Estimation of Vegetation Canopy Leaf Area Index and Fraction of Photosynthetically Active Radiation Absorbed by Vegetation from Remotely Sensed Multi-Angle and Multi-Spectral Data

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ABSTRACT

Large scale ecosystem models require estimates of vegetation canopy leaf area index (LAI) and the fraction of photosynthetically active radiation absorbed by the green leaves (FPAR) in order to simulate the energy, heat and mass (water, carbon, etc) budgets. These variables can be obtained globally and operationally from satellite measurements of reflected solar radiation. While much work on forward modeling of vegetation reflectance has been done, it is only recently, in the context of new satellite sensors such as MODIS (moderate resolution imaging spectroradiometer), MISR (multi-angle imaging spectroradiometer), POLDER (Polarization and Directionality of the Earth's Reflectance), etc., that attention has focused on the inverse problem; that is, estimating LAI (and FPAR) from remote reflectance measurements. This presentation will provide some results on global LAI and FAPAR fields derived from current satellite sensor data.

MATHEMATICAL BASIS FOR MULTI-ANGLE AND MULTI-SPECTRAL REMOTE SENSING OF VEGETATION

The efficiency of any remote sensing technique must be measured against its ability to address important scientific objectives. Requirements of various scientific communities to the remote sensing products were discussed in [1]. Among others, a very important task is to provide a correct temporal and spatial distribution of three-dimensional characteristics of vegetation canopies. The aim of this section is to discuss the mathematical basis for the solution of this problem.

We start our analysis with a theorem recently published in a journal on inverse problems [2]. This theorem states that under some general conditions, the three-dimensional extinction coefficient and the three-dimensional scattering phase function can be uniquely retrieved from boundary measurements. It should be noted, however, that its validity is lost in the case of two or one-dimensional media. This theorem indicates that there is a one-to-one correspondence between the complex three-dimensional vegetation canopy structure and radiation emergent from the canopy boundaries. A question then arises whether or not this correspondence can be specified from multi-angle observations. Let us consider a hypothetical ideal instrument which can provide ideally exact surface reflectances at any spatial point and in any direction, i.e., one has the complete and accurate spatial and angular information on the radiation field leaving the canopy through the upper boundary. The theorem, however, requires information on the upward radiation field at the canopy bottom boundary in order to recover canopy structure. How can this information be obtained?

A specific feature of photon interactions with vegetation lies in the fact that the probability that a photon will interact with phytoelement does not depend on wavelength; that is, the extinction coefficient, which is the sum of wavelength dependent scattering and absorption coefficients, does not depend on wavelength [3]. This property allows us to evaluate canopy transmittance at any wavelength once this variable is known at a fixed wavelength [4]. This allow us to mathematically formulate the inverse problem of recovering three-dimensional canopy structure from multi-angle observations, namely, given "ideal" multi-angle canopy reflectances at a minimum of two spectral bands to find the canopy transmittance at a fixed wavelength and canopy structure. This formulation includes two sets of known multi-angle data and two sets of unknowns, which relate all variables needed for unique retrieval of the three-dimensional structure of the medium. Thus, the main advantage of multi-angle and multi-spectral remote sensing is its potential ability to retrieve realistic three-dimensional geophysical parameters required by many interdisciplinary investigations [1]. It is clear that the above arguments need a rigorous mathematical analysis. However, the facts presented above provided us an impetus for developing LAI/FPAR retrieval techniques for operational use during the EOS Terra mission [4-6].

The inverse problem is said to be well-posed in the sense of Hadamar [7] if: (1) the solution exists; (2) the solution is unique; and (3) the solution depends continuously on the data; that is, the more measured information is available and the more accurate this information is, the more reliable and accurate the algorithm output is (convergence of the algorithm). The problem is said to be ill-posed if at least one of these three statements does not hold. The theorem mentioned earlier allows us to assume the validity of the first two conditions. However, there is no evidence that one can assume the validity of the last condition. Therefore, the

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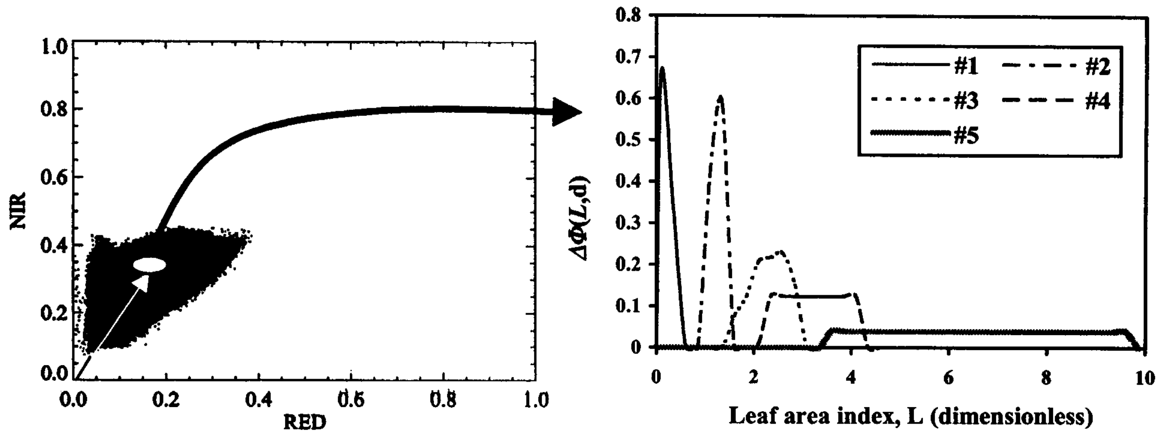

Figure 1. Distribution of vegetated pixels with respect to their reflectances at red and near-infrared wavelength (left) and the solution distribution function for 5 different pixels (right). The domain of uncertainty for a given pair of reflectances at red and near-infrared wavelength is shown as a white ellipse. All canopy/soil patterns for which simulated canopy reflectances belong to this domain are treated as acceptable solutions. The set of all acceptable solutions corresponding to a given domain of uncertainty is used to evaluate the solution distribution function.

inverse problem of recovering the canopy structure must be treated as an ill-posed problem. A fundamental result from the theory of ill-posed problems states that any retrieval technique for solution of ill-posed problems must depend on uncertainties; that is, uncertainty must be an input parameter to the retrieval algorithm in order to avoid numerical instabilities and to provide convergence [8].

