1986

Modelling bidirectional radiance measurements collected by the advanced solid-state array spectroradiometer over Oregon transect conifer forests

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http://hdl.handle.net/2144/22548

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MODELLING BIDIRECTIONAL RADIANCE MEASUREMENTS COLLECTED BY THE ADVANCED SOLID-STATE ARRAY SPECTRORADIOMETER OVER OREGON TRANSECT CONIFER FORESTS

by

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B.S., University of Khartoum, 1986

Submitted in partial fulfillment of the requirements for the degree of Master of Arts

1992
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This thesis brings me to a conclusion of twenty months of graduate studies at Boston University. Many individuals have contributed both directly and indirectly to this study. Foremost among those contributors is Professor Alan Strahler, my principal advisor, without whose insight, careful supervision, constructive criticism and personal help, this study could not have been completed. Professors Xiaowen Li and Curtis Woodcock deserves special mention for their advice and support throughout my studies. Professor Farouk El Baz deserves also special mention for his advice, encouragement and support throughout the course of my education in this institution. I would like also to thank him for his financial support. There are not enough words to express how much greatly they helped me, and my debts to them are manifold.

It was extremely enjoyable experience for me to work with my friends and fellow graduate students at the center, of whom Scott Macomber, Crystal Schaaf and Shunlin Liang deserves special mention for there help, advice and support throughout this research.

The financial support for conducting this research was provided by a grant from NASA Remote Sensing Science Program NAGW-2082, I am greatly in debts for their support.

I would like also to thank Dr. Jay Skiles and Gary Angelici of NASA Ames Research Center for their prompt help and delivery of the ASAS imagery. Mr. Lee Johnson of Ames for his patience and atmospheric correction of the satellite imagery. Mr. Jim Irons and Dave Graham of Goddard Space Flight Center for their help and investigation of the ASAS calibration. For all of them I greatly and deeply appreciate the time they spent for helping me.

My friends Nadir, Ameer and Abumedian have for long been an encouraging and supportive force for my graduate education, my gratitude to them. My family members
back in Sudan deserves special acknowledgement for their continuous support and encouragement. My warmest deep thanks and appreciation for my beloved wife Habab for her patience, understanding, encouragement and love.
DEDICATION

TO ALL MY FAMILY IN SUDAN

WITH SPECIAL DEDICATION TO MY AUNT FATIMA

IN LOVING MEMORY OF MY FATHER AND MOTHER

IN LOVING MEMORY OF MY UNCLE SHEIK IDRIS YOUSIF

TO HABAB, WITH LOVE
MODELLING BIDIRECTIONAL RADIANCE MEASUREMENTS COLLECTED BY THE ADVANCED SOLID-STATE ARRAY SPECTORADIOMETER OVER OREGON TRANSECT CONIFER FORESTS

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ABSTRACT

The primary objective of this research is to test and validate a geometric-optical bidirectional reflectance canopy model developed by Li and Strahler, with respect to actual forest canopy reflectance measurements. This model treats forest canopies as scenes of discrete, three dimensional objects that are illuminated and viewed from different positions in the hemisphere. The shapes of the objects, their count densities and patterns of placement are the driving variables, and they condition the mixture of sunlit and shaded objects and background that is observed from a particular viewing direction, given a direction of illumination. This mixture, in turn, controls the brightness apparent to an observer or a radiometric instrument. The Advanced Solid-State Array Spectroradiometer (ASAS) is chosen to be the sensor having the ability of collecting measurements at various look angles and its imaged reflectance was used to validate the model. The modelled BRF's were compared to actual ASAS measured BRF's in sites with different canopy structures and densities. The comparison revealed excellent match between the modelled and measured reflectance, and great ability of the model in predicting the shape and magnitude of the BRDF, in almost all the sites investigated. It is concluded that the geometric optics approach provided a good way to model the bidirectional reflectance distribution function of natural vegetation canopies, that captures the most important features exhibited by bidirectional measurements of such cano-
pies. Further modifications have been suggested that will improve the predicted BRF's, and yield better results.
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CHAPTER ONE

INTRODUCTION

Remotely sensed data have been commonly used to obtain quantitative information on the biophysical characteristics of vegetation. These characteristics and their spatial and temporal distribution are critical inputs to ecological models that describe the interaction between land surface and climate, energy balance, and hydrologic and biochemical cycles. An important mechanism for the inference of biophysical information is the application of vegetation canopy reflectance models. The contributions of canopy reflectance modelling have been considerable, particularly in improving our understanding of the influence of vegetation parameters on reflectance of radiation. Considerable progress has been gained in the understanding of the total amount of reflected radiation, and its spectral and angular distribution (Suits, 1972; Jackson et al., 1979; Cooper et al., 1982; Kimes, 1984; Ottermann and Weiss, 1984; Li and Strahler, 1986, 1992; Jupp and Strahler, 1991). Much effort has been devoted to understanding and modelling the dependence of the bidirectional reflectance distribution function (BRDF) of vegetation-covered earth surfaces as a function of various environmental, structural, and physiological conditions as well as viewing and illumination geometries. Typical approaches have included two-stream, radiative transfer, geometric optics, hybrids of two or more of these, and numerical simulation. Some are applicable to continuous vegetation cover, such as crops, and others are best utilized for discontinuous covers, such as forests.

