A MODEL OF LIGHT SCATTERING IN THREE-DIMENSIONAL PLANT CANOPIES: A MONTE CARLO RAY TRACING APPROACH

by

Yves M. Govaerts
A Model of Light Scattering in Three-Dimensional Plant Canopies: a Monte Carlo Ray Tracing Approach
Cover: Diagramme showing the principle of a Monte Carlo ray tracing programme. The source of light is represented as a yellow rectangle. Rays are propagated through the scene from this source according to the laws of geometrical optics, taking into account the properties of the objects being encountered. This virtual laboratory allows the estimation of various radiative variables, such as the bidirectional reflectance of the scene, the absorption profile in each object, etc.

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Abstract

The global quantitative monitoring of terrestrial environments from optical remote sensing involves five main steps: (1) identification of the spatial and temporal scales and resolutions at which information on vegetated surfaces are required; (2) characterization of the nature of relevant radiometric signatures; (3) implementation of an instrument designed to observe these signatures; (4) development of mathematical tools capable of interpreting the radiative measurements in terms of the environmental variables of interest; (5) evaluation of the suitability and accuracy of the delivered products. To this end, physically-based models are developed to represent the radiative processes involved in the different steps. The physical processes that control the reflectance of a structured medium (such as a canopy) occur at a variety of spatial scales: the milli-scale which represents the smallest scattering element from a remote sensing point of view, typically a leaf; the meso-scale which concerns the arrangement of scatterers and finally, the macro-scale which includes topography and large landscape features such as the distribution of vegetation types. Clearly, a model to be used in remote sensing should represent those effects that are relevant to the scale of observation.

This thesis focuses on the development of a new radiative transfer model, called Raytran, designed to investigate solar radiation transfer problems in terrestrial environments over a variety of spatial scales. The model is based on Monte Carlo procedures and the latest computer graphics ray tracing and parallelization techniques. The canopy reflectance is estimated on a ray-by-ray basis. This model may be used as a virtual laboratory, to generate reflectances and absorption profiles of three-dimensional complex targets where all geometrical and physical quantities can be controlled explicitly. The accuracy of the model has been established by comparisons with another published Monte Carlo model and with laboratory measurements.

First, we explored the optical properties of a single plant leaf. The three-dimensional cell structure of the leaf is explicitly described and represents the different biological constituents of the leaf. Thanks to the very complex scene which can be described with Raytran and the availability of significant new parallel computing resources, this is the first time that the radiative transfer in a leaf is computed taking into account its three-dimensional structure. The accurate representation of the spatial organization of the canopy is one of the main advantages of the Monte Carlo ray tracing technique. We reviewed different approaches to parameterize the structural organization of the canopy, from simple statistical representations up to more sophisticated grammar-based methods such as the L-systems. We then explored the potential use of laser altimeter echo recovery method to infer the spatial organization of the canopy, discussed the advantages and drawbacks of the method and compared it with classical bidirectional reflectance measurements. Finally, we illustrated the potential of Raytran to evaluate
the quality and accuracy of procedures to extract meaningful biophysical parameters from radiometric observations.

This work demonstrates the potential of Monte Carlo ray tracing techniques to model the transfer of solar radiation in very complex scenes with a high level of accuracy and illustrates the role of modeling in developing new instruments, analyzing measurements, and evaluating retrieval schemes in the general framework of global environment monitoring on the basis of remote sensing data.
Résumé

Au cours des trois derniers siècles, des progrès technologiques importants ont permis le développement rapide d’une activité industrielle intense qui nous assure aujourd’hui plus que de simples conditions de survie mais un réel confort et bien-être. En contre-partie, ces développements ont profondément bouleversé l’environnement au point de devenir une menace à long terme pour la santé et la survie des différentes espèces vivantes qui peuplent la Terre. De plus en plus de preuves irréfutables ont en effet été accumulées sur ces perturbations, comme l’augmentation constante de dioxyde de carbone dans l’atmosphère. Cependant, les conséquences de ces changements sur l’environnement tant dans l’espace que dans le temps sont sujets à de nombreuses controverses au sein de la communauté scientifique. La compréhension des mécanismes qui régissent la biosphère en général et la végétation en particulier, ainsi que leur suivi dans le temps, sont devenus des nécessités pour répondre à ces problèmes. Pratiquement, seul un suivi basé sur des observations satellites est envisageable par rapport aux échelles spatiales et temporelles qui sont en jeu.

Actuellement, l’observation de l’environnement à l’échelle globale par la télédétection consiste le plus souvent à différencier différents types de végétations au moyen de procédures de classifications supervisées ou de combinaisons linéaires simples de mesures radiométriques, appelées indices spectraux, qui sont comparées à des valeurs de seuil ajustées localement. Une observation plus précise est néanmoins requise pour accroître notre connaissance de l’importance des perturbations des grands cycles biogéochimiques (eau, carbone, énergie) qui régulent le fonctionnement de la biosphère. Ces cycles dépendent de paramètres d’intérêt tels que la biomasse, la couverture fractionnaire de végétation ou encore l’activité photosynthétique des plantes. Ces paramètres doivent donc être observés de façon précise, ce qui requiert la mise au point de techniques plus avancées d’observations satellitaires. En effet, les satellites d’observation de la Terre dans le domaine optique ne mesurent pas directement ces quantités mais seulement des luminances au sommet de l’atmosphère pour une géométrie d’observation bien précise, c’est-à-dire la réflexion bidirectionnelle de la lumière solaire par ces surfaces au travers de l’atmosphère. L’élaboration d’un suivi quantitatif global de la végétation par la télédétection repose sur cinq étapes fondamentales.

1. L’identification des résolutions spatiales et temporelles requises pour l’observation de paramètres d’intérêt dans le cadre d’une application particulière.

2. L’étude des signatures spectrales (quelle quantité d’énergie est réfléchie en fonction de la longueur d’onde) et directionnelles (dans quelles directions cette énergie est réfléchie en
fonction de l’angle d’illumination) de ces paramètres. Il s’agit de mettre en évidence les variations maximales dans ces domaines et de voir comment elles peuvent être observées.

3. La conception d’instruments de mesure performants et optimisés pour mesurer ces signatures radiométriques.

4. Le développement d’outils mathématiques capables de convertir les luminances observées en valeurs de paramètres d’intérêt.

5. L’évaluation de la précision et de la vraisemblance des valeurs estimées.

Ces différentes étapes nécessitent la compréhension des processus radiatifs à différentes échelles spatiales dans la végétation: la milli-échelle qui représente l’élément diffusant de base, typiquement une feuille par rapport aux échelles examinées en télédétection; la méso-échelle qui concerne la propagation dans un arrangement homogène d’éléments diffusants; et enfin la macro-échelle qui comprend la topographie et l’organisation du paysage. En outre, il est nécessaire de tenir compte des effets radiatifs liés à la couleur du sol, à l’absorption et à la diffusion du rayonnement par l’atmosphère. Les processus radiatifs associés à ces différentes échelles peuvent être observés et modélisés séparément, mais il est extrêmement difficile d’étudier toutes les interactions possibles entre ces échelles vu le coût et la difficulté d’observations sur le terrain sur de vastes régions. La seule approche raisonnable qui permette de comprendre l’ensemble des interactions possibles entre les différents milieux et la lumière consiste à représenter explicitement ces interactions par un modèle de transfert radiatif.

