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Application of a Quantitative Approach through Mathematical Inversion of a Vegetation Canopy Reflectance Model for Crop Monitoring Using Satellite Remote Sensing

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ABSTRACT

A quantitative approach has been made to retrieve biophysical information of an agricultural crop using multidirectional remote sensing data. The approach consists of retrieving the parameters of the surface bidirectional reflectance model through model inversion against directional data generated by a directional radiative transfer model. Model inversion has been performed applying a non-linear optimization scheme against the simulated directional vegetation reflectance data. The technique provides a reasonably good estimation of the canopy biophysical parameters. Remote sensing data are usually contaminated by different atmospheric effects. As a remedial, standard data correction procedure is available that requires a precise estimation of intervening atmospheric parameters. In this connection, estimation accuracies of biophysical parameters of vegetation have been analyzed with simulated satellite data corrected with improper values of atmospheric aerosol contents. The study reveals that estimation can be significantly influenced by the use of improper values of aerosol content during data correction. Estimation accuracy is higher in the near-infrared as compared to that in the visible for both high and low density canopies. Moreover, accuracy is higher for a low density canopy in comparison to that for a dense vegetation canopy.

KEY WORDS

Vegetation canopy, Optimization, Biophysical parameter, LAI, Reflectance

Introduction

Satellite remote sensing offers an effective way of monitoring vegetation condition at large scale on a repetitive basis. Plant canopy interacts with the incident solar radiation governing the processes of photosynthesis, stomatal resistance and evapotranspiration. Leaf architectural and optical properties result in distinctive variation in the absorption and reflection of solar radiation from plant canopies. The effective use of these characteristics requires a thorough understanding of the radiative transfer through vegetation canopy in relation to their morphological and optical properties. Variation in directional reflectance of a vegetation cover primarily determined by its structural and optical properties under a given illumination and observation condition can provide valuable information on the properties of vegetation crops (Rahman 1996). Recent developments in remote sensing bidirectional data acquisition e.g., airborne sensor like the Advanced Solid-State Array Spectroradiometer (ASAS); space borne sensors like the Polarization and Directionality of the Earth's Reflectance (POLDER); the Multiangle Imaging Spectro Radiometer (MISR) have opened new dimension for information retrieval (e.g., Diner, 1998; Diner et al. 1998; Lavergne *et al*. 2007; Martonchik et al. 1998). Different algorithms/methods have been developed to correct these effects (e.g., Rahman and Dedieu 1994). These correction methods require estimation of the intervening atmospheric parameters at the time of satellite overpass. The uncertainty in the estimation of these parameters can cause an improper correction of satellite images affecting the accuracy of the retrieved parameter values.

This paper deals with the inversion of a canopy bidirectional radiative transfer model in view of monitoring of crop through quantitative estimation of different biophysical parameters characterizing the crop canopy. The use of improper correction of data due to aerosol effect on the accuracy of surface parameter estimation has also been investigated.

APPROACH

Surface Reflectance Model

The SAIL (Scattering by Arbitrary Inclined Leaves) canopy reflectance model (Verhoef, 1984) has been employed in the present work. The model expresses the reflectance of a vegetation canopy as a function of the viewing and solar zenith and azimuth angles. Model inputs are solar and viewing zenith and azimuth angles, leaf transmittance and reflectance, soil reflectance, diffuse sky radiances, leaf area index and the leaf angle distribution (LAD).

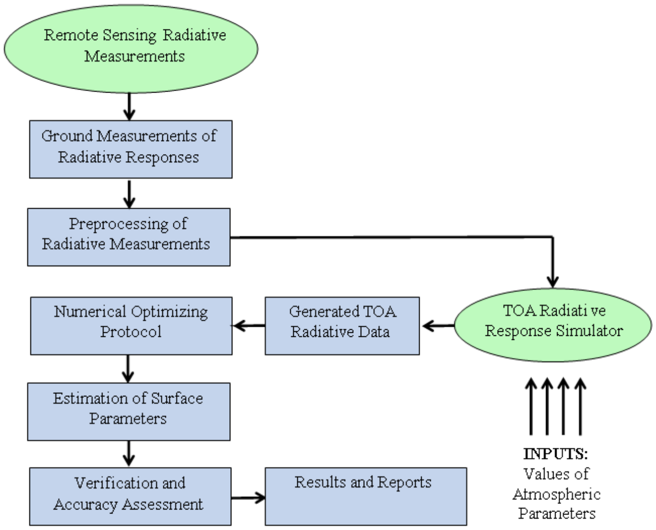

Figure 1: Figure showing the flow chart of the methodological steps as utilized in this work.