All such models have to deal with the interactions that occur within and between individual canopies. These exist at several levels, including single scattering-shadowing of leaves, crowns and background. This effect creates the "hotspot," a peak in directional
reflectance in the antisolar direction that is commonly observed in vegetation canopies when the sun and the observer are at the same position in the hemisphere. It occurs because the leaves, stems and trunks that comprise the plant cover hide their own shadows under these conditions, and thus the scene appears bright due to maximal single scattering.

The earliest practical plant canopy reflectance model is that of Suits (1972), which adds direct irradiation and directional exitance to a two-stream Kubelka-Monk (1931) model. The hotspot is treated as an empirical function reducing the attenuation of existing radiation as a function of the phase angle between illumination and view directions. The model assumes that leaves are Lambertian and either vertical or horizontal. It has been extended by Verhoef (1984) to the case of a variable leaf-angle angle distribution (the SAIL model), and by Reyna and Bhadwar (1985) to include a specular reflectance component. More recently, Jupp and Strahler (1991) have added a proper geometric-optical kernel to the Suits model that is driven by leaf shape, arrangement and spacing.

In classical radiative transfer models, the medium is typically treated as a horizontally uniform series of plane-parallel layers composed of small absorbing and scattering particles. This type of model is well established for interaction between radiation and the atmosphere (Chandrasekhar, 1950), but in the case of a vegetation canopy, the scattering elements, i.e. leaves, are of finite size, and thus a pure radiative transfer approach is not possible. The shadowing behavior that produces the hotspot through enhanced single scattering must be accommodated for a radiative transfer model to be realistic. Sometimes this is included in an empirical phase function for the canopy as a whole (Ross, 1981); in other treatments, the phase function of the leaf surface is separated from a phase function that describes the hotspot (Verstraete et al., 1990). The hotspot function can take several forms, sometimes fully empirical, other times driven by the shape, orientation and/or spacing of the leaves. The functions include piecewise-linear, negative-
exponential, geometric and trigonometric. Examples may be found in the models developed by Gerstl and Simmer (1986), Simmer and Gerstl (1985), Myneni et al., (1988) and (1990), and Marshak (1989). Two-stream solutions have been derived by Nilson and Kuusk (1989) and Nilson and Peterson (1991). These types of models are best applied to continuous vegetation covers such crops or homogeneous grasslands.

In the geometric-optical approach, the bidirectional reflectance is modelled as a purely geometric phenomenon that results when scenes of discrete, three-dimensional objects are illuminated and viewed from different positions in the hemisphere. The shape of the objects, their count densities and patterns of placement are the driving variables, and they condition the mixture of sunlit and shaded objects and background that is observed from a particular view direction, given a certain direction of illumination (Li and Strahler, 1986). This mixture in turn controls the brightness apparent to an observer or a radiometric instrument. Li and Strahler (1985, 1986, 1992) emphasized the individual tree canopy as the functional element in modelling, and have applied geometric-optical models of bidirectional reflectance successfully for open and moderately closed stands of conifers treated as "green" cones or spheroids on a contrasting background. Jupp et al. (1986) used a similar approach for trees as spheroidal objects, and extended the treatment to two crown layers above a background using Boolean logic of Serra (1982). Recently, Strahler and Jupp (1990) have provided a more general Boolean treatment that includes leaves within discrete-crown envelopes as a two-stage nested model.

Although the geometric-optical approach properly models the three-dimensional nature of the scene with due complexity, it greatly simplifies the interaction between elements due to multiple scattering among leaves and individual canopies. Li and Strahler (1986) modelled the reflectance associated with a given viewpoint as an area-weighted sum of four fixed reflectance components, namely sunlit leaves or canopy, sunlit background, shaded leaf or canopy, and shaded background. Since the reflectance of a sunlit
canopy will be a function of canopy depth, which will be lesser near the edges of the crown and greater near the center, this signature will not be uniform. Also, the shaded canopy signature will not be uniform, as it is related to the radiation penetrating through the crown, the diffuse skylight distribution, and multiply scattered radiation from the ground and other crowns into the shaded portion. Due to similar effects, the signatures of sunlit and shaded canopy or leaf will also be heterogenous. However, if the variance in signatures within components is significantly less than that among component signatures, this assumption may not be a significant limitation.

Li and Strahler noted a further problem with their (1986) geometric-optical model when either or both illumination and viewing direction assumed large zenith angles. At such angles, the tops of the trees are more likely to be illuminated and visible than the shaded lower portions, and thus the scene will appear brighter than a model simply based on random shadowing would predict. This gives the BRDF a "bowl shape," in which the reflectance increases for a given sun angle as the observer descends to a position low on the horizon (Kimes et al., 1986). This effect was referred to as the mutual-shadowing problem, since it arises because of the mutual shadowing and obscuring of crowns by one another. A treatment for the mutual-shadowing problem was thus added to the earlier model (Li and Strahler, 1992) the present version properly reflects the shadow interaction given the count density of the objects.

A primary objective of this research is to validate and test the mutual-shadowing geometric-optical model developed by Li and Strahler (1992) against actual directional reflectance measurements collected by the Advanced Solidstate Array Spectrometer (ASAS) (Irons et al., 1991). This airborne pushbroom scanner can be tilted fore and aft, and thus has the unique capability of collecting measurements at different viewing angles. As the experimental target, conifer stands along the Oregon Transect (Waring et al., this volume) were imaged by ASAS. Because the reflectance measurements were col-
lected over various sites with different canopy structures and varying densities, the model can be validated in canopies with different characteristics.

