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EVALUATION OF ATMOSPHERIC PARTICULATE CONCENTRATIONS DERIVED FROM ANALYSIS OF RATIO THEMATIC MAPPER DATA

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ABSTRACT

Thematic Mapper (TM) data in several ratio formats were developed and analyzed with a view to evaluating their ability to indicate different intensities of particulate concentrations above urban areas. Specifically, October 25, 1982 TM data over Chicago, Illinois were analyzed using TM ratio band combinations of 1/2, 1/3, 1/4, 1/5, and 1/6. These data were analyzed in conjunction with EPA - measured particulate data over samples of a low-reflecting surface feature (turbid water) and samples of a high-reflecting surface feature (concrete highways).

The results of these analyses indicate that, for water, decreasing TM ratio values are associated with increasing particulate concentrations in all band combinations used. TM band 1/4 was the best to discriminate between different particulate concentrations over water. Over concrete features, the TM band 1/4 ratio values also followed the predicted pattern, but TM band 1/6 had ratios which were reversed from predicted values. This reversal is possibly attributable to atmospheric absorption and requires additional data inputs to understand.

I. INTRODUCTION

The availability of Thematic Mapper (TM) data has opened new avenues of research. One type of research which has been impossible to attempt using pre-TM satellite data is analysis of atmospheric particulates at a scale suitable to associate particulate density with a specific block or feature in an urban area.

Theoretically, it is possible to determine particulate concentrations in the atmosphere using TM multispectral data based on analysis of the effects of Mie scattering, incident solar radiation, and earth surface feature reflectivity have on spectral responses. It is necessary to compare short visible (or near ultraviolet) wavelengths with longer visible or near infrared (IR) wave lengths in a ratio format to suitably highlight particulate differences. For example, a ratio of blue-green light, such as provided by TM band 1 (.45 - .52 microns), with a reflective IR TM band has the potential to differentiate between atmospheric particulate densities. The 30 meter resolution of the TM data is sufficiently good to evaluate relatively small areas within an urban scene.

Foremost, this research will suggest and explore a preliminary methodology for assessment of atmospheric particulate concentrations derived from theoretical considerations. In situ particulate data (measured by EPA) from the Chicago metropolitan area have been compared and analyzed with spectral ratio data as developed using the methodology described in this paper. The results of these analyses are intended to support, but not prove the feasibility of using the methodology proposed. The focus and primary contribution of this paper is the suggestion of an approach for atmospheric particulate concentration evaluation using TM data. However, intensive testing and possible modifications of the suggested approach, utilizing more and better in situ measured particulate data than were available for this research, is necessary before practical applications are possible.

II. THEORETICAL FOUNDATION

Ratios of TM bands (e.g. 1/4, 1/5, and 1/6) should provide insight into atmospheric particulate concentrations in urban areas such as Chicago. The theory and data which suggest that various ratios can be used to identify concentrations of suspended atmospheric particulates are presented and discussed in this section of the paper.

The mean wavelengths of TM bands 1 through 6 were used in the development of selected tabular data (e.g. atmospheric transmission, solar irradiance) in order to make wavelength dependent calculations more manageable. The incident solar irradiance (ref. 1) at sea level, after passing through two atmosphere air masses, was calculated using mean wavelength data from Table 1. These data are given in Table 2. Thus, the water, carbon dioxide, and oxygen absorption that affect the solar spectrum in traveling to the earth and reflected out to space has been accounted for in the data provided.

Bouguer's Law, the exponential law of absorption (ref. 2), describes the transmission of light (T) through the atmosphere as:

$$T = e^{-\sigma x}$$

Where $T = I(x)/I_o$ is the transmission, I_o is the initial light intensity, $I(x)$ the light intensity after traveling a distance x, σ is the crossection, and x is the path length.

The Mie theory should be used to calculate the crossection. To perform this calculation it is necessary to know the number density of scattering centers per size interval $N(a)$ and the scattering area coefficient $K(a,n)$. where a is the radius of the scatters and n their index of refraction. Considering these parameters $\sigma = \int N(a)\, K(a,n) a^2 da$

These quantities are very difficult to ascertain; thus the cross section may be parameterized by: $\sigma = C/\lambda^2$ where the scattering centers particulate diameters are approximately the same size as the wavelength of the scattered light (ref. 3). In this equation C is a constant. The size of particulates in urban air pollution are reported (ref. 4) to range from .1 to 10 microns.