Cette thèse a pour objet le développement d’un nouveau modèle de transfert radiatif, nommé Raytran, conçu pour étudier les problèmes de propagation du rayonnement solaire dans des environnements terrestres à différentes échelles. Raytran est basé sur des techniques de Monte Carlo, de lancé de rayons et du calcul parallèle. Le transfert radiatif est résolu rayon par rayon. Le système étudié dans le cadre de la télédétection se compose essentiellement de l’atmosphère, de la végétation et du sol. Cependant, plutôt que de représenter directement et exclusivement ce système dans notre modèle, nous nous sommes d’abord intéressés à la représentation de l’interaction du rayonnement avec des objets géométriques en toute généralité. Ces objets sont caractérisés par un ensemble de propriétés qui décrivent comment ils interceptent le rayonnement et modifient sa trajectoire soit à l’interface entre deux objets, soit lors de la propagation du rayonnement à l’intérieur du volume qu’ils définissent. Ces objets représentent des milieux homogènes avec lesquels la lumière interagit. Ils peuvent être assemblés de façon pratiquement illimitée pour décrire de nouveaux milieux d’une complexité nettement plus élaborée. Le modèle est conçu comme un laboratoire virtuel, c’est-à-dire un outil de recherche en transfert radiatif où tous les paramètres peuvent être explicitement contrôlés pour représenter, entre autres, le système sol-végétation-atmosphère. Un grand nombre d’informations sur le transfert radiatif, comme la réflectance bidirectionnelle ou le profil d’absorption dans la végétation, peuvent être calculées. La précision de ce modèle a été évaluée par comparaison avec des données de réflectances mesurées en laboratoire sur une cible artificielle. Nous avons également comparé les résultats de Raytran avec un autre modèle de Monte Carlo, plus simple, pour une scène identique.
Ce modèle a été utilisé pour étudier les problèmes de transfert radiatif lié aux cinq points énumérés ci-dessus. Dans le cas de la végétation, la feuille peut être considérée comme l’élément diffusant de base. Il est donc nécessaire de caractériser correctement ses propriétés directionnelles et spectrales. La réflectance bidirectionnelle d’une feuille est principalement déterminée par la rugosité de son épi- derme. Les concentrations des différents composants d’une feuille (eau, chlorophyle, cellulose, lignine, etc) déterminent son spectre. Cependant, ce spectre est affecté par la répartition spatiale des composants à l’intérieur des cellules de la feuille et par la quantité de lumière transmise à l’intérieur de celle-ci. Cette valeur dépend, entre autres, de la rugosité de l’épiderme de la feuille. Pour comprendre les effets respectifs de ces facteurs et leurs interactions mutuelles, nous avons décrit explicitement en trois dimensions la structure cellulaire d’une feuille. Les valeurs caractéristiques de la taille des cellules, de l’épaisseur des membranes qui les composent et de la répartition des composants dans les tissus ont été trouvées dans la littérature. Cette approche, la première du genre en trois dimensions, a permis d’améliorer notre compréhension du transfert radiatif dans une feuille et d’étudier les effets de la structure cellulaire sur le spectre des feuilles.

A l’échelle d’une plante, la représentation correcte de son architecture est un paramètre clé qui détermine la précision et le réalisme des simulations du transfert radiatif. Cette représentation peut se baser sur des observations de terrain mais celles-ci sont toujours limitées dans le temps et dans l’espace. Il est préférable de comprendre les mécanismes responsables de l’architecture d’une plante (règle de croissance, de branchages, de phylotaxie, etc.) et de les représenter au moyen de techniques appropriées allant de la simple description statistique jusqu’à une représentation explicite du fonctionnement des organes de la plante. Une approche basée sur les systèmes de Lindenmayer offre un bon compromis entre la complexité de mise en œuvre et le réalisme obtenu. Une représentation correcte de l’hétérogénéité verticale et horizontale du feuillage telle qu’elle apparaît dans la végétation permet de résoudre des problèmes avec un haut niveau de réalisme et d’explorer ainsi les signatures spectrales et directionnelles d’un grand nombre de scènes. A leur tour, ces études permettent l’élaboration d’instruments pour mesurer l’information désirée.

Nous avons examiné le potentiel d’un altimètre laser avec enregistrement complet de l’écho réfléchi par le sol et la végétation pour étudier le profil vertical de la biomasse sur différents types de densités foliaires. Cette technique s’avère extrêmement prometteuse pour l’étude des forêts et devrait permettre un suivi précis de leur éventuelle dégradation. Jusqu’à présent, cette méthode a été utilisée avec succès par le Goddard Space Flight Center de la NASA à partir d’un altimètre aéroporté opérant dans le proche infra-rouge. Dans un tout proche avenir, un essai d’utilisation de cette technique sera effectué à bord de la navette spatiale. La mise au point d’un tel instrument est extrêmement complexe à cause du grand nombre de paramètres qui caractérise sa performance: le laser qui émet les pulsations, le télescope qui reçoit l’écho et enfin le détecteur électronique qui échantillonne temporellement l’écho. Nous avons simulé la réflexion d’une pulsation laser sur plusieurs densités de couverture forestière pour mettre en évidence le rôle de ces différents paramètres. Nous en déduisons que la résolution verticale qui peut être attendue à partir d’observations satellitaires est inférieure au mètre. Nous avons également étudié les effets de distorsion de l’écho réfléchi lié à la diffusion multiple dans la végétation. La mise au point de ce type d’instrument et d’algorithmes pour en extraire une information quantitative sur la distribution de la biomasse ou la rugosité de surface nécessitera...
encore beaucoup d’efforts de recherche.

Finalement, nous avons abordé le problème de l’évaluation de la précision et de la fiabilité de l’information estimée à partir d’observations satellitaires. Cette étape est extrêmement importante car il est en effet peu utile d’utiliser des mesures satellitaires sans pouvoir évaluer la précision des données qui en sont extraites. Nous jugeons ici à la fois la précision des mesures de luminance et de l’algorithme utilisé pour en extraire de l’information. La méthode qui consiste à comparer directement les observations effectuées sur le terrain avec des observations satellitaires est limitée à cause du manque de cohérence entre les échelles spatiales de mesures, spécialement dans le cas de basses résolutions satellitaires. De plus, il est difficile de tenir compte de tous les facteurs susceptibles d’influencer la mesure satellitaire comme l’absorption et la diffusion atmosphérique ou la brillance du sol. Nous préconisons plutôt d’introduire les observations de terrain dans un environnement contrôlé comme il est possible de le faire avec Raytran, ceci permet d’assurer la cohérence des échelles. Le modèle de transfert radiatif sert à générer des réflectances synthétiques correspondant à un environnement où tous les facteurs sont parfaitement contrôlés et pour lequel les paramètres de départ sont parfaitement connus. Cette méthode doit cependant tenir compte des imprécisions liées à la mesure de la luminance. Il est alors aisé d’estimer la fiabilité et la précision de l’inversion d’un modèle de réflectance bidirectionnelle ou d’un indice spectral pour déduire les valeurs des paramètres originaux qui ont servi au calcul de la réflectance. Différentes analyses statistiques peuvent être appliquées pour évaluer l’efficacité et la précision des méthodes utilisées. L’utilisation du concept du rapport signal sur bruit pour évaluer la performance des indices spectraux est particulièrement pertinente.

Ce travail a permis de démontrer le potentiel d’une approche basée sur des procédures de Monte Carlo et du lancé de rayons pour calculer le transfert radiatif dans des milieux de complexité arbitraire avec un haut niveau de réalisme. Bien que la modélisation du transfert radiatif dans l’atmosphère joue un rôle important en télédétection, nous nous sommes limités dans ce travail au transfert radiatif dans la végétation, un grand nombre de modèle ayant déjà été consacré à la propagation du rayonnement dans l’atmosphère. Nous avons également montré comment un tel modèle permet d’augmenter nos connaissances de base en transfert radiatif en modélisant notamment la propagation de la lumière dans une feuille. Raytran s’avère également un outil de recherche puissant pour la mise au point de nouveaux radiomètres ou encore l’évaluation de procédures développées pour extraire des propriétés liées à la végétation à partir des mesures de luminance.
# List of Acronyms

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
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<tbody>
<tr>
<td>AVHRR</td>
<td>Advanced Very High Resolution Radiometer</td>
</tr>
<tr>
<td>APD</td>
<td>Avalanche PhotoDiode</td>
</tr>
<tr>
<td>BR</td>
<td>Bidirectional Reflectance</td>
</tr>
<tr>
<td>BRF</td>
<td>Bidirectional Reflectance Factor</td>
</tr>
<tr>
<td>CAD</td>
<td>Computer Aided Design</td>
</tr>
<tr>
<td>CEC</td>
<td>Commission of the European Community</td>
</tr>
<tr>
<td>CIE</td>
<td>Commission Internationale de l'Eclairage</td>
</tr>
<tr>
<td>CSCS</td>
<td>Centro Sizzero di Calcolo Scientifico</td>
</tr>
<tr>
<td>CSG</td>
<td>Constructive Solid Geometry</td>
</tr>
<tr>
<td>DMPP</td>
<td>Distributed Memory Parallel Processors</td>
</tr>
<tr>
<td>FAPAR</td>
<td>Fraction of Absorbed Photosynthetically Active Radiation</td>
</tr>
<tr>
<td>FOV</td>
<td>Field Of View</td>
</tr>
<tr>
<td>GEMI</td>
<td>Global Environment Monitoring Index</td>
</tr>
<tr>
<td>HNSM</td>
<td>Homogeneous Non-Scattering Medium</td>
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<td>HRV</td>
<td>High Resolution Visible</td>
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<td>HSM</td>
<td>Homogeneous Scattering Medium</td>
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<td>Institute for Remote Sensing Applications</td>
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<td>Illumination Zenith Angle</td>
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<td>Acronym</td>
<td>Description</td>
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<tr>
<td>LND</td>
<td>Leaf Normal Distribution</td>
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<tr>
<td>MISR</td>
<td>Multiangle Imaging SpectroRadiometer</td>
</tr>
<tr>
<td>MPI</td>
<td>Message Passing Interface</td>
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<tr>
<td>MTV</td>
<td>Monitoring Tropical Vegetation</td>
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<tr>
<td>NASA</td>
<td>National Aeronautics and Space Administration</td>
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<tr>
<td>NDVI</td>
<td>Normalized Difference Vegetation Index</td>
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<tr>
<td>NIR</td>
<td>Near-InfraRed</td>
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<tr>
<td>NOAA</td>
<td>National Oceanic and Atmospheric Administration</td>
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<tr>
<td>RM</td>
<td>Ross Marshak</td>
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<tr>
<td>RMS</td>
<td>Root Mean Square</td>
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<td>SI</td>
<td>Spectral Index</td>
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<tr>
<td>SLICER</td>
<td>Scanning Lidography of Canopies by Echo Recovery</td>
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<tr>
<td>SNR</td>
<td>Signal-To-Noise Ratio</td>
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<td>SZA</td>
<td>Sun Zenith Angle</td>
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<tr>
<td>TOA</td>
<td>Top-Of-Atmosphere</td>
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<tr>
<td>TOC</td>
<td>Top-Of-Canopy</td>
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<td>VI</td>
<td>Vegetation Index</td>
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Chapter 1