The general procedure is to compare the BRDF shape and absolute reflectance as predicted by the model to that observed by the ASAS. This will be carried out by running the model at the test sites using actual tree measurements and component signatures measured with spectral radiometer, yielding the model-calculated BRDF. Processing the ASAS images, to calculate mean radiance and bidirectional reflectance factors (BRFs) will yield the actual shape and absolute reflectance values of the BRF of the test sites. A comparison will be carried out between the predicted model BRFs and the actual measured BRFs.
CHAPTER TWO

LI-STR AHLER GEOMETRIC-OPTICAL BRDF MODEL

The Li-Strahler model treats canopies as three-dimensional objects with fixed shape but varying size. The objects are randomly distributed on a contrasting background, and are illuminated at a given direction. A tree crown is taken as a simple geometric object, in this case a spheroid, centered at some distance above the ground. The form parameters that describe the shape of the spheroid relative to its height above the ground are known previously and are invariant, while tree size varies. The radiance of a pixel is an area-weighted sum of the radiance signature for four components, namely, sunlit crown, sunlit background, shaded crown and shaded background. It is the size and density of the tree crowns that determine the proportions of these components within a pixel. That is

\[ R = K_g G + K_c C + K_t T + K_z Z \]

where \( R \) is the brightness of a pixel, \( G, C, T, \) and \( Z \) are the spectral signatures of the respective components, \( K_g, K_c, K_t, \) and \( K_z \), stand for the areal proportions of sunlit background, sunlit crown, shaded crown and shaded background.

In Li and Strahler (1986), the BRDF of a pixel is modelled as the limit of its directional reflectance factor \( R(i,v) \):

\[ R (i,v) = \iiint_A \frac{R(s) <i,v> <v,s> I_i (s) I_v (s) ds}{A \cos \theta_i \cos \theta_v} \]  

(1)

where \( ds \) is a small Lambertian surface element over area \( A \) of a pixel; \( R(s) \) is the reflectance of \( ds \); \( i, v, \) and \( s \) represents the directions of illumination, viewing and the normal to a surface element respectively; \(<...>\) is the cosine of the phase angle between two directions; \( I_i (s) \) and \( I_v (s) \) are indicator functions, equal to one if \( ds \) is illuminated
\((I_1)\) or viewed \((I_v)\) zero otherwise; and \(\theta\) is the zenith angle of a direction. Here the double integral shows that \(ds\) is integrated over the pixel-i.e., the footprint of the sensor’s field of view.

To explain the analysis further, let us assume that there are only two kinds of surfaces over the pixel area \(A\), namely background surface and crown surface with Lambertian reflectance \(G\) and \(C\), respectively. \(A_g\) and \(A_c\) will denote the area of background that is both illuminated and viewed and the area of crown both illuminated and viewed, respectively; both are as projected onto the sensor’s footprint on the ground. Then \(R(i,v)\) may be written as:

\[
R(i,v) = K_g G + \frac{C}{A} \int \int_A \frac{<s_i,s>}{\cos \theta_i} \frac{<s_v,s>}{\cos \theta_v} \ ds
\]

where \(K_g = \frac{A_g}{A}\) is the proportion of background both illuminated and viewed. Considering that the union of \(A_g\) and \(A_c\) is the intersection of the set of surface elements that are illuminated and the set of those that are viewed, only when \(v\) and \(i\) coincide can \(A_g\) and \(A_c\) achieve a maximum, provided that the surface elements have no spatial orientation preference. Thus the hotspot is well explained by this equation. Another obvious and important meaning of this equation is that the directional reflectance of a scene depends not only on the material reflectance (related to \(G\) and \(C\)) but also on its spatial structure, which determines \(A_g\) and \(A_c\).

It will be helpful to investigate the two terms of (2). The first term describes how the sunlit background proportion proceeds to a maximum as viewing and illumination coincide, and the second describes how the sunlit crown surface, composed of Lambertian facets, similarly becomes maximally exposed to view at the hotspot.
OVERLAP FUNCTION FOR CROWNS

To investigate how the first term in (2) varies with illumination and viewing geometry, the crowns are assumed to have the shape of a spheroid (Strahler and Jupp, 1990) with vertical half-axis equal to \( b \), horizontal radius equal to \( R \), and height to the center of the spheroid \( h \). For accommodating the spheroidal shape easily in the derivations of the shadow areas that follow, a transformation will be used that simply replaces \( \theta \) by the angle that would generate the same shadow area for a sphere; that is \( \theta' = \arctan \left( \frac{b}{R} \tan \theta \right) \). The symbol \( \lambda \) will denote the density of spheroids, that is \( \lambda = \frac{n}{A} \) where \( n \) is the count of crown centers within the sensor's footprint \( A \). Assuming that \( G \) and \( C \) are constant as average signatures over \( A_g \) and \( A_c \), (2) will thus need to properly model \( K_g \) and \( K_c = \frac{A_c}{A} \).

Using the Boolean model of Strahler and Jupp (1990), \( K_g \) in (2) can be expressed as:

\[
K_g = e^{-\lambda \pi R^2 \left[ \sec \theta'_i + \sec \theta'_v - \bar{O} (\theta_i, \theta_v, \phi) \right]}
\]

where \( \bar{O} (\theta_i, \theta_v, \phi) \) is the average of the overlap function between illumination and viewing shadows of individual crowns as projected onto the background. Here \( \phi \) is the difference in azimuth angle between viewing and illumination positions.