Figure 1: shows the block diagram representing the whole operational procedure for implementing the work as described.

Effect of Inaccurate Atmospheric Correction

Simulation of directional reflectance

Reflectance data have been generated at the top of the atmosphere (TOA) applying the Coupled Surface-Atmosphere Reflectance (CSAR) model developed by Rahman et al. (1993). The model expresses, the reflectance at the top of the atmosphere ρTOA as follows (neglecting environmental effect),

$$\rho_{TOA}(\theta_1,\theta_2,\phi)=tg(\theta_1,\theta_2)\left[\rho_a(\theta_1,\theta_2,\phi)+\frac{T(\theta_1)T(\theta_2)}{1-\Re(\theta_1,\theta_2,\phi)S}\left\{\rho(\theta_1,\theta_2,\phi)+\left(\Re(\theta_1,\theta_2,\phi)-\rho(\theta_1,\theta_2,\phi)\right)F_d(\theta_1,\theta_2)\right\}\right]\quad (1)$$

Here, $\rho(\theta_1,\theta_2,\phi)$ is the component of reflectance for the contribution due to direct radiation and $\Re(\theta_1,\theta_2,\phi)$ is the reflectance component that takes into account the contribution due to diffuse radiation. In this equation θ1 and θ2 represent the illumination and viewing zenith angles, ϕ is the relative azimuth between illumination and viewing plane.

$\rho_a(\theta_1,\theta_2,\phi)$ is the atmospheric reflectance and tg (θ1,θ2) is the double way gaseous transmission for the incoming and outgoing solar radiation. $T(\theta_1)$ and $T(\theta_2)$ represent the total diffuse transmission of the atmosphere for incoming and outgoing directions respectively due to combined direct and diffuse radiation, S is the spherical albedo of the atmosphere. The factor $1/\{1-\Re(\theta_1,\theta_2,\phi)S\}$ takes into account the multiple reflections between the surface and the atmosphere. The diffuse irradiance, $\Re(\theta_1,\theta_2,\phi)$ is approximated by the following equation.

$$\Re(\theta_1,\theta_2,\phi)=A+B\rho(\theta_1,\theta_2,\phi)$$

where, A and B are the two spectral band dependent coefficients. Values of A and B are taken to be 0.331 and 0.032 respectively in the visible and 0.328 and 0.085 respectively in the near-infrared for typical terrestrial surface conditions. The function Fd(θ1,θ2) in equation 1 is given as follows,

$$F_d(\theta_1,\theta_2)=\frac{t_d(\theta_1)}{T(\theta_1)}+\frac{t_d(\theta_2)}{T(\theta_2)}\times\frac{T_{dir}(\theta_1)}{T(\theta_1)}$$

where Tdir(θi) is the atmospheric transmission for the direct radiation only, td(θi) is the transmission for the diffuse radiation and i=1 or 2 for solar and viewing angle respectively. The first term in equation 1 containing $\rho_a(\theta_1,\theta_2,\phi)$ represents the atmospheric backward component, second term containing $\rho(\theta_1,\theta_2,\phi)$ in equation 1, represents the purely bidirectional property of the surface and the third term containing Fd (equation 1) approximates the contribution due to diffuse radiation. In this study, atmospheric functions of equation 1 are provided by the simple function of SMAC (Simplified Method for the Atmospheric Correction) (Rahman and Dedieu 1994).

The SAIL canopy reflectance model has been used to generate the surface reflectance for the Coupled Surface Atmosphere Reflectance (CSAR) model. A series of reflectance data set have been generated in the visible and near-infrared region of the solar spectrum with the model parameters corresponding to a soybean canopy (Bunnik, 1978). The values of model parameters corresponding to a soybean canopy used in this study are given in table 1.

Table 1: Values of the parameters of the canopy reflectance model used for the present study (Verhoef, 1984).

