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Retrieval of aerosol parameters from the oxygen absorption band of Hyperion hyperspectral image validated with spectroradiometry

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Abstract

This work presents a method for assessing spatial distribution of aerosol effect using the sharp absorption band of atmospheric oxygen (O_2-A) around 760 nm of radiation. The measured radiance spectrum acts as the information source and no other reference like the extraterrestrial radiation is needed for calibration. A simple mathematical model is presented for the aerosol optical depth that is validated with spectroradiometric data and Hyperion hyperspectral image analysis for urban aerosols. Comparing the extent of radiation absorption due to aerosol with that due to cloud cover and seasonal variations it is concluded that the present method is suitable for comparing the aerosol effect at different places under the same atmospheric condition.

1. Introduction

Atmospheric aerosols like marine salt, mineral dust, biological debries, organics, soot and industrial dust suspended in air have significant influence on global climate through absorption of solar and terrestrial radiation, cloud formation, precipitation, transport of pollutants and other atmospheric phenomena. Aerosol effects are estimated with both active remote sensing techniques with lidars [1] and passive remote sensing of radiometric measurements [2]. International collaborations are established on ground based measurements of aerosol, such as EARLINET [3] and AERONET [4]. Different satellite based systems, such as POLDER & MERIS [5], MODIS [6], METEOSAT [7] and SCIAMACHY [8] are applied to aerosol estimation and intersystem comparisons are also executed [5,9].

An important parameter in connection with the spatial distribution, particulate concentration and size estimation of aerosols is the optical depth, which is estimated with Beer-Bouguer-Lambert law [4] using the information on the transmission of radiation of some specific wavelengths through the atmosphere with less attenuation. The extraterrestrial radiation at the top of the atmosphere is needed as a reference.

In the case of strong gaseous absorption wavelengths, the present work treats the absorption phenomenon in a different way and puts forward a simple method for estimating the aerosol optical depth using the O_2-A band and validates it with ground-measured spectroradiometric data. It is different from the earlier studies [5] in that it employs two non-absorbing band, instead of one, on either side of the absorbing band. No reference parameter like top-of-atmosphere reflectance is needed. The advantage of using O_2-A band is its precise, universal location at different atmospheric conditions. The sharp absorption band enables a hyperspectral instrument to measure accurately the absorption peak and the oxygen absorption takes place irrespective of the source and the intensity of illumination.

2. Methodology

2.1. Working Principle

For a radiation of wavelength λ penetrating the atmosphere, the radiance (L_λ) after traversing the atmospheric column is generally expressed in terms of Beer-Bouguer-Lambert law. However, the present formulation in the case of strong gaseous absorption wavelength, such as that due to the O_2-A band is developed in a different way as follows. For any arbitrary wavelength, the radiance (L_m) measured at the sensor is the algebraic sum of the source radiance (L_s) emitted from the source or reflected from the object surface, atmospheric gaseous absorption, if any, and path radiance (L_p) acquired due to scattering from aerosols and Rayleigh scattering. For the NIR wavelength range (750–775 nm) around O_2-A band, Rayleigh scattering is negligible and only the aerosol contribution is significant. The water vapour absorption is assumed to be uniform except for the strong absorption bands (around 710-740 nm and 800-840 nm) beyond the range under consideration. Therefore the measured radiance at the wavelength of maximum absorption within O_2-A band can be expressed as

$$L_{ma} = TL_s + L_{pa} \quad (1).$$

T is the atmospheric transmittance in this band. The subscript 'a' stands for 'absorption'. For any other non-absorbing wavelength outside this band, the measured radiance is

$$L_m = L_s + L_p \quad (2).$$

Here T becomes unity (100%) because of no specific gaseous absorption. If L_s becomes negligibly small, the measured radiance (L_m) is essentially the path radiance (L_p). The transmittance in O_2-A band is obtained from Eqs. (1) and (2). If, instead of a single wavelength, several reference wavelengths are used, (2) can be generalized as (Schlapfer et al. 1998)

$$T = \frac{L_{ma} - L_{pa}}{\sum_i w_i (L_{mi} - L_{pi})} \quad (3).$$

Here w_i is the relative weight of the i-th band. For each wavelength pair λ_1 and λ_2 on either side of the absorbing wavelength λ_a, the weights are expressed as

$$w_1 = \frac{\lambda_2 - \lambda_a}{\lambda_2 - \lambda_1} \text{ and } w_2 = \frac{\lambda_a - \lambda_1}{\lambda_2 - \lambda_1} \quad (4).$$