Strahler and Jupp (1990) approximated the overlap function by the overlap area of two disks with the original areas and center positions of the two ellipses. To improve the accuracy and preserve the proper hotspot width information, Li and Strahler (1992) developed another approximation better suited to the case of ellipses intersecting at arbitrary angles.
CONTRIBUTION OF SUNLIT CANOPY SURFACE

The modelling of the effect of the sunlit canopy on the bidirectional reflectance (second term in (2)) is more difficult because it depends on both the density and the angular distribution of ds in (2). Strahler and Jupp (1990) assumed that each crown could be modelled as a sphere without mutual illumination shading between ds elements. Thus, the second term can be approximated as:

\[ K_c \cdot C = \frac{1}{2} \left( 1 + <i, v> \right) \left( 1 - e^{-\lambda \pi R^2 \sec \theta_v} \right) C \]  \hspace{1cm} (4)

In this expression, the first term is the illuminated proportion of the area of a single sphere viewed at position v and illuminated at position i, which ranges from one, at zero phase angle, to zero, when both viewing and illumination are opposite and the phase angle is therefore \(\pi\). This is weighted by the second term, which is the proportion of the area of spheres visible from zenith angle \(\theta_v\). Since both terms vary smoothly between zero and one, this contribution to the hotspot is quite flat; in the case of a spheroid, \(<i, v>\) can replaced by \(<i', v'>\), where

\[ <i', v'> = \cos \theta'_i \cos \theta'_v + \sin \theta'_i \sin \theta'_v \cos \phi \]  \hspace{1cm} (5)

The first term in (4) ignores the mutual shadowing of one canopy by another. That is, when either the view or illumination direction is near the horizon, viewing and/or illumination shadows will fall on the spheroids, thus shading or obscuring some of the facets. Li and Strahler (1992) developed a simple approximation to describe the effect for vegetation covers composed of collections of individual, discrete canopies. Their approach applies one-stage geometric optics to deal with the spatial relationship between the part of the crown surface that is mutually shaded in the illumination direction and the part mutually shaded in the view direction.
MUTUAL SHADOWING TREATMENT

In developing a mathematical formulation for the mutual shadowing index, let us consider the proportion of crown surface that will be mutually shaded by other crowns. In the direction of illumination, each crown has an area $\pi R^2 \sec \theta_i$ projected onto the ground, and the total projected area (as a proportion of $A$) then will be $\lambda \pi R^2 \sec \theta_i$, if there is no mutual shadowing. Because of the mutual shadowing, however, the net projected area will be $1 - e^{-\lambda \pi R^2 \sec \theta_i}$. The difference therefore will indicate the total mutual shadowing. Thus a quantity $M_i$, can be defined as the mutual shadowing proportion in the illumination direction, as

$$M_i = 1 - \frac{1 - e^{-\lambda \pi R^2 \sec \theta_i}}{\lambda \pi R^2 \sec \theta_i}$$

$M_i$ will therefore be an index showing the degree of mutual shadowing in the illumination direction. In other words, each spheroid will, on average, have a proportion that will not be sunlit, which will likely be in the lower part of the spheroid. This means that we may also take $M_i$ to be a normalized shadow area, which we assume will occupy the lower part of the spheroid (Fig 1a). Similarly, mutual shadowing proportion in the view direction can be defined as:

$$M_v = 1 - \frac{1 - e^{-\lambda \pi R^2 \sec \theta_v}}{\lambda \pi R^2 \sec \theta_v}$$

Clearly, the proportion of sunlit crown the sensor can see depends on both zenith and azimuth differences between the illumination and view directions. At the hotspot, $M_i$ and $M_v$ boundaries will overlap and the sensor will see no mutual shadowing. When the view zenith angle is larger than the illumination zenith angle, $M_v$ will be greater than $M_i$, and little or no mutually-shaded crown will be visible. Thus, this simplification captures the essence of the mutual shadowing effect (Li and Strahler, 1992). However, the true
situation is that the mutual shadowing won’t be strictly under the $M_i$ or $M_v$ boundaries unless the crown centers are uniformly located at the same height which may be referred to as "uniform" case. In contrast is the "random" case, where illumination and viewing shadows are independently scattered on other crowns, and thus both the hotspot and bowlshape contribution of mutual shadowing can be ignored, and this applies to the case where crowns are well separated.

In general, the practical situation is always between these two extremes, depending upon the height distribution. If all crowns are at the same height, the situation will be very close to the "uniform height" case the mutual shadows will always fall on the lower part of the crowns and get higher and higher when zenith angle increases, and thus the crown-top viewing effect will be strong. However, when tree heights are distributed over a wide range, the top layer of the forest canopy will play a more important role in determining the BRDF of the canopy than lower layers. So, in general when crown heights are distributed in a wide range, the bowl shape of the BRDF will be determined basically by size, shape and height of crowns in the top layer. Thus, Li and Strahler (1992) considered a single top layer only, and assumed that when the range of distribution of height approximately equals or exceeds twice the vertical axis of the spheroid, the random case dominates, whereas when the heights are uniform, the uniform case dominates. The empirical parameter $\beta$ was used to describe the variation between these two extremes.

Since their 1992 paper, Li and Strahler have derived a better formula for $\beta$. The new formula for the mutual shadowing coefficient is

$$\beta = \frac{\lambda \Gamma_i}{\lambda \Gamma_i + \left( \frac{h_2 - h_1}{D} \right) \lambda \Gamma_i} \frac{1 - e^{-\lambda \Gamma_i + \left( \frac{h_2 - h_1}{D} \right) \lambda \Gamma_i}}{1 - e^{-\lambda \Gamma_i}}$$

where $D$ is the decorrelation depth of a single crown at nadir viewing, defined as, $D = R \cot \left( \frac{\theta_i}{2} \right)$. This equation is simple but includes almost all factors which
determine the canopy structure and illumination geometry. The ratio \( \frac{h_2 - h_1}{D} \) represents the thickness of canopy in units of correlation depth, and plays a role relating canopy structure and illumination geometry together.