Parameter	Spectral band	
	Visible	Near-infrared
Leaf reflectance	8.78	45.40
Leaf transmittance	9.32	51.80
Soil reflectance	11.75	23.18
Diffuse sky radiance	22.57	16.48
Leaf area index (LAI)	2.0 and 8.0	2.0 and 8.0

TOA reflectances ρTOA are generated in the visible and NIR region of the solar spectrum corresponding to channel 1 and channel 2 of NOAA AVHRR, using equation 1 from each of the above data set under an atmospheric aerosol loading of 0.2 at 550 nm. The simulated data are then corrected from atmospheric scattering effect by using different aerosol optical depth at 550 nm, δ550, from 0.17 to 0.24 by step of 0.1, which resulted in improperly corrected (with under estimation and over estimation in aerosol content) and properly corrected data. These corrected data are then used to estimate different biophysical parameters of the canopy reflectance model through the optimization of the model (equation 1) using a non-linear optimization technique (Rahman, 2011). An average continental model of aerosol has been considered throughout the study.

Inversion Procedure

If ρsi and ρmi are the measured and modelled reflectances, the inversion problem can be formulated as follows:

$$F = \sum_{i=1}^{N} W_i \left(\rho_{si} - \rho_{mi} \right)^2$$

where *F* is a merit function, N is the total number of observations and Wi is the weight given to the ith measurement. An iterative numerical approach is used to determine the best-fit parameters.

Application of the inversion technique

The values of the canopy parameters namely leaf transmittance and reflectance, soil reflectance, leaf area index (LAI) and diffuse sky light are retrieved through application of the inversion procedure against the simulated data. Values of leaf angle distribution (LAD) were introduced directly during inversion to minimize the total number of parameters to be estimated. The accuracy of the retrieved canopy parameters is evaluated in terms of percent relative error (RE) as calculated from Pt and Pe (true and estimated values respectively).

$$RE = 100x\frac{P_t - P_e}{P_t}$$

RESULTS AND DISCUSSIONS

Bidirectional Reflectance Characteristics of Vegetation

Figures 2a and 2b show for wheat, the plot of directional reflectance as a function of viewing angle in the principal plane in the visible and near-infrared region of the solar spectrum respectively on three different dates January 15 and 21 and February 7. These measurements were made over the crop field in Sonargaon area under Narayanganj district using ground-based spectro-radiometer Model-100 AX on different dates in 2006. The solar zenith angles during measurements on the three dates were between 40 and 46°. Measurements exhibit significant variations in reflectance amplitude for varying viewing zenith angles and its value decreases from backward to forward scattering direction. Reflectance obtains its maximum value in the backscatter direction for the viewing angle that corresponds approximately to the solar zenith angle at the time of measurements (hot spot effect). Reflectance values are higher in the near-infrared as compared to that in the visible. This is due to the fact that in the visible, strong absorption of incident solar radiation by the chlorophyll for photosynthetic process reduces the radiative response values for green vegetation. As a result, reflectance is relatively small in the visible spectral region. While, in the near-infrared, minimal absorption occurs and the leaf scattering mechanisms result in high levels of spectral reflectance.

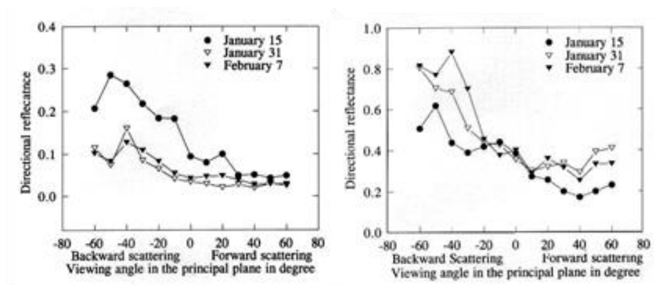

Figure 2a and 2b show for wheat crop canopy, the plot of directional reflectance as a function of viewing angle in the principal plane in the visible and near-infrared region of the solar spectrum respectively on three different dates January 15 and 21, 2006 and February 7, 2006. The solar zenith angles during measurements on the three dates were between 40° and 46°.