A primary focus of this research is the calculation of ratios of designated TM bands for any pixel at differing levels of particulate-induced pollution. Rather than attempt an absolute calculation, the constant C and path length x defined a new constant. This constant was adjusted in order that the transmission in TM band 1 assumes the values of 90%, 75%, 50%, and 25%. The transmission in each of the other bands was calculated based on a designated percent transmission for TM band 1 (Table 3).

Analysis of Table 3 highlights several important facts among which are:

1. The transmission of electromagnetic energy at TM wavelengths increases from band 1 through band 6 at all different levels of pollution concentration. For example, when TM band 1 has 75% transmission, band 6 has 99% transmission and when band 1 has 25% transmission, band 6 has 94% transmission.
2. The increase in transmission of electromagnetic energy at TM wavelengths between adjacent bands becomes particularly large when band 5 is considered. For example, considering the 50% band 1 transmission category, there is an absolute increase of 15% transmission between bands 4 and 5 while only a 9% to 10% absolute increase is common from bands 1 to 2, bands 2 to 3, and bands 3 to 4.
3. TM bands 5 and 6, even under conditions of heavy particulate pollution, have higher transmission characteristics than do visible TM bands (particularily bands 1 and 2).

Considering the data from Table 3 only, it can be seen that a TM ratio such as band 1/band 4 under conditions of 90% band 1 transmission is .900/.965 or .933. Under conditions of higher pollution and great particulate concentration such that band 1 has 50% transmission, the band 1/band 4 ratio is .500/.793 or .631. It is evident that lower ratio values theoretically will have higher particulate concentrations.

However, Table 3 transmission (T) data should not be used alone since variations in solar irradiance (S) between bands and variations in reflectivity (R) between bands for designated surface features may exist. Thus, data derived from the equation $T(\lambda)S(\lambda)R(\lambda)$ should be used to more accurately determine theoretical ratio values for particulate concentration estimation.

In this research, particulate concentration estimates derived from TM ratios were tested over low reflective somewhat turbid water sites and highly reflective concrete highways with similar physical characteristics. Table 4 presents R(λ) or reflectivity data (ref. 5) associated with selected water conditions. Table 5 contains the calculated T(λ)S(λ)R(λ) or TSR values associated with turbid water which were derived by multiplying transmission data (Table 3) by solar irradiance data (Table 2) by turbid water reflectivity (Table 4). These data can be used to calculate the ratios which initially can be used to estimate particulate concentration. For example, a TM 1/4 band ratio using Table 5 data gives a value of 3.35/4.46 or.751 assuming a 90% band 1 transmission. A TM 1/4 band ratio gives a value of 1.86/3.83 or 0.486 assuming a 50% band 1 transmission. It is evident that theoretically the smaller ratio value is associated with higher pollution/particulate concentration levels.

In the non-water and non-vegetation case of a highly reflective concrete highway class, the R(λ) is characterized by bands 1 through 6 reflectance values (ref. 6) indicated in Table 4. Table 6 gives the T(λ)S(λ) R(λ) or TSR values associated with this highly reflective concrete highway dominated feature. Tables 5 and 6 provide data which can be used to predict the ratios which, theoretically, are most likely to be effective in discriminating and estimating particulate concentration above pixels of turbid water and concrete dominated features.

The analysis of radiance from high reflectance surfaces is complicated by the presence of absorption. Radiative transfer model calculations (ref. 7) of the light scattered by absorbing atmospheres reveal a completely different behaviour for high reflectance surfaces than for low reflectance surfaces. The behaviours outlined above in the single scattering approximation remain valid for low reflectance surfaces even in the presence of absorption or multiple scattering.

These model calculations reveal that in the presence of absorption by the atmospheric aerosols for surfaces of high reflectance an increase in the density of scattering particulates leads to a decrease in the radiance observed by the satellite. As an example, a surface with a reflectivity of .55 modeled in the .5 - .6 micron band produces 82% of the radiance seen without any atmosphere under conditions of an average absorbing haze (Figure 1). An increase in the number of scatters without increasing the relative amount of absorption to represent strong haze reduces the radiance to 70% of that seen without any atmosphere (ref. 8).