From (8), it would be noted that for given coverage and sun position \( (\lambda, \Gamma) \), \( \beta \) will decrease from one to zero with increasing canopy depth from zero to infinity; and for given canopy depth, \( \beta \) increases from a value determined by canopy depth to one with increasing coverage from zero to infinity.
CHAPTER THREE

FIELD SITES AND DATA COLLECTION

TEST SITES

This research was carried out as part of the overall OTTER project. The main objective of the Oregon Transect Ecosystem Research (OTTER) Project was to test and validate an ecosystem process model, FOREST-BGC, across a broad range of coniferous forest ecosystem conditions on a seasonal to annual basis. An overview and description of the OTTER project is provided by Waring et al. (this volume).

The Oregon test sites were selected on a west-to-east transect, along a temperature and moisture gradient that produces a large variation in ecosystem structure and function. This transect, established by Gholz (1982), offers a very wide range of leaf area index values and crosses seven distinctive conifer vegetation zones. Each zone varies considerably in elevation and climate (Spanner et al., 1984). Conifer species composition of the vegetation zones is described in detail in Peterson et al. (1987). Canopy closure exceeds ninety percent for some of the western stands, and is as low as fifty percent for the eastern stands. The understory vegetation along the transect is composed of highly varying proportions of ferns, shrubs and grasses, with little exposed rock or soil (Spanner et al., 1988). There are two sites at Cascade Head: a closed canopy forest of mature conifers with virtually no understory, and a closed canopy of red alder with some understory. There are also two sites at Scio: an unfertilized site of closed canopy douglas fir with virtually no understory; and a large fertilized stand with similar characteristics. Two sites are also found at Metolius River: both are open stands of ponderosa pine, recently cut over, with one site a control and the other being treated with nitrogen-rich sewage sludge. All of the other sites are large single stands of undisturbed forest. Only five sites have
been used in this study. Namely, Juniper, Scio fertilized, Metolius control, Waring Woods and Cascade Head. The table below provides an overview of the sites.

<table>
<thead>
<tr>
<th>No.</th>
<th>Code</th>
<th>Name</th>
<th>Location</th>
<th>Species</th>
<th>Crown closure</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>JU</td>
<td>Juniper</td>
<td>Bend</td>
<td>Juniper</td>
<td>10-25%</td>
</tr>
<tr>
<td>2</td>
<td>MR</td>
<td>Metolius River</td>
<td>East Cascades</td>
<td>Ponderosa/Jeffery Pine</td>
<td>25-50%</td>
</tr>
<tr>
<td>3</td>
<td>WW</td>
<td>Waring Woods</td>
<td>Corvalis</td>
<td>Douglas fir, oaks</td>
<td>&gt;90%</td>
</tr>
<tr>
<td>4</td>
<td>CH</td>
<td>Cascade Head</td>
<td>Coastal</td>
<td>Western hemlock, silva spruce</td>
<td>100%</td>
</tr>
<tr>
<td>5</td>
<td>SC</td>
<td>Scio</td>
<td>West Cascades</td>
<td>Douglas fir</td>
<td>100%</td>
</tr>
</tbody>
</table>

TIMBER MEASUREMENTS

The timber measurements were made in August 1991, at each of the five sites. The objective was to select 20 trees at each stand for the measurement of height, crown width, DBH (diameter at breast height) and height-to-crown distance. The data were collected using variable-radius plot sampling. The general procedure was to lay out a transect through the stand using steel tape and hand-held compass and locate "points" along the transect. Each point is the center of a variable-radius plot (Dilworth, 1977). The points are separated by 100-150 feet, depending on the size of the stand and the prism factor. The prism factor was selected in advance to require about four prism points to attain a sample of 20 trees.

The height, height-to-crown and crown width were measured in feet (Fig 1b). The height was obtained by clinometer for angle and steel tape for distance, while the crown width was measured using steel tape from below by looking up and judging when the tape indicates the edge of the crown. The DBH is measured in inches with a diameter
tape. In some stands (e.g. Juniper), trees with multiple stems were common; in that case, the DBH's of the multiple stems were measured and then their basal areas were combined and reduced to a single DBH value to give the combined area. From the measurements, count density (trees per hectare) was determined and basal area weighted means of $h$, $b$, and $r$ were calculated.

SE-590 RADIOMETRIC MEASUREMENTS

The geometric-optical model requires component signatures for calibration. These were collected using a Spectron Engineering model SE-590 spectral radiometer. Since these component signatures will obviously vary according to time of day, the measurements were made whenever possible at a time close to the time of the ASAS overpass.

