5M	1	0	0	99
	1M	1	0	0	99
	2.5M	1	0	0	99
	5M	1	0	0	99
	10M	1	0	0	99
Case (6)	.5M	0.989148	3.68901	141.4748	26.62
	1M	0.988026	6.71129	299.9486	23.36
	2.5M	0.981576	7.39157	344.2764	22.76
	5M	0.977649	4.96517	180.7631	25.55
	10M	0.991651	3.48528	99.6658	28.145

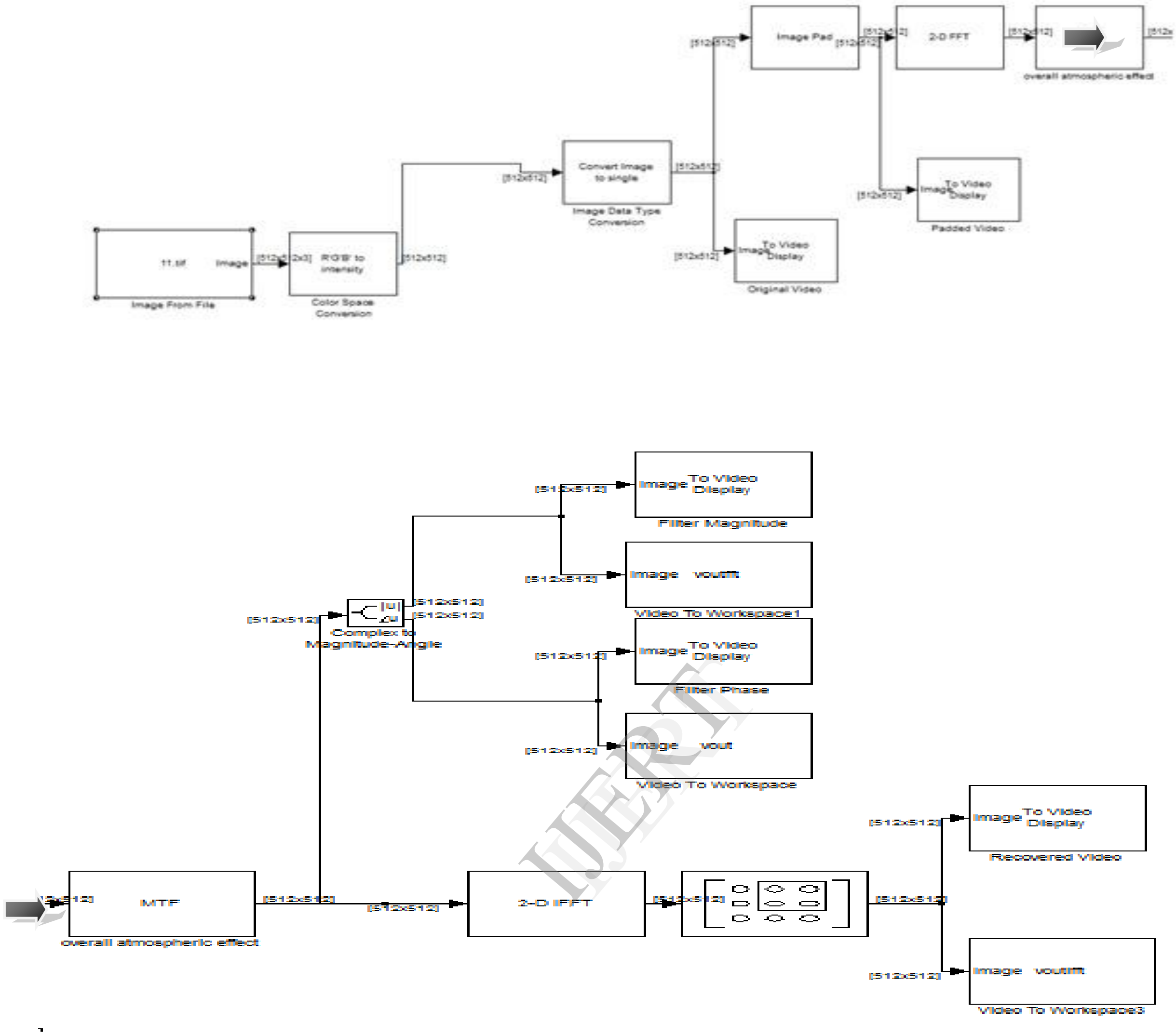

Fig (1) Algorithm of atmospheric MTF simulation