From this it follows that there exists a critical reflectance where, in the presence of absorption, any change in the density of scatters produces no change in the radiance observed by the scanner. The value of this critical reflectance depends upon the proportion of absorbers and how they are mixed with the scatterers as well as the size distributions.

The ratios which can be developed from Table 6, that are solely derived from standard T(λ)S(λ)R(λ) values, do not incorporate all the data which might be occasionally important under conditions such as those discussed above. Additional data, particularly those of critical reflectance value and albedo for single scattering, may require evaluation in some cases. Thus, under some circumstances, theoretically derived ratios from Table 6 realistically might be expected to vary from those derived from actual spectral and in-situ particulate analysis. However; the values presented in Table 6 include the dominant parameters associated with evaluation of particulate concentrations, thus they are suitable to use for an initial analysis over highly reflective concrete features. Refinement of this Table to consider other, usually less important factors, will be considered in future phases of this research.

III. THE STUDY AREA, IN-SITU DATA, AND SPECTRAL DATA CHARACTERISTICS

Thematic Mapper data (scene ID 40101-16025) were acquired at 9:02 a.m., Monday, October 25, 1982 for the Chicago Metropolitan and surrounding area. Three 512 by 520 pixel subareas were extracted from the full frame for analysis in this research. Each of these subareas contained all seven TM bands registered on a separate file of a computer compatible tape(CCT). Each subarea focused on a different part of the city and included segments of: (1) O'Hare International Airport area, (2) Inner City, and (3) Lakefront (residential, commercial, and Lake Michigan water). Collectively, parks, forest, water, commerce, industry, transportation (road, air, and rail) and various densities of residential areas are found in the three study areas. Within these areas is a diversity of particulate pollutions patterns in the metropolitan area.

Particulate data (ref. 9) were collected by the EPA at 52 sites in the greater metropolitan area at noon, Tuesday, October 26. Measurements of particulates were in units of micrograms per cubic meter. Eleven of the 52 particulate collection sites were in the three small study areas. The range of particulate concentrations in these eleven sites ranged from 98 to 172; a range which almost encompassed the range of the entire 52 sites. Compared to yearly average statistics, the particulate concentration was above average on October 26. The EPA collection sites were described in such geographic detail that they could be located to the pixel on 1:24,000 USGS topographic maps which were used to provide some ground information about the study sites.

There was a 27 hour difference between time of TM data collection and EPA particulate data collection which conceivably could make it difficult to compare spectral data with particuate data. However, climatic conditions were analyzed (via NOAA weather maps) and on both days (October 25 and 26) the Chicago area was in the middle of a high pressure cell with virtually no wind (calm to 5 mph NNW winds). This information in combination with the fact that both days of data collection were typical work days led the authors to conclude that the particulate concentrations measured by EPA on October 26 adequately represented the particulate concentrations on the October 25th date of TM data collection.

IV. METHODOLOGY

The methodology employed in this research focused on developing and analyzing data to evaluate the hypothesis that TM data in ratio format are a potential indicator of atmospheric particulate concentration intensity. This methodology did not intend to address data development to the point of operational use of TM ratios to estimate particulate concentrations in Chicago; however, development of such a methodology is possible to consider if the TM ratio analysis conducted in this research basically supports the theory developed.

Thematic Mapper relative spectral responses were analyzed for two types of ground features in the Chicago metropolitan area. These features were low reflectance slightly turbid water and high reflectance concrete highways. The spectral data associated with each one of these classes of features were developed in a different manner because the water samples generally were not geographically centered at an EPA particulate collection site while the concrete features analyzed were centered at an EPA particulate collection site. The reason for this difference was due to the paucity of water sites (except for Lake Michigan), only one of which was directly adjacent to an EPA collection site. Water sites of a similar turbid character were identified in the study area using the first four TM bands as input into a supervised non-parametric classification procedure. The EPA particulate measurements associated with these water sites selected were estimated by analyzing the particulate values at the nearest EPA measurement station in conjunction with dominant wind direction and major particulate sources between an EPA measured point and the water test site. In general, the EPA site and water sites were within 3 km of each other.