In collecting the radiance measurements, targets were selected to be representative of the types of surfaces within the ASAS field of view. Generally, targets were observed at zenith view angles of +45, 0, and -45 degrees in the principal plane (here +45 is taken as the direction near the hotspot peak). These angles were determined using a clinometer held against the case of the radiometer head. In the +45 direction, it was often necessary to move away from the target in an azimuthal direction to avoid the shadow of the instrument and the operator. In general, measurements were made from one-half to one meter away from the target and a single set of measurements was made for each target. During the measurement process, the first activity at a site was to record the radiance of a Spectron panel. The clinometer was used to measure the solar zenith angle and the time of day was recorded. Then the radiances of the various cover types were measured, the scan number was recorded and the cover type and viewing position were noted. After the measurements were collected, the panel was measured once again and the solar zenith angle and time of the day were also recorded.
The data normalization was carried out in two steps. First, the appropriate panel reference was established. Since the panel radiance varied between the start and end of the measurement period, a simple linear interpolation of the panel radiances was carried out between the first and last measurements. This established a separate panel reference for each measurement, which was then divided into the observed radiance. The second step was to adjust this reflectance to that of the Ames-2 SE-590 radiometer and the Ames-2 Spectron panel using a set of calibration factors. These were standards agreed upon by the OTTER investigators. These calibration factors were calculated by ratioing the measurements of our panel by the Ames-2 radiometer with that made by the Ames-2 radiometer on the Ames-2 panel. A single calibration factor was calculated for every channel by combining these two ratios, and was later applied to the measured reflectance.

**ASAS IMAGERY**

The Advanced Solid-state Array Spectrometer (ASAS) is a pointable spectroradiometer with a unique capability to collect high spectral resolution data in the visible and near-infrared region of the spectrum at several view directions. It consists of an area array covering 32 channels from 450 to 900 nm with an approximately 15 nm band width. Imagery from ASAS has a pixel size determined in the across-track direction by platform altitude, and in the along-track direction by the electronic readout rate and its 25 degree field of view. For the conditions of our acquisition, nadir pixel size was nominally 2.5 by 4.0 meters.

The ASAS instrument is currently operated and flown on NASA's C-130 aircraft, based at the Ames Research Center, Moffett Field, California. Data were collected during the period June 19 to 21, 1990; measurements were made for both high and low sun angles for all the sites under investigation. ASAS imagery were obtained from the Ames node of the Pilot Land Data System. Due to uncertainty and flight plans, it was not
always possible to collect radiometric measurements concurrently with the overflights.

Table (2) shows the correspondence between times and dates of collection.
PROCESSING OF THE ASAS IMAGES

1) Enhancement & Display

ASAS data were received in a format of two header records followed by 29 bands recorded in band-sequential format. The original 16-bit data were compressed to 8-bits as needed for image display, matching available software capabilities. Using three bands 9 (556-570 nm), 16 (656-670 nm) and 21 (730-746 nm) to be coded as blue, green and red respectively, a color composite image was constructed for every scene. In order to give a better color image and still retain the different reflectance characteristics of each look angle, all images were stretched according to a histogram-normalized look-up table derived from the image closest to the hotspot position. Therefore, the images preserve their original brightness relative to each other.

The figures 2-11 attached show the sets of the stretched images. For each site, two sets are shown where the first set shows the look angles in the hotspot direction (+15, +30, +45) together with the nadir image and the second set shows nadir and remaining look angles in the forward scattering direction (-15, -30, -45).

2) Bands Mean Brightness Calculation

For the model validation two ASAS bands 16 (656-670 nm) and 25 (788-805 nm) were selected; which closely matched channels 107 (RED) and 151 (NIR) of the SE-590 radiometer. For these bands the mean brightness for each site at each look angle was calculated from 16-bit data. These mean brightness values were not calculated for the whole image, but instead, for only that part of the image where the ground radiometric measurements were made. The delineation of the sites in the satellite images was aided by the use of color infrared airphotos Figures 12-21 display the mean brightness of the sites for the various look angles for bands 16 and 25. Table (3) shows the calculated
brightness values for the five sites (The values are given for the means in the 16-bit format).

3) Atmospheric Correction

For accurate and proper comparison between the model reflectance and the actual ASAS measured reflectance, the ASAS images were atmospherically corrected, within the process of retrieving the BRF from the measured radiance.

The procedure of retrieving the BRF from the ASAS data consisted of applying a series of models. A BRF model at the surface level, a radiative transfer atmospheric model at the atmosphere level and a model for the measured radiance at the sensors level; principally with the available information about any two models the third one can be retrieved. In this case with the ASAS measured radiance at the sensors level and the atmospheric parameters availability the BRF values were calculated. The BRF model is a statistical one consisting of six parameters, the atmospheric model involved using a two stream approximation and the atmospheric parameters of Rayleigh and aerosol optical depths were calculated from sunphotometer measurements which were collected approximately at the same times and dates of the ASAS overpass. An optimum algorithm was then applied to estimate the BRF. More details can be found in Liang and Strahler (1992).

BRDF CALCULATION

The calculation of the BRDF for each site involved the specifying of a number of parameters ranging from the timber data to the component signatures. In addition, the sun illumination angle and a value for $\beta$, calculated from the tree data according to (8), were also specified. Table (4) presents these parameters.
Figures 22-41 display BRDFs calculated for the sites in red and near-infrared bands. In these figures the BRDF's are displayed in a rectangular coordinate system. Each viewing position in the hemisphere is taken as a pair of polar coordinates, resolved onto the $x$–$y$ plane as a vector of unit length, and the reflectance at that position is taken as the $z$-value. This produces a three-dimensional surface which is then displayed as if viewed from behind. To aid the comparison of the model reflectance and the ASAS reflectance, a cross-section line representing the reflectance through the principal plane of the model was extracted from each BRDF plot.
CHAPTER FOUR

RESULTS AND DISCUSSION

The following discussion compares the BRF shape as captured by the ASAS in the mean brightness of bands 16 and 25; with the Li-Strahler mutual shadowing model, which predicts the general shape of the BRDF. In addition, the absolute magnitude of the BRDF’s of the model and the BRFs of the ASAS will be compared for band 25.