Introduction

Over the last few hundred years, technological progress has permitted a significant increase in human industrial activities driven not only by the need to guarantee survival conditions but also to improve the comfort and health of human populations. These developments have significantly altered our environment over the same period, and are largely responsible for the unprecedented rates of change in the chemical composition of the atmosphere, ground water quality, soil fertility and in the ecological balances of many ecosystems. These effects have been documented beyond doubt. An increasing awareness of these issues and the fear of serious consequences for the welfare of humanity have prompted the scientific community to set up major international efforts to understand the causes and implications of these changes. If there is no doubt about the reality of the global increase in atmospheric CO\textsubscript{2} and other perturbations of ecosystems, there are vigorous debates in the scientific community on the nature and extent of the implications of these changes in the long run. For instance, the Earth carbon cycle remains one of the major unresolved problems: significant amounts of CO\textsubscript{2}, released by human activities and which is largely responsible for the greenhouse effect, cannot be accounted for in the CO\textsubscript{2} concentration rise observed in the atmosphere nor in the oceanic carbon storage. Various studies have suggested that the missing sink of carbon probably lies in the terrestrial biosphere. Clearly, the main mechanisms responsible for these changes should be understood if corrective or preventive actions are to be taken, and these will, in turn, require an accurate documentation of the state and evolution of the environment, including the biosphere. Among the various components of the biosphere involved in these changes, the state of the vegetation is of paramount importance because it regulates the energy fluxes at the soil - vegetation - atmosphere interface, as well as the water and carbon cycles. Furthermore, plants provide raw organic materials and energy to all higher forms of life, in particular animals and human beings.

Vegetation constitutes the most prevalent form of life on Earth: over 99% of the living biomass is located in plants (Ajtay et al. 1979). Plants have developed organs and ‘strategies’ to seek useful light, to discard excessive radiation and to ensure their growth under specific climatic and nutritional conditions (Gates 1980). Human activities, such as deforestation, contribute directly to the modification of land cover whose effects on the climatic system are documented, at least at the regional scale. The importance of these phenomena at the global
scale therefore need to be fully assessed. Continuous worldwide observations of the actual land cover state are required in order to contribute directly to our knowledge and understanding of the Earth as a global and integrated system.

So far, remote sensing from Earth-orbiting satellites provides the only observation technology available to repetitively monitor the state and evolution of large areas at the required scale and resolution. Satellite instruments can only measure one or a few radiation characteristics, such as light intensity in a limited number of spectral intervals and angular directions, even though the radiation itself has been affected by many processes on its way to the instrument. Essentially, three different media interact with the observed radiation: the atmosphere, the vegetation and the underlying soil. Like all surfaces, vegetation canopies reflect light differently in different directions, depending on their optical and structural properties. As a result, observations of these surfaces obtained with a limited field-of-view instrument depend not only on the intrinsic properties of this surface and on the position of the sun, but also on the direction of observation. Remote sensing data analysis requires an adequate quantitative understanding of the processes controlling the transfer of radiation in the different interacting media in order to extract the required information from the observations. The current generation of instruments, designed a few decades ago, provides radiometric measurements with limited spectral resolution and lacks on-board calibration mechanisms. Consequently, quantitative applications are possible, but the accuracy may be not good enough. The characterization of the surface properties is most often based on simple linear combinations of radiometric values (spectral indices) and supervised classification procedures. For instance, land cover type discrimination is typically based on the determination of locally adjusted threshold values.

Clearly, a more meaningful characterization of the observed surfaces, as would be necessary to assess the carbon cycle in the vegetation for instance, requires more reliable techniques. Fundamentally, the global quantitative monitoring of terrestrial environments in the optical domain involves five main steps:

1. **Identification of the spatial and temporal scales and resolutions at which information on vegetated surfaces are required.** According to Townshend et al. (1994), land data are required for climate studies, biochemical and hydrological cycles, atmospheric chemistry, and finally ecosystem response to environmental changes. The diversity of the applications requires observations at very different spatial and temporal resolution.

2. **Characterization of the nature of relevant radiometric signatures.** Sensitivity studies are required to assess the possibility of detecting specific biomes or ecological processes from radiometric observations. These studies can be carried out on the basis of actual or simulated space-borne observations.

3. **Implementation of instruments designed to observe these signatures.** These instruments must be designed to measure the spectral and directional variability of the observed radiances to permit the retrieval of the information of interest.

4. **Development of mathematical tools.** These tools must be capable of interpreting the radiative measurements in terms of the environmental variables of interest, taking into account the perturbing effects such as the atmospheric aerosol and cloud extinction.
5. **Evaluation of the suitability and accuracy of the delivered products.** This step requires ground observations or very realistic simulations to evaluate the accuracy and suitability of the retrieved parameters.

This reasoning requires the understanding of the radiative processes at various spatial scales in the vegetation, from a single plant leaf to complex heterogeneous landscapes. Besides, it is also necessary to account for the radiative effects of the soil brightness and the atmospheric absorption and scattering. These different processes can be locally observed for specific environmental conditions, but it is extremely difficult to study all the interactions between the different scattering media at various spatial scales. **A rational approach to tackle this issue consists of representing the different underlying physical processes within a meaningful numerical model which should be able to account for the extinction processes in the different media and to describe the scattering processes at the appropriate scale.**

Basically, the nature and behavior of electromagnetic waves is described by Maxwell’s equations, and the fundamental interactions of radiation with atoms and molecules can be studied with the methods of quantum physics. The transfer of radiation through macroscopic natural media, however, cannot be described explicitly in terms of quantum interactions because of the number of photons involved and the diversity and complexity of the materials in the environment. Therefore, specific models need to be designed to represent this macroscopic interaction between fields of radiation and multiple finite-size objects, and to account for the measurements made with common instruments. Models that represent the reflectance of material surfaces as a function of the positions of both the source of illumination and the observer are called bidirectional models. Most of the methods which have been developed so far to design such models for vegetation canopies rely on the need to derive elegant integrable forms of the radiative transfer equations at the expense of simplifying the representation of the spatial organization and spectral properties of plant organs. Basically, most of these models are based on the radiative transfer theory in turbid media, possibly accounting for the finite-size and orientation of the scatterer. The vegetation is simply represented as a one-dimensional medium whose structural properties is statistically defined by the scatterer density and orientation. These parameters are used to characterize the interception and scattering of radiation by the scatterers.

However, according to the five steps mentioned above, it is important to specify the intrinsic properties of the vegetation in a meaningful way in order to properly characterize the radiative signature of specific events such as environmental changes or other types of forcing conditions. In other words, the problem of modeling the canopy reflectance should not be exclusively centered on the manipulation of radiative transfer equations but should also pay attention to the accurate representation of plant canopy physiological and morphological properties. Traditionally, researchers have attempted to retrieve plant physiological properties from observations of spectral variations, and more recently, morphological and structural properties from the directional variance of the data. Clearly, all plant properties are intimately linked and affect both types of variabilities. As a result, the spectral and directional signatures are interwoven and the proper quantitative estimation of these properties must account for and take advantage of both types of variation. Such methods need to be greatly improved if we are
to take full advantage of the available data. Consequently, a canopy reflectance model should clearly account for both the spectral properties of the scattering elements and their spatial arrangements at different scales. In addition, radiation-matter interaction modeling must be physically-based and the model should be able to represent radiometer characteristics such as the instantaneous field of view or the aperture.