The particulate data associated with water sites, in the three subareas of the greater study area, were considered to be satisfactory for the ratio analysis suggested by theory. Specifically, TM ratio data of the band combinations 1/2, 1/3, and 1/4 were developed and evaluated. The TM ratios 1/5 and 1/6 were not developed because the water almost totally absorbed the electromagnetic energy associated with TM bands 5 and 6, thereby making of these ratios difficult to interpret in this single scattering approximation.

A large number of concrete test sites were available for analysis. It was not difficult to locate some of these concrete test areas at or very near an EPA particulate measurement site. Initially, a supervised non-parametric classification approach was implemented using the first six bands of TM data. This classification isolated a relatively homogeneous class of concrete features associated with highways.

A program was written which randomly selected pixels which were classified as concrete that were found within a 60 by 60 pixel matrix centered on an EPA particulate measurement site. Five such sites were evaluated; two sites had low particulate concentration, one site had moderate particulate concentration, and two sites had high particulate concentration. Each one of the five sites was evaluated three times using different sets of randomly selected concrete-classified pixels. This program was used to develop TM ratio values for 1/4, 1/5, and 1/6 for each randomly selected concrete-classified pixel. It was these three ratios which theoretically were likely to provide the most discrimination between different levels of particulate concentrations. The mean value, standard deviation from the mean, and a measure of statistical significance was calculated for each set of concrete-classified pixels. Ratio set statistics which had acceptable standard deviations and level of significance were used to evaluate the hypothesis of this research.

V. RESULTS AND DISCUSSION

The use of TM ratios to evaluate particulate concentrations above earth features is, in some ways, less complex if the earth feature has low reflectance properties. Particulate concentration estimates above high reflectance features can be greatly effected by the factors discussed in the previous section of this paper. Thus, a TM ratio analysis from each one of these different types of reflectance surfaces requires individual discussion.

A. LOW REFLECTANCE--TURBID WATER

Particulate and TM ratio data for turbid water are presented in Table 7 and Figure 2. It is evident from analysis of these data that the pattern of increasing particulate concentration is associated with decreasing ratio values. This pattern is consistent for all three ratios analyzed. Thus, what was anticipated in theory from Table 5 is supported by actual measured spectral and particulate data. Also, as predicted from Table 5, the TM 1/4 ratio discriminates particulate concentrations better than does TM ratios 1/3 or 1/2. For example, in Table 5 the 1/2 ratio at 90% band 1 transmission is .55 which decreases to 0.47 for the 1/2 ratio at 50% band 1 transmission. However, comparable values of the TM 1/4 ratio is .72 (at 90% band 1 transmission) and .49 (at 50% band 1 transmission). Both the TM 1/2 and 1/4 ratios support the hypothesis that decreasing ratios are associated with increasing particulate levels, but the TM 1/4 ratio does so more effectively than either the 1/3 or 1/2 ratio.

B. HIGH REFLECTANCE--CONCRETE HIGHWAY

Particulate and TM ratio data for a concrete feature are given in Table 8 and Figure 2. It is evident that in a comparative analysis of these actual data with the theoretical data from Table 6 that there is good correspondence in some instances and a reverse of anticipated results in other instances.

Three different trends are observed from an examination of the ratios for the high reflectance pixels. The ratio of band 1 to band 4 has the behaviour expected from a non-absorbing atmosphere or a low reflectance surface. The ratio of band 1 to band 5 is essentially a constant independent of the amount of particulates. This behaviour is similar to that of a surface with a critical reflectance. Finally, the ratio of band 1 to band 6 exemplifies the behaviour expected from a high reflectance surface with an absorbing atmosphere.

There are several speculations that might explain this behaviour. The simplest assumption would be that the atmospheric absorption mechanism is sensitive to the wavelength of light with a cut-on wavelength between 1 and 2 microns. An alternate assumption would be that the actual reflectance of the surface changes rapidly among bands 4, 5, and 6 with the surface behaving like a low reflectance surface in band 4 and a high reflectance surface in band 6. Some experimental measurements of surface reflectivity taken by NASA support this contention (ref. 5). Additional data and research will be required to better understand selected TM 1/5 and 1/6 ratio relationships with atmospheric conditions.