Figures 12, 13, 14 and 15 present plots of mean brightness values observed by ASAS in red and infrared for the Juniper and Metolius sites. These figures can be directly compared with figures 23, 25, 27 and 29, which show the modeled BRDF’s. The shape of the modelled curves generally fit the ASAS brightness values well. The hotspot peak, clearly shown in the model curves, is not apparent in the ASAS curves, because the sun angle at the time of the ASAS overpass (50 for Juniper and 47 for Metolius) is greater than the maximum look angle of the ASAS at 45 degrees, and is thus beyond its field of view, though the ASAS curves shows tendency of higher reflectance at the hotspot image. Similar conclusions can be drawn with regards to the Scio site (figures 20, 21, 35 and 36).

Modelled BRFs and ASAS brightness values for Waring Woods and Cascade Head may be compared in figures 16, 17, 18, 19 and 31, 33 and 35. For these two sites, the curves of the model and the ASAS show a good fit. The hotspot position is shown more precisely in the model than by the ASAS values, as the aircraft images are restricted to a 15-degree increment.

The overall conclusion to be drawn from this analysis is that the ability of the model to predict the general shape of the BRDF is generally good. Encouraged by these results, we further attempted to validate the model by comparing its absolute BRDF values to the
ASAS BRF values calculated by the Liang and Strahler (1992) method. The Liang and Strahler method have been explained earlier.

These comparisons are only for the infrared (Band 25). This is because upon converting the ASAS brightness to units of radiance for the red (Band 16), it was found that the calculated radiances are far lower than the path radiances predicted by the atmospheric model. This anomalous result is most likely due to incorrect calibration of the ASAS detectors. Band 16, centered at 664 nm, is near the chlorophyll maximum absorption and consequently, the signal received by the ASAS in band 16 is typically very low for vegetated targets. The ASAS detectors do not behave well at low signal levels; the responsivity of the detectors is low at low signal levels and this has been referred to as "build-up lag" (Irons, personal communication). These low light levels are below those available using existing calibration procedures, and consequently calibration factors may be inaccurate. For these reasons, our comparison is restricted to the infrared (Band 25).

Careful investigation of figures 37-41 shows that the match between the model BRF's and the ASAS ones is very good for both Juniper and Metolius sites. The general shape of the BRF is well predicted in both sites as well as the magnitude of the BRFs; however, the ASAS BRFs in the Metolius site have steeper slope than those of the model, probably due to a somewhat anisotropic soil BRDF that is unaccounted for by the model. The Juniper site is very sparse and most of the reflectance is from the soil surface rather than from the tree canopy. The model, being a tree canopy model, simply assumes a Lambertian soil surface BRDF.

In the Cascade Head and Waring Woods sites, the model tends to underestimate the scene BRF's. For both sites the time of the ground SE-590 observations of component signatures and the ASAS overpass did not coincide because some of the ASAS overflights were cancelled or obtained data of poor quality. This appears to have strongly affected the modelled BRF's. While the ASAS overpass over Cascade Head was early in
the day (sun angle is 22.258), the SE-590 ground measurements were made late in the
day (sun angle is 68); thus the component signature used to calculate the BRF’s are prob­
ably darker than the actual ones measured by the ASAS. Had the two measurements
coincided in observation timing better results would have been displayed.

The lack of coincidence in time between ground and aircraft overpass is also
believed to have affected the model BRF’s of the Waring Woods site. The SE-590 obser­
vations were made early in the mid-morning (sun angle is 38), while the ASAS overpass
was early afternoon (sun angle 22). Thus, the ASAS measurements are brighter than
those predicted by the SE-590 component signatures.

In an attempt to enhance the fit and rectify the problem of darker signatures, it will
be assumed that the component signatures varied similarly as the cosine of the sun angle
at the time of the two measurements. The variation for the Cascade Head site is approxi­
mately 55%; by increasing the SE-590 signatures by this amount, it was possible to
reduce the discrepancy in the magnitude of the BRF’s (figure 42). Similarly the signa­
tures of the Waring Woods were increased by approximately 13%, to provide the better
results in fig (43). Although the improvement is in the right direction, it appears that a
simple cosine correction does not boast the signal sufficiently.

The results from the model for the Scio site (figure 41) are different than the other
ones. This is the most dense site of all the five, with nearly 100 % crown closure and a
different canopy structure. In the figure, the ASAS images shows higher BRF’s than
those of the model; in dense canopies where the trees are spaced very closely the model
assumes that the major portion of the area is in sunlit crown. For the Scio site, sunlit
crown signatures were collected from tower branches of trees exposed to full sunlight at
the edge of the stand. A signature obtained from the top of the tree looking into the
canopy would be expected to be significantly brighter, due to multiple scattering in the
infrared.
CHAPTER FIVE

CONCLUSIONS

Because many natural vegetation covers may be regarded as assemblages of plant crowns that are located on a background plane and interact with light as discrete objects, geometric optics can provide an approach to model the bidirectional distribution function of natural vegetation canopies that captures the most important features exhibited by bidirectional measurements of such canopies. The Li and Strahler geometric-optical model here presents a model that exploits the primary mechanism of three-dimensional shadowing that relates size, shape and count density of plant crowns to viewing and illumination positions and crown-background reflectance contrasts. By comparing this model to ASAS observations a number of improvements can suggested. The most significant is the improvement for measurement technique of component signatures. Because in the difficulty in obtaining radiometer measurements of sunlit and shaded tree canopy from above, measurements taken from trees at the edge of the stand under direct solar illumination were used. These are most likely different—probably lighter in the red and darker in the infrared—than measurements that correspond to the ASAS instrument's viewpoint. Also, measurements should coincide in time with the ASAS overpass whenever possible to insure that the signatures that are measured in the modelling process and this will eventually improve the model calculated BRF's.