The atmospheric path radiance within O_2-A band may or may not be equal to that outside the band. In either case, the former can be expressed as a fraction or multiple of the later so that

$$L_{pi} = q_i L_{pa} \quad (5).$$

q_i being a constant of proportionality for the i-th band. Using (5) in (3) and rearranging one can obtain a relative optical depth for the gaseous absorption as

$$T_0 = T + \frac{L_{pa}}{\sum_i w_i L_{mi}} (1 - T \sum_i w_i q_i) \quad (6).$$

$T_0 = \frac{L_{ma}}{\sum_i w_i L_{mi}}$ is the experimentally measurable relative optical depth of O_2-A band in presence of aerosols. Equation (6) includes the contribution of both oxygen absorption and aerosol scattering. Putting $L_{pa} = 0$ in (6) makes $T_0 = T$ indicating that in absence of any aerosol, the relative optical depth corresponds to the transmittance in O_2-A band is solely due to the gaseous absorption. It is termed 'relative' because the absorption is estimated with respect to the measured spectral data itself. No absolute reference, such as the extraterrestrial radiation is considered for the radiation passing through the atmosphere.

2.2. Ground Truth and Image Analysis

The area under spectroradiometric study was a populated urban zone of Kolkata metropolis (22°39′19.24" N, 88°23′00.33" E). The incident solar irradiance spectrum was measured at 1.4 nm resolution throughout the ultraviolet-visible-near-infrared (UV-vis-NIR) range with Analytical Spectral Devices FieldSpec spectroradiometer fitted with remote cosine receptor on 25° field-of-view fiber and kept facing vertically upward irrespective of the solar elevation. Data were collected at different seasons and different atmospheric conditions placing the instrument in open air at the same place and height. Generally the measurements were taken at around solar noon. In order to compare the measured data with those derived from satellite images, Hyperion hyperspectral images for Kolkata and nearby area (centred around 22°35′ N, 88°24′ E) were downloaded from USGS website. ENVI 4.7 image processing software was used for the analysis. The raw DN values obtained from the pixels at different wavelengths were converted to reflectance using the standard technique.

3. Results and Discussion

Figure 1 compares the spectral variation of the optical depth determined from the present measurements with the standard results obtained from several nearest available AERONET sites, both being based on Beer-Bouguer-Lambert law. The optical depth values obtained with the present measurements [Figure 1(a)] were calculated for the wavelengths having minimum fluctuation in radiance with respect to that in neighbouring wavelengths. Strong absorption bands like that of oxygen or water vapour were avoided. The standard AERONET data [Figure 1(b)] were procured for the same or nearest day as that of the present measurement for the same and previous years, as far as possible. It is noted that the absolute values change widely but the nature of variation remains the same as that of Figure 1(a), which justifies that the relative change in irradiance values with wavelengths can produce similar information on optical depth as that obtained from absolute values. This concept is applied in the present methodology.

Figure 2 generates different theoretical values of optical depth using (6) changing q_i and L_{pa} parameters. The aerosol path radiance values are assigned as different percentages of the measured radiance (L_{ma}) within O_2-A band; zero percent being the state of no aerosol. It is noted that even with much exaggerated values of q_i, the transmittance does not reduce by more than 17%. Therefore, it is not unjustified to assume $q_1 = q_2 = 1$ meaning the same path radiance throughout the wavelength range under consideration.

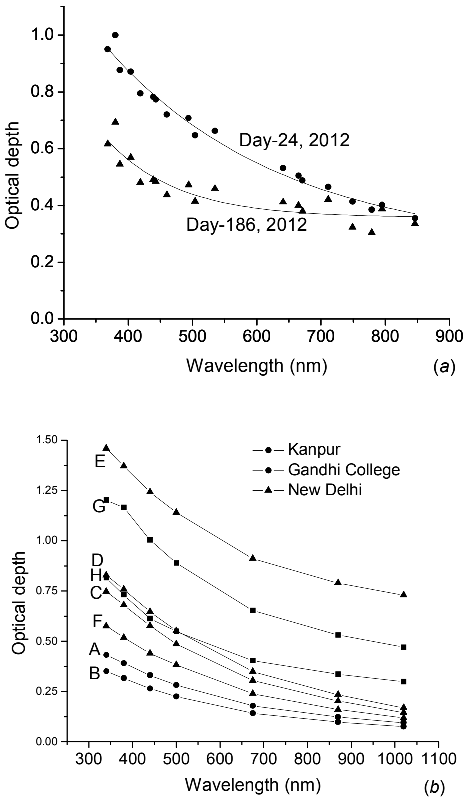

Figure 1. Comparison of optical depth values obtained from (a) present measurements (22°39′19.24" N, 88°23′00.33" E) and (b) AERONET sites: Kanpur (26°30′46" N, 80°13′55" E), Gandhi College (25°52′15" N, 84°07′40" E) and New Delhi (28°37′48" N, 77°10′30" E) for different days of different years indicated against the curves as follows: A=Day-24,2012; B=Day-25,2012; C=Day-25,2012; D=Day-27,2012; E=Day-183,2011; F=Day-188,2011; G=Day-184,2009; H=Day-187,2009.