A concept of the solution distribution function introduced in [5] is used to provide the convergence of the algorithm. We perform our retrievals by comparing observed radiances with modeled radiances for a suite of canopy structure and soil patterns that covers a range of expected natural conditions. The set of canopy/soil patterns for which the magnitude of the residuals in the comparisons does not exceed uncertainties in observed radiances is then used to evaluate the distribution of LAI and FPAR values, and to specify the most probable value of desired parameters. Fig. 1 schematically demonstrates the logic of this approach. The left plot shows the distribution of measured canopy reflectances in the red-near-infrared spectral space. In reality, however, any model can simulate a process only to within a certain degree of accuracy. Also, measurements cannot be carried out exactly. This means that the model predicts a domain O_S to which the "true reflectance" belongs. The same is true for measured reflectances; that is, we can only specify a neighborhood O_M around a measured reflectance to which the "true value" belongs. Any elements from these domains can be considered true values with a high probability. The neighborhoods O_M and O_S are domains of uncertainties in the measurements and simulations. In Fig. 1, the domain O_M is schematically shown as a white ellipse. Domains of uncertainties depend on the direction of direct solar radiance, view directions and the ratio of direct radiation to the total (direct and diffuse) radiation incident on the pixel. Thus, the algorithm requires not only measured canopy reflectances but also their domain of uncertainties. All canopy/soil patterns for which simulated canopy reflectances belong to the domain O_M are treated as acceptable solutions to the inverse problem. Given the set of all acceptable solutions corresponding to a measured set of spectral and multi-angle canopy reflectances **d**, one counts numbers $N(\mathbf{d})$ and $N(l;\mathbf{d})$ of different values of LAI and those of them for which LAI is less than a given value l. The solution distribution function $\Phi(l;\mathbf{d})$ is then defined as the ratio of $N(l;\mathbf{d})$ to $N(\mathbf{d})$; that is, $\Phi(l;\mathbf{d}) = N(l;\mathbf{d})/N(\mathbf{d})$. A precise mathematical definition of how to count "continuous" values of LAI is presented in [5]. The left plot in Fig. 1 demonstrates the function $\Delta\Phi(l;\mathbf{d}) = \Phi(l+0{:}25;\,\mathbf{d}) - \Phi(l;\mathbf{d})$ for five different pixels. LAI value can now be evaluated as a weighted mean in accordance with the frequency of occurrence of a given value of l, namely

$$LAI(\mathbf{d}) = \int l\, d\Phi(l,\mathbf{d}), \qquad (1)$$

where the integration is performed over the interval of all possible variations of l. We note some properties of this estimation [5]: Equation (1) is sensitive to values of LAI, but not to the canopy/soil patterns generating the same LAI value. This allows the use of three-dimensional models of canopy structure for which a retrieved parameter may not be in the model parameter list. If the inverse problem has a unique solution for a given **d**, then (1) coincides with this solution. Given the solution distribution function $\Phi(l;\mathbf{d})$, one can evaluate fraction of photosynthetically active radiation absorbed by vegetation (FPAR) in a similar way [4-5].

When executed on proper input, the algorithm results in (a) cases where no solution was found; (b) cases where solutions were found and the solution distribution function localized a desired value of LAI (curves 1,2,3 in Fig. 1); (c) cases where solutions were found, however, there was no localization of LAI value (curve 5 in Fig. 1). When this happens, the LAI value (1) is said to be retrieved under a condition of saturation [5]. To characterize the algorithm performance, the success index (the ratio of the number of pixels for which a LAI value was found to the total number of pixels processed) and frequency of LAI under condition of saturation is introduced.

PROTOTYPING RESULTS

The above approach was implemented into the standard processing algorithm for producing global LAI and FPAR fields from canopy reflectance data measured by MODIS (moderate resolution imaging spectroradiometer) and MISR (multi-angle imaging spectroradiometer) instruments aboard the Earth Observing System Terra spacecraft. We present global LAI and FPAR fields estimated with our algorithm from the atmospherically corrected SeaWiFS (Sea-viewing Wide Field-of-view Sensor), LASUR-AVHHR (LAnd SUrface Reflectances derived from the Advanced Very High Resolution Radiometer), LANDSAT TM (Thematic Mapper) and POLDER (Polarization and Directionality of the Earth's Reflectance) data. The algorithm can use multi-angle and multi-spectral surface reflectances and their uncertainties to recognize non-vegetated pixels and estimate the surface parameters such as LAI and FPAR with related accuracy information. However, the quality of the retrievals can not be better than the quality of the worst spectral BRF (Bidirectional Reflectance Factor), if uncertainties in spectral BRF's are not available. Evaluation of the uncertainties in atmospherically corrected surface reflectances is critical to improve the quality of the LAI/FPAR product, and to realize the full potential of multi-angle and multi-spectral instruments. The use of multi-angle data essentially benefits over single- angle data in the cases of heterogeneous three-dimensional canopy structure.

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