Attempts to account for the three-dimensional structure of the vegetation in radiative transfer models have started in the early 1980s. These models represented the canopy as elementary cells, each treated as a turbid medium, but could not describe mutual shading effects between scatterers. Later, Monte Carlo reflectance models have been developed to represent explicitly the position of the scattering elements, at least for highly idealized plant architectures. Recently, canopy reflectance models have been designed to take advantage of the latest computer graphics techniques. However, none of these models are able to represent arbitrary complex media, mainly because of their fundamental design limitation. They do not account for the sensors characteristics. Moreover, radiation-matter interactions are modeled in a rather simplistic way.

To overcome these limitations, we choose to develop a new Monte Carlo ray tracing model, called Raytran. It takes full advantage of the latest developments in computer graphics techniques, parallel processing and method to represent complex systems. The design of this model is based on the concept of virtual laboratory in order to investigate radiative processes in terrestrial environment at different spatial scales. This virtual laboratory is a mathematical model, where almost all the different subsystems can be individually characterized, where their mutual interactions are explicitly controlled and which provides customized results as a function of the investigated phenomena. The design relies on the idea that each individual process is known and can be modeled or observed, but the result of their combination is unknown and very difficult to assess. The model can be used to generate reflectances as well as absorption profiles for arbitrarily complex three-dimensional targets where all geometrical and physical quantities can be specified explicitly. The main objective of the present research concerns the development, the validation and the exploitation of this virtual laboratory. The exploitation of massively parallel computers to accelerate the model represents a secondary objective of this work.

This thesis is organized into two main parts. The first one is dedicated to the description of the model principles and the evaluation of its accuracy. Chapter (2) provides some background discussion on the state of the art in radiation transfer modeling in the vegetation, arguing the advantages of the Monte Carlo ray tracing approach. The underlying principles of the model are explained in Chapter (3). Chapter (4) is dedicated to the evaluation of the model accuracy by comparisons with another published simple Monte Carlo model and with laboratory measurements.

The second part demonstrates the potential of the virtual laboratory concept to address radiative transfer issues in relation with the space-borne observations of terrestrial surfaces and represents the major contribution of this thesis in the context of current research efforts in remote sensing in particular and radiative transfer problems in general. The optical and directional properties of a single plant leaf are simulated in Chapter (5). At a larger scale, leaf mutual shadowing is responsible for directional effects, and in particular for the hot spot
phenomenon. Various techniques to generate realistic artificial plant canopies are investigated in Chapter (6). In Chapter (7), we simulate the principle of the laser altimetry technique to analyse the potential of this method to retrieve the structural properties of the vegetation. Finally, in Chapter (8), we suggest a strategy to validate the products which are delivered from satellite observations based on the simulation of the reflectance of realistic scenes. This strategy takes into account the difference of spatial resolution between ground and remote sensing observations.
Chapter 2

Motivation for a Monte Carlo ray tracing approach

This Chapter provides some background discussion on the state of the art in radiation modeling, focusing on the description of the reflectance of natural surfaces. The physical problem that must be addressed by a general purpose radiative transfer model dedicated to space-borne remote sensing data analysis of vegetated land is presented in Section (2.1). The principles of canopy reflectance models are reviewed in the next section. Section (2.3) discusses the role and specific contribution of the ray tracing approach, in particular its advantages and drawbacks, and surveys the progress made by this technique in computer graphics.

2.1 Statement of the physical problem

Space-borne radiometers in the optical spectral region measure top-of-atmosphere (TOA) radiances in a particular direction within a narrow field-of-view which corresponds to a ground resolution ranging from tens of meters up to kilometers. Sunlight interacts with three different media before illuminating the detector optics: the atmosphere, the vegetation and the underlying soil. Since these three media differently affect the transfer of radiation, their effects must therefore be explicitly described. Atmospheric gases and aerosols scatter and absorb part of incoming solar radiation. At the Earth’s surface, the radiation is reflected, transmitted and absorbed by the vegetation. The complexity of the representation of the transfer of radiation in the vegetation results in part from the fact that natural surfaces reflect light differently in different directions. This anisotropy is driven by the optical and the structural properties of the medium. Finally, the soil acts as the lower boundary condition of the radiative system. Ideally, a general purpose bidirectional reflectance model dedicated to remote sensing studies of vegetated land surfaces should include the following features:

- It must take into account the optical and the structural properties of all intervening media over a variety of spatial scales.
- Radiation-matter interaction modeling must be physically-based.
• Atmospheric effects must be taken into account.

• It must represent the radiometer characteristics as the instantaneous field of view or the aperture.

These different points are addressed below.

2.1.1 The spatial scale

In the solar spectral region, according to the approach of Westin et al. (1992), we may assume that the overall canopy reflectance results from a combination of radiative effects at three different scales.

The milli-scale

With regard to the bulk structure of the canopy, the milli-scale is defined as the scale of the basic scattering object \textit{i.e.}, a leaf or any other phyto-element in the case of a plant canopy. The main effect of a single leaf on light transfer is to reflect, transmit or absorb the radiation as a function of the wavelength and the type of surface. This implies that leaves are considered as "black boxes" when part of a canopy reflectance model. In fact, this scale conceals another scale, the \textit{micro-scale} which deals with the cell structure of a leaf. The interaction of light with these cells is difficult to represent explicitly because the scatterers are then about the same size as the wavelength. In this case, other physical processes must be taken into account, such as diffraction. As mentioned in Chapter (1), it is neither possible nor desirable to express the radiation transfer in the vegetation in terms of wave or even quantum interactions. All these effects are statistically embodied at the milli-scale through statistical distribution functions such as the scattering phase function. This scale is thus mainly characterized by spectral effects resulting from the cellular structure and chemical composition of the scatterers and directional effects resulting from leaf epidermis properties.

The meso-scale

The meso-scale deals with the spatial organization of the single scatterers or phyto-elements in space, typically a single plant or a homogeneous set of plants. The mutual shadowing effect due to the finite size of the scatterers causes the so-called \textit{hot-spot} phenomenon. Its intensity depends principally on the scatterer’s size, density and orientation. The canopy architecture at this scale is most often described in terms of leaf area density (LAD) and leaf normal distribution (LND) which define the optical thickness of the medium. This scale is governed by directional effects resulting from the leaf arrangement.
The macro-scale

The range of the macro-scale runs from plant local heterogeneous arrangements to the broad landscape patterns. The effects of this scale on the reflectance result mainly from heterogeneities due to the ground cover, the fragmentation of the landscape and the topography within the field-of-view of the sensor. So far, this scale suffers from a lack of structural parameterization. As a consequence, quantification of these effects remains very difficult.

Obviously, in the case of laboratory reflectance measurements from a single leaf, only the milli-scale effects have to be considered. On the contrary, to model or to extract information from low resolution space measurements such as those provided by the AVHRR instrument on the NOAA platform, the full range of effects should be taken into account. The description of the spatial organization of plant canopies at these different scales is detailed in Chapter (6).

2.1.2 Radiation-vegetation interaction

When radiation interacts with a surface, its energy, direction and polarization may be modified. The interaction of radiation with plant surfaces is extremely complex. The mechanism of leaf reflectance is of considerable significance in remote sensing of vegetation. The development of detailed radiative transfer models requires thus the best possible knowledge of how radiation interacts with individual phyto-elements (Govaerts et al. 1995). The following discussion will focus on the spectral and directional behavior of individual phyto-elements for various wavelengths.

Figure 2.1: Reflectance and transmittance of a clover leaf. The absorptance of the leaf is given by the difference between the two curves.
Spectral behavior

Standard reflectance and transmittance spectra of leaves clearly show three different regions in the solar domain: visible, near-infrared and middle-infrared (Figure 2.1).

- In the visible wavelengths (0.4–0.7 \(\mu\)m), approximately 2–3 percent of the incident radiation, or about half of the total reflectance is reflected from the surface (cuticle) of leaves and does not penetrate or interact with the deeper leaf tissues (Bauer 1985). The amount and nature of cuticular reflectance depends on the surface characteristics (wax layer) which are uniquely related to species. The greatest portion of incident radiation enters the leaf and interacts with the internal leaf components and structures where it is strongly absorbed by chlorophyll and other pigments. Chlorophyll absorption gives rise to fluorescence mechanisms, i.e., non-elastic interactions. Fluorescence contributes to less than 1% of the re-emitted radiation in this band in case of natural illumination\(^1\).

- In the near-infrared (NIR) region (0.7–1.3 \(\mu\)m), 40 to 50 percent of the radiation is reflected by the leaf, only 5 percent of the incident energy is absorbed and the rest is transmitted. The high reflectance and transmittance value is explained by multiple reflections in the internal mesophyll structures, caused by differences in refractive indices of the cell walls and intercellular cavities.