Another factor in the departure of the model from reality is the assumption that the crowns are opaque, and thus shadowed signature are uniformly dark. This is unrealistic for real canopies; light may pass directly through a tree crown in gaps between branches and leaves, and further, leaves have transmittance and therefore radiation passes through leaves. Also, the model does not account for the multiple scattering between crowns and
the ground. These effect yield lower BRF's than real ones, at least in the infrared portion of the spectrum.

Modification of the Li-Strahler model to accommodate these effects, as well as improvements in the radiometric measurement techniques, will most likely improve the accuracy and performance of the model, thus guiding the further development of inversion procedures to extract the basic information about plant canopies from remotely-sensed data.
REFERENCES


Jackson, R. D., Reginato, R. J., Pinter, P. J. Jr. and Idso, S. B. (1979), Plant canopy information extraction from composite scene reflectance or row crops, Applied Optics 18:3775-3781.


Spanner, M. A., Peterson, D. L, Hall, M. J, Wrigley, R. C Card, D. H and Running, S. W.


APPENDIX A
Fig (1b)
Juniper Site

Mean Brightness Band 16

![Graph showing mean brightness vs viewing angle for Juniper Site. The y-axis represents brightness ranging from 0 to 250, and the x-axis represents viewing angle ranging from -60 to 60 degrees. The graph shows an upward trend as the viewing angle increases.](FIG (12))
Juniper Site

Mean Brightness Band 25

FIG (13)
Metolius River Site

Mean Brightness Band 25

![Graph showing the mean brightness band 25 for the Metolius River Site. The graph plots brightness on the y-axis against viewing angle on the x-axis. The curve indicates an increase in brightness as the viewing angle increases.](image-url)
Metolius River Site

Mean Brightness Band 16

Fig (15)
Waring Woods Site

Mean Brightness Band 16

Viewing Angle

Fig (16)
Waring Woods Site

Mean Brightness Band 25

Fig (17)
Cascade Head Site

Mean Brightness Band 16

Fig (16)
Cascade Head Site

Mean Brightness Band 25

Fig (19)
Scio Site

Mean Brightness Band 16

Fig (20)
Scio Site

Mean Brightness Band 25

Fig (21)
Model BRF Juniper RED

Viewing Angle

Fig (23)
Model BRF Juniper IR

Fig (24)
Fig (25)

Metolius River Site

Red

Infra-red
Model BRF Metolius RED

Fig. (26)
Waring Woods Site

Red

Infra-red

Fig (28)
Model BRF Waring Woods RED

![Graph showing BRF vs Viewing Angle]

Fig (29)
Model BRF Waring Woods IR

![Graph showing BRF values across different viewing angles. The x-axis represents viewing angles from -90 to 90 degrees, and the y-axis represents BRF values from 0.000 to 0.400. There is a peak in BRF around 15 degrees. Figure (30).]
Model BRF Cascade Head RED
Scio Site

Red

Infra-red

Fig (34)
Model BRF Scio RED

![Graph showing BRF versus Viewing Angle](image)

*Fig (35)*
Model BRF Scio IR

Viewing Angle

Fig (36)
Juniper: Model BRF VS ASAS BRF

![Graph showing the relationship between BRF and Viewing Angle with data points and a curve fit.](image-url)
Metolius: Model BRF VS ASAS BRF

Fig (38)
Waring Woods: Model BRF VS ASAS BRF
Cascade Head: Model BRF VS ASAS BRF
Scio: Model BRF VS ASAS BRF

Viewing Angle

Fig (41)
Waring Woods: Model BRF VS ASAS BRF

Viewing Angle

BRF

Fig (42)
Cascade Head: Model BRF VS ASAS BRF

Figure (43)
<table>
<thead>
<tr>
<th>Site</th>
<th>ASAS Overpass</th>
<th>Ground Observations</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Date Time</td>
<td>Date Time</td>
</tr>
<tr>
<td>Juniper</td>
<td>June 19, 1990</td>
<td>16:17:05 GMT</td>
</tr>
<tr>
<td>Metollus</td>
<td>June 19, 1990</td>
<td>16:37:00 GMT</td>
</tr>
<tr>
<td>Waring Woods</td>
<td>June 19, 1990</td>
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</tr>
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<td>Cascade Head</td>
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</tr>
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<td></td>
<td>June 20, 1990</td>
<td>23:50:00 GMT</td>
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Table 3: ASAS Bands Brightness

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<th>Angle</th>
<th>Juniper Site</th>
<th>Metolius River Site</th>
<th>Waring Woods Site</th>
<th>Cascade Head Site</th>
<th>Scho Site</th>
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<tbody>
<tr>
<td></td>
<td>Band 18</td>
<td>Band 26</td>
<td>Band 18</td>
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<td>Band 18</td>
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### Table 4: Timber Parameters And Component Signatures

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<thead>
<tr>
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<th>Juniper Site</th>
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<th>Waring Woods Site</th>
<th>Cascade Head Site</th>
<th>Scio Site</th>
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<tbody>
<tr>
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