VI. SUMMARY AND CONCLUSIONS

This research has demonstrated that there exists a good potential to correlate TM band ratios with the amount of particulates in the atmosphere. We expect to continue this work and improve the results in several ways.

Preparation is being made to expand the theoretical treatment so that the effects of multiple scattering and absorption in a calculation utilizing the radiative transfer equation can be included. The use of a simple parametization of Mie scattering and absorption is anticipated.

In order to solidify the correlations developed in this paper it is necessary to acquire more particulate data. Further, these data should be limited to the inhalable particulates (less than 10 microns in diameter). Another difficulty involves the extrapolation of the particulate data from the EPA measuring site to the pixels of interest. We have begun to approach this problem by an application of some of the smaller eigenvalues (the "yellowness" vector) in the Tasseled Cap transformation.

To further refine the methodology, other surfaces such as asphalt or gravel roofs should be evaluated in instances where it is possible to utilize measured values of the reflectance to further refine the methodology. The long term goal in this project is to develop a method that will make it possible to predict the amount and absorptivity of particulates in the atmosphere.

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Table 1. Thematic Mapper Wavelength Characteristics.

Band	Minimum Wavelength (microns)	Maximum Wavelength (microns)	Mean Wavelength (microns)	Width (microns)
1	.45	.52	.48	.07
2	.52	.60	.56	.08
3	.63	.69	.66	.06
4	.76	.90	.83	.14
5	1.55	1.75	1.65	.20
6	2.08	2.35	2.22	.27

Table 2. Solar Irradiance Characteristics Associated with Thematic Mapper Bands.

Band	Solar Irradiance (Watts/m^2)
1	82.8
2	94.6
3	70.0
4	120.8
5	39.8
6	20.4

Table 3. Percent Atmospheric Transmission of TM Bands 1-6.

	Atmospheric Transmission (T%) of TM Band 1			
Band	T=90	T'=75	T''=50	T'''=25
1	.900	.750	.500	.250
2	.925	.809	.601	.360
3	.946	.859	.693	.480
4	.965	.908	.793	.629
5	.991	.976	.943	.889
6	.995	.986	.968	.937

Table 4. Reflectivity of Selected Earth Features in TM Bands 1 through 6.

Band	Reflectivity(R) Clear Water	Reflectivity(R) Turbid Water	Reflectivity(R) Concrete Highway
1	.038	.045	.195
2	.050	.070	.248
3	.035	.085	.281
4	<.010	.040	.302
5	<.010	<.010	.363
6	<.010	<.010	.338

.01 = 1% reflectivity

Table 5. TSR Values of TM Bands 1 through 6 for Turbid Water at Selected Atmospheric Transmissivities.

Band	T(λ)S(λ)R(λ) (Band 1/T=.90)	T(λ)S(λ)R(λ) (Band 1/T=.75)	T(λ)S(λ)R(λ) (Band 1/T=.50)	T(λ)S(λ)R(λ) (Band 1/T=.25)
1	3.35	2.79	1.86	.93
2	6.13	5.35	3.98	2.39
3	5.63	5.11	4.12	2.86
4	4.66	4.39	3.83	3.04
5	0	0	0	0
6	0	0	0	0

Table 6. TSR Values of TM Bands 1 through 6 for a Concrete Highway at Selected Atmospheric Transmissivities.

Band	T(λ)S(λ)R(λ) (Band 1/T=.90)	T(λ)S(λ)R(λ) (Band 1/T=.75)	T(λ)S(λ)R(λ) (Band 1/T=.50)	T(λ)S(λ)R(λ) (Band 1/T=.25)
1	14.53	12.11	9.30	4.04
2	21.70	18.98	14.10	8.45
3	18.60	16.90	13.63	9.44
4	35.21	33.13	28.74	22.79
5	14.30	14.10	13.62	12.84
6	6.86	6.80	6.68	6.46

Table 7. Thematic Mapper Ratio Data and Associated Particulate Concentrations for Turbid Water

TM Band Ratio Value (multiplied by 25)			EPA Particulate Value (μg/cu meter)
1/2	1/3	1/4	
67	49	126	172
69	91	144	146
70	94	167	104
74	109	200	<104

Table 8. Thematic Mapper Ratio Data and Associated Particulate Concentrations for Concrete Highway.