- The middle-infrared region (1.3–2.6 \(\mu\)m) is characterized by lower reflectance and transmittance than in the NIR. Absorption is controlled by the leaf water content, and is nearly complete at wavelengths greater than 2 \(\mu\)m (Gates 1980).

- In the far or thermal infrared (±3–50 \(\mu\)m), leaf reflectance is about 0.05 with a peak at 10 \(\mu\)m for some species. A plant leaf emits thermal radiation in accordance with its temperature.

- The spectral behavior of leaves in the microwave bands (from 0.03 to 30 cm) is mainly governed by their dielectric properties. Because the dielectric constant of water is much greater than that of dry vegetation, water content plays a dominant role at these wavelengths (Daughtry et al. 1991).

Directional behavior

The direction in which the radiation will be scattered is difficult to determine \textit{a priori}. When striking an object, the radiation can undergo multiple interactions before escaping from the surface. In the visible band, leaf transmittance is nearly Lambertian (Brakke et al. 1989) while the reflectance direction depends on the source incidence angle. Leaf reflectance exhibits both diffuse and specular characteristics. The diffuse reflectance results mostly from the interaction of light with the internal leaf structure where the radiation through the leaf tissue encounters different internal surfaces of varying geometrical configuration and refractive indices (Kumar and Silva 1973). Specular reflectance is due to the light scattered primarily by the surface.

\(^{1}\)G. Schmuk, personal communication.
of the leaf (Rondeaux and Herman 1991) and its contribution increases at large angles of incidence. This specular angular dependence is attributable to surface roughness (McClendon 1984).

### Polarization

The polarization of the electromagnetic fields after the interaction may convey information about the physiological status of the leaf surface (Vanderbilt et al. 1991). According to Grant et al. (1987), the degree of polarization of reflected light in the visible region varies from 10 (in the red) to 50 (in the blue) percent.

#### 2.1.3 Atmospheric effects

Atmospheric constituents contribute to the absorption and scattering of radiation on its way from the sun to the Earth’s surface and back to the satellite sensors. The main constituents which affect the transfer of radiation are gases (water vapor, carbon dioxide, ozone, ...) and aerosols which are composed of small liquid or solid elements suspended in the air. Light scattering in the atmosphere depends on its wavelength and the size, shape and type of particle. Rayleigh scattering applies when rays interact with molecules whose size is much smaller than the radiation wavelength. When the radiation interacts with spherical particles whose size is comparable to the wavelength, so-called Mie scattering occurs. In the atmosphere, the former type of scattering dominates. The main effects of the atmospheric scattering is to generate the sky radiation which illuminates both satellite sensors and the Earth surface. Typical sky radiance contributions range from 15% to 30% of the direct solar radiation under clear sky conditions. Atmospheric scattering contributes also to the polarization of the light.

The atmospheric absorption strongly depends on the wavelength. The regions of the solar spectrum where the atmospheric transmission is very high are numerous in the 0.4 – 1.3 \( \mu m \) region which is of prime interest for vegetation observations and especially in the visible between 0.35 and 0.75 \( \mu m \) and 0.85, 1.06 , 1.22 and 1.60 in the near-infrared (Vermote et al. 1995).

#### 2.1.4 Instrument effects

Space-borne electro-optical sensors or radiometers are complex devices which transform the radiation received by an optical system into digital counts through the instrument electronics. From a radiative transfer point of view, it is important to understand the effects of the sensor optics such as the aperture and field-of-view. The size of the instrument’s optical aperture controls the amount of energy collected during the recording time and is responsible for diffraction phenomena (Norwood and Lansing 1983). For a given instrument altitude, the field-of-view determines the ground resolution and thereby the probability of observing homogeneous land cover types.
CHAPTER 2. MOTIVATION FOR A MONTE CARLO RAY TRACING APPROACH

2.2 Principles of canopy reflectance model

Models that represent the reflectance of plant canopy surfaces as a function of both the source of illumination and the observer are referred to as “canopy bidirectional reflectance” models. They should include the different effects described in the previous section for the analysis and understanding of radiative transfer processes involved in space-borne radiometric measurements. Whatever the complexity and details of the representation of the physical processes, the design of such models relies on three basic questions:

1. How to represent the interacting media optical and structural properties?
2. How to set up the system of equations which describes the propagation of light in these media?
3. How to numerically solve these equations?

Although the description of the spatial organization of the canopy can be limited to a one-dimension medium, the radiative transfer equations should always account for the propagation in three dimensions. The complexity of the radiative transfer equations are driven by the accuracy of representation of the plant canopy optical and structural properties. Verstraete et al. (1990) proposed an elegant analytical solution to describe the radiation transfer in a semi-infinite medium composed of finite-size and oriented scatterers using the classical equations of radiative transfer in turbid media (Chandrasekhar 1960) but taking the mutual shadowing effects into account. Later, Iaquinta and Pinty (1994) introduced the effect of a Lambertian soil using the discrete ordinate numerical method to solve the radiative transfer equations. While very efficient in terms of computing requirements, these models do not permit the representation of plant canopy spatial heterogeneities. The structural properties of the canopy is simply represented with the LAD, LND and a parameter to account for the mean sunfleck area in the canopy. Classical radiation transfer theory, based on the solution of differential equations, has become a mature field but has also reached its limitations when it comes to the precise representation of radiation scattering in complex media. To allow realistic sensitivity studies, canopy reflectance models should, in principle, include the effects of the three spatial scales described in Section (2.1.1). The state of the art approaches currently emphasize the photon transport approach, taking advantage of the solution of particle transport equations derived by nuclear physicists (e.g., Shultis and Myneni 1988; Myneni and Asrar 1993), or the computer graphics based approach, driven by the need to represent as precisely as possible the transport of light in a medium of arbitrary complexity (Goel et al. 1991). This latter method has reached a very high level of realism, taking into account most of the physics of the light propagation. Two methods are actively being investigated: ray tracing and radiosity.

2.3 Computer-based approaches

Computer models have been developed to describe explicitly the transfer of light in canopies. These models allow realistic simulations of the radiation regime in a canopy but require significant computer resources. Recently, Dauzat and Hautecoeur (1991) and Borel et al. (1991)
have successfully demonstrated the possibilities of computer graphics techniques such as ray tracing and radiosity to develop canopy reflectance models. Each method has its own advantages and drawbacks. The choice of the approach selected here depends mainly on the representation of the radiative processes described in Section (2.1).

The radiosity approach, initially developed to solve thermal engineering problems, describes the scattering of light between ideal diffuse surfaces independently of the observer position. The target is divided into \( n \) small elementary plane surfaces called “patches”, each with its own emissivity and reflectivity. The main idea is that each patch is exchanging radiation with all others. To solve this problem, a form-factor, accounting for how much of a patch is lit by another, is computed for each pair of patches. The treatment of this problem in terms of the radiosity approach can be expressed as a linear system (a \( n \times n \) matrix of form-factors). Properly optimized, this method is computationally efficient. For remote sensing applications, i.e., canopy reflectance modeling, the advantage of the radiosity method is that the form factor matrix can be computed once and for all, so that the reflectance of a scene viewed from different directions can be computed quickly. However, the method suffers from intrinsic limitations such as the difficulty of dealing with weak radiation and the necessary assumption of Lambertian surfaces. Immel et al. (1986) extended the radiosity method to account for specular reflection. They partition the hemisphere over the patches into a finite set of solid angles, each of which establishes a direction for incoming or outgoing energy. However, this approach leads to a less computationally attractive method especially if highly specular surfaces are modeled (Foley et al. 1990).

With ray tracing, light propagation through a medium is conceptualized as individual rays propagating in the described medium. When a ray hits a surface, it is either absorbed or scattered. Basically, rays can be traced in the forward or reverse direction. In the latter case, the rays are traced from the observer to the source. This method allows an accurate representation of the simulated observer optics but does not account efficiently for complex illumination. It is particularly well-suited to the creation of realistic images, and is extensively used in advertising and movie making industries. In the forward mode, the principle is to generate a ray from the illumination source(s) to the target scene. Only the rays that will effectively reach the target are generated. The ray path through the vegetation is tracked from interaction to interaction with phyto-elements until the ray is absorbed or escapes from the target area. However, the method does not produce a synthetic image as in the case of the computer graphics approach. The main results are an exact description of the history of each ray path, i.e., a distribution of the locations where radiation-matter interactions took place, together with a detailed description of the outcome of such interactions. Clearly, the forward mode is much more meaningful from a radiative point of view.