Effect of Aerosol Correction

Figures 3a and 3b show for soybean canopies having two different vegetation densities with leaf area index, LAI= 2 (relatively low density) and 8 (relatively high density) respectively, the effect of atmospheric correction on reflectance value using inaccurate atmospheric aerosol content in the visible region of the solar spectrum. While figures 3c and 3d show the same except, for near-infrared (NIR) region of the solar spectrum.

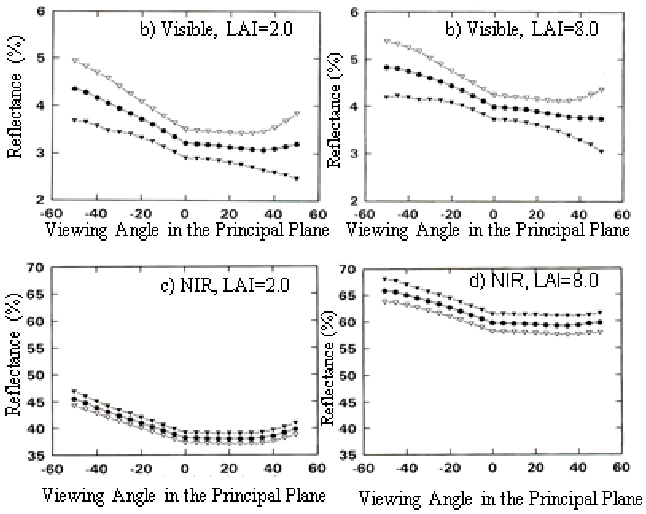

Figure 3: Directional reflectance plotted as a function of viewing angle in the principal plane for a solar zenith of 35 showing effect of atmospheric correction with inaccurate atmospheric aerosol content for a soybean canopy. Reflectance (ρTOA) generated at the top of the atmosphere with an aerosol optical depth of 0.2 at 550 nm & then data corrected for aerosol effect considering aerosol contents of 0.16 (∇) and 0.24 (∇). (●) Surface.

Here, reflectance has been plotted as a function of viewing angle in the principal plane for a solar zenith angle of 35°. Using the CSAR model, reflectance data (ρTOA) have been generated at the top of the atmosphere with an aerosol optical depth of 0.2 and then data have been corrected considering two different atmospheric aerosol loadings of 0.16 and 0.24. In the visible, the reflectance is relatively lower for the high density canopy than that for the low density vegetation canopy due to relatively high chlorophyll absorption in this spectral region caused by high vegetation amount. The angular pattern of the directional reflectance for the low density and the high density canopy differs particularly in the forward scattering direction, where, reflectance increases slightly towards larger viewing angles for the high density canopy and but for the low density canopy it does not.

Effect of atmospheric aerosol correction of data with a lower value of aerosol content as compared to the actual results in an increase of reflectance in comparison to the surface reflectance value over the viewing angles considered for both low and high density canopies. Atmospheric correction with a higher value of aerosol content decreases the reflectance value in comparison to surface reflectance for both high and low density canopies (Rahman, 1996). Atmospheric correction with improper values of aerosol content also changes the angular pattern of the directional reflectance particularly in the forward scattering direction. Figures 3c and 3d show the plot of directional reflectance in the near-infrared (NIR) for soybean canopies having low and high vegetation densities respectively, as a function of viewing angle in the principal plane for data corrected with atmospheric aerosol thickness of 0.16 and 0.24. Data have been generated by using an aerosol optical depth of 0.2. In this spectral region, amplitude of directional reflectance at the surface is relatively higher for the high density canopy as compared to low density canopy due to increased scattering caused by increased vegetation. The angular pattern of the directional surface reflectance differs slightly between low and high density canopies particularly in the backward scattering direction. For low density canopy, reflectance increases towards larger viewing angle (from nadir) almost linearly, whereas, a slightly leveled-off behaviour is observed for high density canopy.