TM Band Ratio Value (multiplied by 25)			EPA Particulate Value (μg/cu meter)
1/4	1/5	1/6	
46	29	57	98 (Low)
42	28	60	132 (Medium)
37	31	69	169 (High)

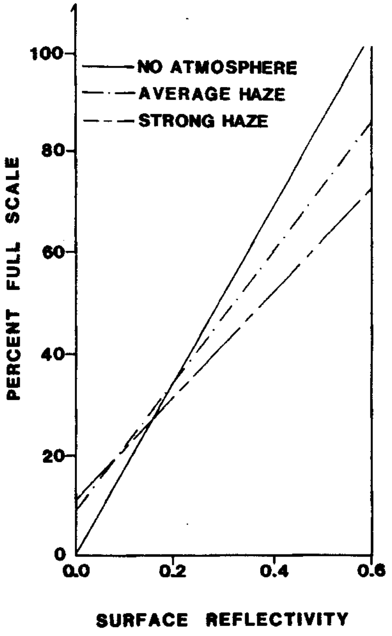

Figure 1. Apparent Reflectivity as a Function of Surface Reflectivity. Each curve represents a different concentraton of an absorbing atmosphere.

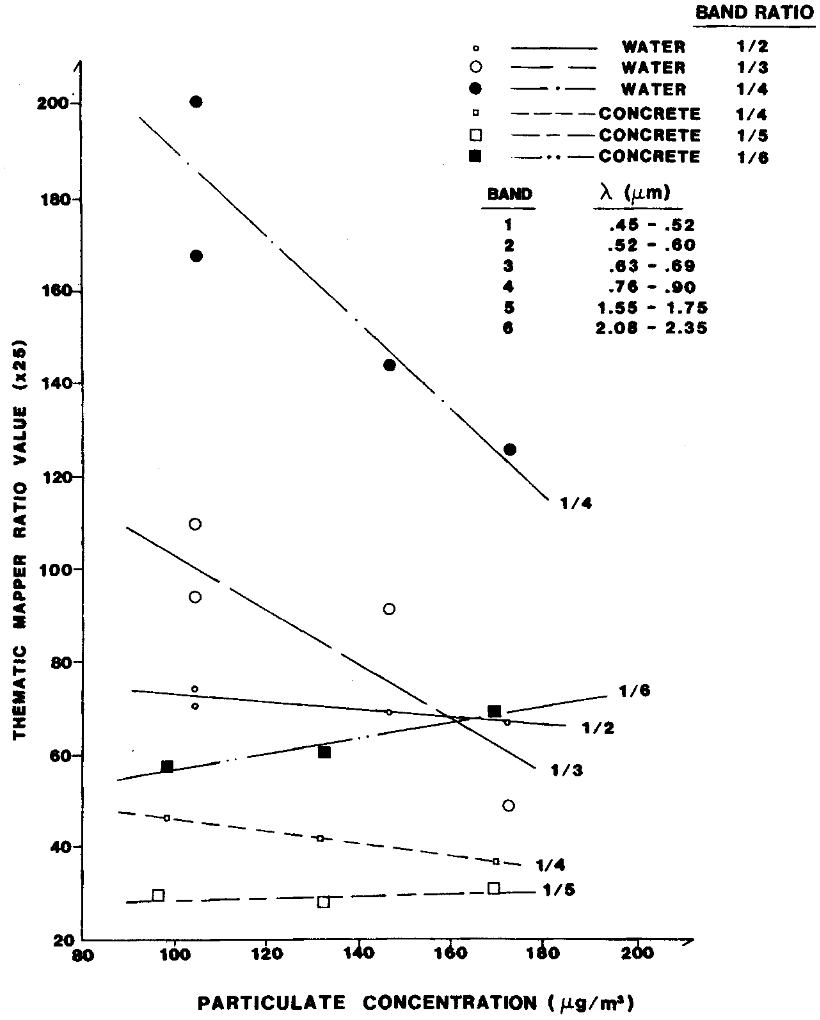

Figure 2. Plots of Particulate Concentrations Associated with Selected TM Band Ratios from Water and Concrete Sites in Chicago, Illinois.