The weakness of the ray tracing approach is the large computational requirement, especially when diffuse scattering occurs, due to the high number of rays needed to adequately represent the angular distribution of rays. However, even if the radiosity approach is particularly adapted to describe diffuse light scattering by Lambertian surfaces, ray tracing is better able to work out a multipurpose light transport model. Some recent attempts have been made to combine the two approaches, but require to define \( a \ priori \) the correct distribution between the diffuse and specular reflections. Specifically, Monte Carlo ray tracing offers the following advantages
CHAPTER 2. MOTIVATION FOR A MONTE CARLO RAY TRACING APPROACH

with regard to the physical processes which have to be represented.

- This method is perfectly well suited for the development of a general purpose radiative transfer model because each subproblem is solved independently. This property allows a very modular design where the surface properties of each scatterer can be easily changed as a function of the radiation wavelength and of the surface composition.

- It accounts for all types of radiation-matter interactions supported by the geometrical optics theory. Multiple scattering does not involve new physical problems.

- The forward mode allows a very realistic illumination for the incident direct and/or diffuse light. The complexity of the illumination models has essentially no effect on the computational expense and is completely independent of the target structure and scatterer optical properties.

- The method is very versatile and is therefore appropriate for developing a virtual laboratory.

- It can be trivially parallelized and offers attractive performance on massively parallel computers.

- It allows extraction of a wide variety of different statistics on the radiation transfer in the scene such as the mean free path, the mean number of interactions, the vertical extinction profile or more simply the bidirectional reflectance (BR).

Kimes and Kirchner (1982) pioneered Monte Carlo methods in three-dimensional canopies. Their canopy is divided into elementary cells, each of which is treated as a turbid medium so that shading and the related hot spot effects cannot be described. Cooper and Smith (1985) developed a Monte Carlo reflectance model, limited to the case of a non flat soil coupled with a canopy bidirectional reflectance model. Ross and Marshak (1988) developed an attractive Monte Carlo model for light transport in three-dimensional canopies. This model allows the study of the influence of the canopy geometry (e.g., density, height, number of leaves per plants) on the hot spot. They later introduced a specular component in the leaf reflectance properties (Ross and Marshak 1989). Unfortunately, this model represents only a very simple and idealized canopy architecture. More detailed reviews of Monte Carlo method applied to canopy radiative transfer can be found in Goel (1988), Myneni et al. (1989) or Ross and Marshak (1991). In brief, one can say that Monte Carlo methods are used to study radiation propagation in heterogeneous canopies and the influence of various canopy geometries (e.g., leaf dimensions, distance between leaves, leaf orientation) on the absorption or scattering of solar radiation. However, none of these models are able to represent arbitrarily complex media, mainly because of their fundamental design. Moreover, ray-matter interactions are rather simply modeled.

To overcome these limitations, a new Monte Carlo ray tracing model, called Raytran, has been designed and takes full advantage of the latest developments in computer graphics techniques, parallel processing and methods to represent complex systems. The principles of this model as well as its originality with regard to the existing ones are presented in the next Chapter.
Chapter 3

Description of the Raytran model

3.1 Introduction

Raytran has been designed to permit the description of a variety of, complex, three-dimensional scenes with realistic optical properties, under simulated natural or artificial illumination conditions. It has not been designed for a specific type of application, but to address most of the radiative transfer problems in relation with the remote sensing observation of terrestrial surfaces such as sensitivity studies, target spectral signature analysis, sensor and retrieval procedure evaluation, etc. This model relies on the following main hypotheses:

1. **Light propagation is exclusively described in terms of geometric optics** The phase and the polarization of the radiation are not currently represented in the model, but these light characteristics can be added in the future. While this model allows the description of the phase and polarization propagation, they have not been included in the model because of the lack of available information to properly model them. In addition, present satellites are not able to measure such quantities.

2. **Incident radiation can be simulated with a finite number of rays which do not interact between each other.**

3. **Scattering events are elastic, neglecting the effects of quantum transitions and diffraction.** We saw in Section (2.1.2) that the contribution of the fluorescence of the chlorophyll is less than 1% under natural illumination conditions.

4. **The structural properties of the medium can be described with geometrical primitives.**

5. **Optical properties of the elements can be defined with probability distribution functions.**

The radiative transfer is solved on a ray-by-ray basis using Monte Carlo ray tracing techniques, generating rays in the forward direction, i.e., from the energy source to the scene.
Monte Carlo modeling is essentially a statistical method used to estimate certain average characteristics of a process. In the present case, this technique is used to generate incident radiation, to define the type of interaction when collisions occur, and to compute the scattering angles. The mathematical principle of Monte Carlo procedures is described in Annex (A). Monte Carlo procedures need to be optimized in order to limit the number of trials required for a given result accuracy. Classical optimization methods rely on variance reduction techniques which have been the subject of an abundant literature (e.g., Hammersley and Handscomb 1964). However, there is no unique optimal sampling strategy and the solution may depend on the nature of the problem (Shirley et al. 1996). When applied to radiative transfer computation with ray tracing methods, most commonly used optimization approaches are based on reverse ray tracing, i.e., the rays are generated from the detectors to the scene, and ray weighting mechanisms, i.e., a probability is assigned to each ray trajectory. The first method is not very efficient in case of complex illumination. Perfect energy conservation is hard to ensure with the second method since ray paths are abandoned when the probability of the trajectory becomes too small. As explained in the previous Chapter, we simulate ray propagation in a physically meaningful way, i.e., in the forward direction and without any weighting mechanism. As a consequence, the radiative transfer computation is based on a very simple straightforward Monte Carlo scheme. However, this approach is very computer time consuming and the design of the code has been strongly optimized to take advantage of the latest hardware and software parallelization developments. Indeed, Monte Carlo ray tracing techniques provide a well defined and well adapted problem for parallel computing (refer to Annex B).

Basically, three main preliminary steps are necessary to define an experiment with this model. The first one consists of creating the target with geometrical primitives (refer to Section 3.2), and assigning an interaction model to each object. The description of the scene is therefore completely independent of Raytran which has no predefined scene. Energy sources from which the rays are generated need next to be defined. Finally, one has to define measurements and filters to extract relevant information from ray paths. The computation of the radiation transfer in the scene is composed of 5 main steps.

1. **Generation of the rays.** Rays are generated in the forward mode from one or more energy sources (see Section 3.4).

2. **Localization of the ray-surface intersection.** This step constitutes the main task of any ray tracer and is described in Section (3.3).

3. **Determination of the type of interaction.** When an interaction occurs, the type (absorption, reflection, transmission) is selected according to the probability density function of the corresponding events (Section 3.5).

4. **Determination of the new direction.** In case of scattering, the new direction is defined with a Monte Carlo procedure applied to the interaction model (Section 3.5).

5. **Extraction of relevant information from the path.** This step, which consists of performing “virtual measurements”, is described in Section (see 3.6).
Steps 1 to 5 are executed for all generated rays, while steps 2 to 4 are repeated until rays are either absorbed or leave the outer boundary of the modeled scene.

### 3.2 Geometrical description of the target

The objects \( n_l = 1, \ldots, M \) that interact with radiation are represented explicitly as three-dimensional structures, which are generated before any radiation experiment takes place. Since the early 1970s, the rapid development of computer graphics and computer-aided design (CAD) has promoted a new branch of mathematics commonly called geometric modeling or sometimes computational geometry (Preparata and Shamos 1985). To describe the geometrical primitives, we have adopted the Rayshade\(^1\) syntax which allows the definition of various solid objects (e.g., polygons, discs, spheres, cylinders, cones, boxes) characterized by their location, orientation, and dimension. Object positions are given with respect to a world Cartesian coordinate system as shown in Figure (3.1). Primitives can be combined (union, difference, intersection) to produce more complex objects with the Constructive Solid Geometry (CSG) technique (Mortenson 1985). Geometrical transformations (rotation, translation and scaling) can be applied to any primitive or set of primitives. Primitives may be divided into two categories: open or closed objects. Closed primitives (e.g., spheres, boxes, torus) enclose a portion of space for which “inside” can be clearly distinguished from the “outside” with a surface whose normal is pointing outward. CSG allows the construction of complex closed objects from simple primitives such as triangles or polygons, provided the normals are correctly oriented and that there are no holes left in the surface. To simulate a horizontally infinite scene, the target is assumed to be surrounded by similar ones such that rays which escape the scene from one lateral side are translated to the opposite side while the direction remains unchanged. It is not an actual horizontally infinite scene but rather a “periodic” one. An interaction model, which characterizes how radiation interacts with matter, must be assigned to each object. The different interaction models are described in Section (3.5).

In principle all targets of interest to environmental remote sensing studies may be represented, i.e., from a single leaf or needle up to a large valley. The smallest object size which can be represented is determined by the intrinsic limitation of the principle of the geometrical optics theory. This theory is valid only at distances sufficiently large from the point of interaction (i.e., distance of observation \( \gg \) wavelength) and is not able to account for interactions between rays and objects whose size is smaller than the wavelength of light (Born and Wolf 1964). Raytran has no predefined scene. The generation of a meaningful scene represents one of the main tasks of the realization of an experiment and is discussed in Chapter (6).