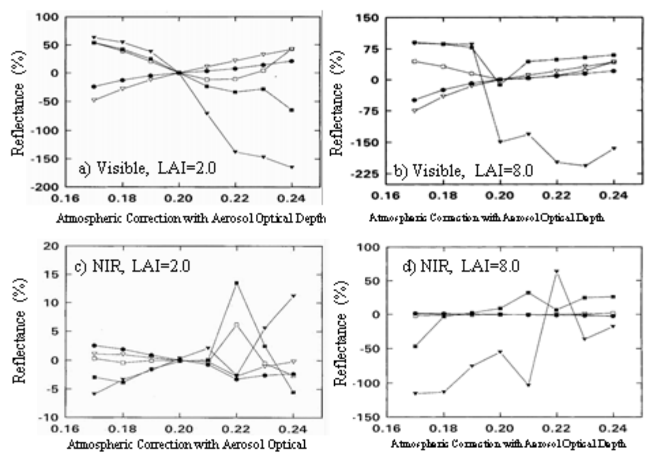

Figure 4: Relative error (%) in estimation of different biophysical parameters of the canopy reflectance model for soybean canopy, as a function of atmospheric aerosol optical depth (δ550). (●) Leaf reflectance, (∇) Leaf transmittance, (▼) Soil reflectance, (□) Sky radiance and (■) Leaf area index.

Inversion against Atmospherically Corrected Data
Effect of aerosols on inversion

Figures 4a and 4b show in the visible for vegetation canopies, having two different densities as mentioned above, the results of inversion of the canopy reflectance model against simulated data atmospherically corrected with improper values of aerosol content (δ550=0.17 to 0.24). The actual value of the atmospheric aerosol optical depth is 0.2 (aerosol content value that has been used during simulation of signal at the top of the atmosphere) whereas correction has been made by using aerosol content varying from 0.17 to 0.24 by a step of 0.1, that results in variations from -15 to 20 per cent in aerosol content from the actual value. For low density vegetation canopy, atmospheric correction with a lower aerosol content relative to the actual value results in an over estimation of the values of leaf reflectance and leaf transmittance. Decrease in aerosol content value increases the relative error in estimation. The estimation accuracy is maximum for data corrected with proper value of aerosol content. Increase in aerosol content above the actual value again decreases the estimation accuracy. A gradual increase of relative errors is observed with an under estimation of leaf reflectance and transmittance. The soil reflectance seems to be the most sensitive parameter to inaccurate atmospheric aerosol correction as is evident from the values of relative error.

For the dense vegetation canopy, the retrieval accuracy of the leaf reflectance and transmittance seems to be higher for reflectance data corrected with aerosol optical depth of 0.2 and above. The correction of data with increasingly lower values of atmospheric aerosol content resulted in a gradual increase in relative error with an under estimation of diffuse sky radiance value and an over estimation of leaf reflectance and transmittance values. Here, it should be noted that the error in estimation of soil reflectance and LAI are very much sensitive where significant effect of atmospheric contamination is observed on the retrieval of both LAI and soil reflectance values. The inversion procedure obtains the minimum RMS value for data corrected with aerosol optical depth of 0.2 at 550 nm.

Figures 4c and 4d show in the NIR for two different vegetation densities, the results of inversion for simulated data atmospherically corrected with improper values of aerosol content (δ550=0.17 to 0.24). Inversion process yields parameter values much more accurately than that in the visible. For low vegetation density, the retrieved values of leaf reflectance and leaf transmittance are more accurate in comparison to other parameters with maximum relative errors. However, accuracy of other three parameters, e.g., soil reflectance, LAI and diffuse sky radiance do not lag much behind to that of the leaf reflectance and leaf transmittance. But for a high density canopy, the accuracies in the retrieved values of leaf reflectance, leaf transmittance and sky radiance are still high, but the estimated value of soil reflectance incorporates large amount of error and error in LAI estimation is also significant. However, accuracy in parameter estimation is much better NIR region than those from the visible.

CONCLUSIONS

Recent development of satellite borne sensors like POLDER, MISR, MODIS etc., have opened a new avenue for space technology-based geoinformation acquisition. In the present study, crop biophysical parameters have been quantitatively estimated through application of inversion scheme using directional remote sensing data. The study reveals that such a numerical approach provides reasonably accurate estimation of different parameters of the canopy reflectance model for contamination free data. The effect of improper atmospheric correction of satellite data on the accuracy of the retrieved parameter values has been investigated. Retrieval accuracy of different crop biophysical parameters is not equally affected by the same atmospheric perturbations. Atmospheric correction of data with improper values of atmospheric aerosol content plays a major role on the accuracy of the retrieved parameter values, The study also reveals that estimation of different vegetation parameters for a low density canopy is more accurate than that for a dense vegetation canopy.

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