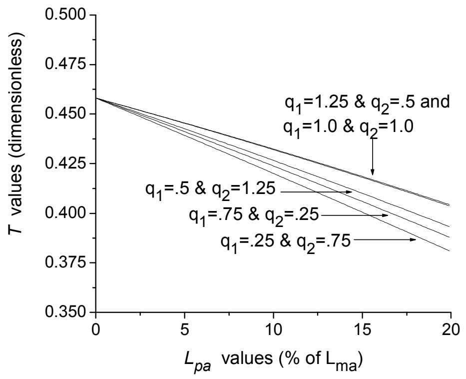

Figure 2. Theoretical variation of relative optical depth within O_2-A band (760 nm) generated with Eq. (8) for different percentages of aerosol path radiance (L_{pa}) and relative contributions of two reference wavelengths (756 nm and 772 nm) to path radiance defined by q_1 and q_2, respectively.

Comparing the absorption depth variation in radiance measurement (not shown here) at full-sun and cloud-covered conditions and that at summer and winter seasons it was verified that the above change caused by the aerosols is detectable in the same scale as that due to other atmospheric parameters. So the aerosol related change can be compared only between two situations of similar atmospheric condition of solar illumination and solar elevation. Thus the present methodology of assessment of aerosol parameter is more suitable for estimating the spatial distribution of aerosol effect at a certain place at a certain time.

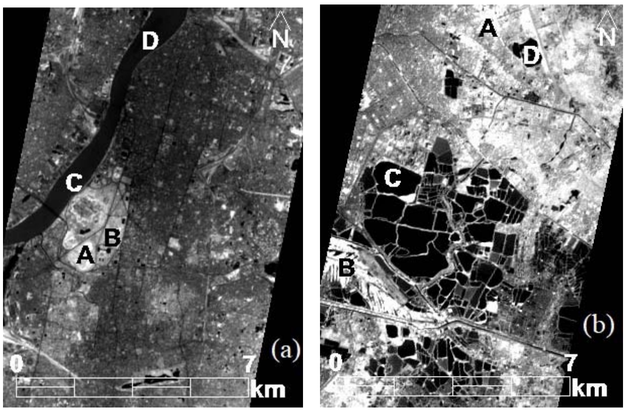

Figure 3. Hyperion images of Kolkata dated (a) July 27, 2002 and (b) January 6, 2010 showing vegetated zones ‘A’ & ‘B’ and waterbody ‘C’ & ‘D’

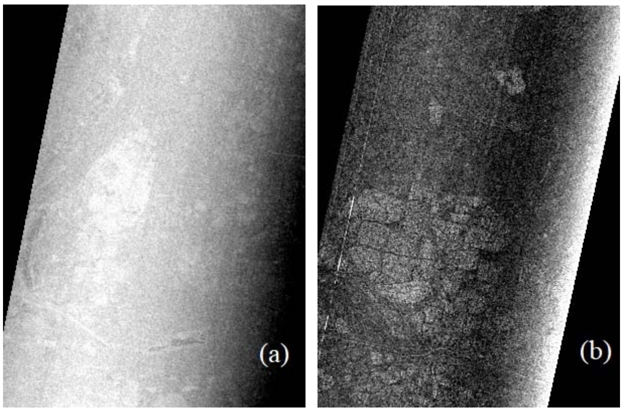

Figure 4. Spatial variation of relative optical depth due to aerosol obtained from (a) Fig. 7(a), 0.95 to 1.02 and (b) Fig. 7(b), 0.64 to 0.69.

Two Hyperion images of densely populated urban areas of Kolkata for two different years and seasons, as shown in Figures 3(a) and (b), were employed for determining the spatial variation of relative optical depth (T_0) using (6) and the relevant bands, namely band-41 (762.6 nm) corresponding to oxygen absorption and bands 40 (752.4 nm) and 42 (772.8 nm) the two reference wavebands on its two sides. The portions of the image displayed represent densely populated urban area with a river flowing by the side. Regions ‘A’ and ‘B’ are isolated vegetated lands within the city and regions ‘C’ and ‘D’ are parts of river and inland waterbody. The spatial variation of the optical depths obtained from these two images, as calculated from (6) are shown in Figures 4(a) and (b), respectively.

4. Conclusion

The present work demonstrates that utilizing the sharp atmospheric oxygen absorption band of 760 nm and two non-absorbing wavebands as reference, one can assess the effect of aerosol solely from the spectral curve of terrestrial radiation without taking the help of any extraterrestrial radiation. The same is validated with ground based hyperspectral solar irradiance measurement and the radiance data derived from Hyperion hyperspectral images. The present method is suitable for assessing the relative spatial variation of aerosol loading over a certain place from the satellite image at the same atmospheric condition like solar illumination and solar elevation.

5. References

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