### 3.3 Localization of the ray-surface intersection

Computing the point of intersection with the surface closest to the ray origin is the basic operation of the ray tracer. Geometrical rays are characterized by an origin and a direction.

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\(^1\)Rayshade is a public domain computer graphics ray tracer written by Craig E. Kolb which is available on the World Wide Web server http://www.cs.princeton.edu/\simcek/rayshade/
CHAPTER 3. DESCRIPTION OF THE RAYTRAN MODEL

Figure 3.1: The structural properties of the scene is described with geometrical primitives whose location, orientation and dimension are given in a word Cartesian system. One or more energy sources may be located either inside or outside the scene.

The intersection point is searched for, using an optimized geometrical sorting algorithm, based on bounding individual or list of objects in axis-aligned bounding boxes, and/or by a uniform subdivision of part of the scene in smaller volumes called “voxels” (Arvo and Kirk 1989). The aim of the former method is to substitute costly intersection checks by cheaper ones. Indeed, if a ray does not intersect a bounding box, for sure it will not interact with all the included objects. In the latter method, each voxel contains the list of all totally or partially included objects. The choice of one technique over another depends mainly on the organization of the target which can have a repetitive structure, large void areas or be composed only of simple geometrical primitive objects. An intersection point is characterized by its world coordinates $P$ and the direction of the normal $\Omega$ $(\theta_l, \phi_l)$ to the surface at that point.

3.4 Lighting models

Monochromatic incident radiation is generated from different energy sources located inside or outside the scene. These energy sources are defined by an area (point, rectangular or circular) over which the origin of the rays is uniformly distributed. However, an energy source is not considered as an actual object which can itself intercept rays. The direction of the generated rays is simulated with an emissivity distribution function $\epsilon(\Omega_0)$ which may represent artificial or natural illumination conditions. In the first case, the light is typically characterized by quite a small area and a beam with a controlled divergence. Different energy sources can be combined to simulate complex illumination conditions. In the case of natural lighting conditions, the illumination is composed of direct radiation from the Sun and scattered radiation by the
atmosphere. Direct emissivity is simply simulated by a Dirac delta function $\epsilon(\Omega_0) = \delta(\Omega - \Omega_0)$ where $\Omega_0$ is the direction of emission. Raytran has been mainly designed for top-of-canopy (TOC) reflectance simulation. However, atmospheric scattering effects, described in Section (2.1.3), responsible for the sky radiance, may not be neglected when such a level of complexity and realism is to be achieved. To model the radiation extinction profile in the vegetation, or the canopy bidirectional reflectance as observed from ground measurements, only the shape of the sky radiance acts as an upper boundary condition which must be represented in the illumination of the scene. Neglecting the multiple scattering effect between the vegetation and the atmosphere, the sky radiance can be easily simulated with an appropriate emissivity distribution function. The most simple and widely used sky radiance model assumes isotropic radiation. The isotropic emissivity distribution function is given by $\epsilon(\theta_0, \phi_0) = \sin \theta_0 d\theta_0 d\phi_0 / \pi$ and the corresponding random variate is simply defined as $\theta_0 = \arccos u$ where $u \in [0, 1]$.

Figure 3.2: Comparison between clear sky radiances in the principal plane as computed by the physically-based model of Zibordi and Voss 1989 (dashed line) and the CIE formula (solid line) at 0.75$\mu$m for a SZA of 50°.

The simulation of accurate clear sky radiance distributions is important for many sensitivity studies. Several physically-based models have been developed to model the clear sky radiance and account for the scattering and absorption by the different components of the atmosphere (e.g., Zibordi and Voss 1989; Vermote et al. 1995). In the present case, we are more interested by the shape of the diffuse solar radiance than by its physical modeling. Therefore, we use an expression as simple as possible. On the basis of previous works (e.g., Steven 1977), the CIE (Commission Internationale de l’Eclairage) suggests an empirical formula for the clear sky radiance

$$E(\theta_0, \phi_0) = E_z \frac{(0.91 + 10 \exp(-3g) + 0.45 \cos^2 g)(1 - \exp(-0.32 \sec \theta_0))}{0.274(0.91 + 10 \exp(-3\theta_s) + 0.45 \cos^2 \theta_s)}$$

(3.1)

where $E_z$ is the observed radiance at the nadir, $\theta_s$ is the Sun zenith angle (SZA), $\theta_0$ is the zenith angle of observation and $g$ the phase angle between the Sun and the observation direction. Figure (3.2) shows the comparison between the CIE formula and the model of Zibordi and Voss (1989) for a SZA of 50°. Equation (3.1) has been implemented in Raytran to model the sky radiance emissivity distribution but with variable parameters to allow the simulation
of different atmospheric optical thicknesses. The value of the parameters can be fitted by
inverting equation (3.1) against measurements or physically-based model results. The ratio
between the diffuse and direct illumination contribution is merely controlled by the number
of rays emitted by each source.

In the framework of space-borne data analysis, the simulation of TOA reflectances is much
more desirable. In that case, models such as 6S (Vermote et al. 1995) can be used to ac-
count for the atmospheric attenuation of radiation. While very elaborate, codes such as 6S
suffer from approximations, mainly concerning the representation of ground–atmosphere inter-
actions. Since Raytran is capable of modeling radiative transfer in turbid media as will be seen
in Section (3.5), it is possible to simulate explicitly the atmospheric scattering and absorption
effects taking into account its vertical heterogeneity, the multiple interaction between the soil
and the atmosphere and the presence of clouds.

3.5 Interaction models

When a ray collides with an object of the scene, its trajectory can be modified according
to the optical properties of the object. It is therefore necessary to model, in the context of
geometrical optics, how rays interact with matter in general and with biological surfaces in
particular as described in Section (2.1.2). The “optical path” of the light can be rigorously
deduced from Maxwell’s equations when the wavelength tends to zero and is characterized
by a vector whose direction is normal to the wave-front and whose magnitude is equal to the
product of the energy density and velocity (Born and Wolf 1964). This vector is also called the
“geometrical light ray”. These rays present some similarities with photons in quantum physics,
even though the equations of geometrical optics are not directly derived from this latter theory.
In quantum physics, a photon is defined by its energy \( E = \frac{hc}{\lambda} \), its impulse vector \( \vec{p} = \left( \frac{E}{c} \right) \vec{n} \)
and its spin are subject to the uncertainty principle of Heisenberg (\( h \) is Planck’s constant and
\( c \) the light velocity). For these reasons, we will avoid speaking of photons. Since no phase and
polarization effects are simulated, a ray is merely characterized by its wavelength, origin and
direction. The origin \( P_0 \) of a emitted ray (referred to as \( \Xi^E \)) is randomly located in the energy
source area and its direction \( \Omega_0 \) is defined by the associated emissivity distribution function.
We shall always assume that a scattered ray has the same energy (wavelength) as the incident
one, such that a ray is either completely absorbed or re-emitted (\( i.e., \) quantum transitions are
excluded). The origin \( P_1 \) of a first scattered ray is the point of ray-matter interaction and the
new direction \( \Omega_1 \) is modeled with empirical or physically-based equations which characterize
the object optical properties.

In Raytran, rays are always travelling in a “medium” which may be absorbing and/or scatter-
ing. A medium is a geometrical object defined by its position, spatial extension and an interaction model. It may contain other objects with different optical properties
(Figure 3.3). Raytran essentially simulates interactions at the interface between two media
and the propagation of rays in these media. Interaction models characterize the scattering
process at the interface between two media as well as the propagation in the medium. They
should provide the type of interaction (reflection transmission or absorption), noted \( \Xi \), and
the outgoing direction $\Omega_2$ on the basis of the knowledge of the characterization of incident ray direction $\Omega_1$, intersection point coordinates $P_1$ and the surface normal to that point $\Omega_L$.

Infinitely thin media may also be defined with open objects. They are considered as a degenerate case where the interaction at the interface is the only one defined. This kind of medium is useful to describe plant leaves for instance.

Only homogeneous, (i.e., the physical properties which describe the radiation propagation are identical everywhere) interacting media have been considered. When a light beam propagates in a medium, it can be weakened by its interaction with matter. This lost of intensity may be due to absorption by the “mass” of the medium or by scattering. In the first case, the radiation is transformed in another form of energy. In the second case, the radiation will reappear in another direction. Hence, we consider two different types of medium. In the first type, we assume that the lost of radiation field intensity is only due to absorption. It is referred to as homogeneous non-scattering medium (HNSM). In the second type of medium, the attenuation of radiation field in one direction is due both to absorption and scattering. Henceforth, we will call it homogeneous scattering medium (HSM). The choice of the type of medium is essentially driven by the size of the object to which it is assigned. For instance, a small volume of water or atmosphere may be considered as a HNSM. As the size of the volume increases, the probability of interaction with a molecule increases and the scattering processes may not be neglected. HSM may be used when a large collection of small scatterers is considered as a whole, its overall properties can be represented statistically with a single object, as for instance a tree crown. This feature permits the simulation of scenes such as entire landscapes, without having to represent each leaf of each tree individually.
3.5.1 The HNSM interaction model

Type of interaction at the interface between two HNSM

Optical properties of HNSM are defined with an index of refraction \( n \) and an absorption coefficient \( a \) [m\(^{-1}\)]. When a plane wave falls onto a boundary between two homogeneous media of different optical properties, it is split into two waves: a transmitted wave proceeding into the second medium and a reflected wave propagated back into the first medium. If one traces the path of a ray, the question is to determine which, of the transmitted or reflected wave, will be followed. Assuming non absorbing media (\( a = 0 \)) and unpolarized incident radiation, the reflectance \( r \) is given by the Fresnel’s formulae

\[
F(\theta'_1, n_1, n_2) = \frac{1}{2} \left( r_\parallel^2 + r_\perp^2 \right)
\]

where

\[
r_\parallel = \frac{n_2 \cos \theta'_1 - n_1 \cos \theta'_2}{n_2 \cos \theta'_1 + n_1 \cos \theta'_2}
\]

(3.3)
is the ratio of the amplitude of the incident radiation and the reflected radiation for the direction parallel to plane of incidence and

\[
r_\perp = \frac{n_1 \cos \theta'_1 - n_2 \cos \theta'_2}{n_1 \cos \theta'_1 + n_2 \cos \theta'_2}
\]

(3.4)
is the ratio of the amplitude of the incident radiation and the reflected radiation for the direction perpendicular to plane of incidence. The symbol ‘ refers to the angles in a coordinate system local to the interaction point such that \( \theta'_1 = \arccos(\Omega_1 \cdot \Omega_L) \). Both \( r_\parallel \) and \( r_\perp \) belong to the interval \([0, 1]\). The indices 1 and 2 refer to the incident and transmitted radiation respectively such that \( n_1 \) is the index of refraction of the medium in which the ray is currently propagating and \( n_2 \) is the index of refraction of the intercepted medium. To determine whether the ray will be reflected or transmitted, the reflectance is first calculated with equation (3.2). A random number \( u \), uniformly distributed in \([0, 1]\) is then generated. The ray is reflected if \( u \leq F(\theta'_1, n_1, n_2) \), otherwise the ray is transmitted. In theory, reflection of light from a conducting medium is affected by both the absorption coefficient and the index of refraction. When the absorption coefficient is small, the reflection may be fairly well approximated with equations (3.3) and (3.4). Exact formulations are given in Hapke (1993), equations (4.31) and (4.32). Moreover, relations (3.3) and (3.4) are valid only for infinite plane surfaces. In practice, when the object is not flat, but large with respect to the wavelength being generated, the portion of the surface interacting with a ray can be considered as locally flat and effectively infinite, and the Fresnel equations may be used.

Reflection direction

The law of specular reflection is defined by \( \theta'_2 = \theta'_1 \) and \( \phi'_2 = \pi - \phi'_1 \). Given the incident direction \( \Omega_1(\theta_1, \phi_1) \) and the normal \( \Omega_L(\theta_l, \phi_l) \) to the surface, the direction of reflection \( \Omega_2^R(\theta_2^R, \phi_2^R) \) may be expressed with (Glassner 1989)

\[
\Omega_2^R = \Omega_1 - 2(\Omega_L \cdot \Omega_1)\Omega_L
\]

(3.5)
Transmission direction

The transmitted (refracted) direction $\Omega_T^2$ is given by the law of refraction or Snell’s law

$$\sin \theta_1 / \sin \theta_2 = n_2 / n_1 = n_{12}. \quad (3.6)$$

When $n_2 > n_1$, one says that the second medium is optically denser than the first medium and there is a real angle $\theta_2$ of refraction for every angle of incidence. If, however, the second medium is optically less dense than the first one (i.e., $n_2 < n_1$), one obtains a real value for $\theta_2$ only for angles of incidence $\theta_1$ for which $\sin \theta_1 \leq n_{12}$. For larger value of $\theta_1$, so-called “total internal reflection” takes place. No radiation enters the second medium and the reflection law may be used to determine the new direction. The transmitted direction may be expressed as (Glassner 1989)

$$\Omega_T^2 = n_{21} \Omega_1 + \Omega_L \left( n_{21} (-\Omega_L \cdot \Omega_1) - \sqrt{(1 + n_{21}^2 ((\Omega_L \cdot \Omega_2)^2 - 1))} \right) \quad (3.7)$$

where $n_{21}$ is equal to $n_1 / n_2$.

Ray propagation in a HNSM

The absorption of irradiance $J$ covering a distance $x$ in a HNSM is described by Beer’s law $J(x) = J(0)e^{-ax}$ where the absorption coefficient $a$ determines how much of the intensity of the radiation is absorbed when traveling a unit distance in the medium. Another measurement of absorption is sometimes more readily available. It is called the extinction coefficient $\kappa_0$, and is related to the absorption coefficient in the following manner (Born and Wolf 1964)

$$a = \frac{4\pi \kappa_0}{\lambda_0} \quad (3.8)$$

where $\lambda_0$ is the wavelength measured in a vacuum. If the wavelength $\lambda_0$ is replaced by the wavelength in the material $\lambda$, then $\kappa_0$ can be replaced by $\kappa$ using the relationship $\kappa_0 = n\kappa$, where $n$ is the index of refraction for the medium, which implies that

$$a = \frac{4\pi \kappa}{\lambda} \quad (3.9)$$

The coefficient $a$ is used to estimate the ray free path $d_a$ when travelling in the medium such as

$$d_a = -a^{-1} \ln u \quad (3.10)$$

where $u \in [0, 1]$. If $d_m$ is the maximum distance that the ray can cover in the medium (Figure 3.4), the ray will be absorbed when $d_a < d_m$.

Figure 3.4: A ray entering a HNSM at $P_1$ will be absorbed if the simulated mean free path length $d_a$ is smaller than the maximum distance $d_m$ that may be covered in the medium.
3.5.2 The HSM interaction model

In the case of a scattering medium, the problem is much more complicated and the outgoing direction is rather hard to determine. In Raytran, such a medium is defined by an envelope surface which encloses a portion of space (i.e., a closed object). The propagation of radiation may be affected by the interaction with that envelope and/or the optical properties inside the envelope. The interaction of rays with the envelope is simulated with probability distribution functions. The propagation of radiation inside the medium is simulated with a Markov’s chain (Antyufeev and Marshak 1990b).

Definition of the surface properties

Let us consider the case of a ray intersecting an open surface or the envelope delimiting a scattering homogeneous medium. The type of interaction with that surface is defined first, then the outgoing direction. Generally speaking, surface properties are expressed as the probabilities that a ray coming from direction $\Omega_1(\theta_1, \phi_1)$ is reflected

$$\rho_p(\theta_1, \phi_1) = \int_0^{2\pi} \int_0^{\pi/2} \rho(\theta_1, \phi_1; \theta_2, \phi_2) \sin \theta_2 d\theta_2 d\phi_2,$$

(3.11)

transmitted

$$\tau_p(\theta_1, \phi_1) = \int_0^{2\pi} \int_0^{\pi/2} \tau(\theta_1, \phi_1; \theta_2, \phi_2) \sin \theta_2 d\theta_2 d\phi_2$$

(3.12)

or absorbed

$$\alpha_p(\theta_1, \phi_1) = 1 - \rho_p(\theta_1, \phi_1) - \tau_p(\theta_1, \phi_1).$$

(3.13)

Only two probability density functions need to be defined to describe the surface properties. $\rho(\theta_1, \phi_1; \theta_2, \phi_2)$ and $\tau(\theta_1, \phi_1; \theta_2, \phi_2)$ are called the bidirectional reflectance and transmittance functions respectively. The function $\rho$ describes the conditional probability that a ray coming from a solid angle $d\omega_1 = \sin \theta_1 d\theta_1 d\phi_1$ centered on direction $(\theta_1, \phi_1)$ is reflected into another solid angle $d\omega_2 = \sin \theta_2 d\theta_2 d\phi_2$ centered on direction $(\theta_2, \phi_2)$. The same definition holds for the function $\tau$.

Type of interaction

The type of interaction $\Im$ is simulated by generating a random variable $u$ uniformly distributed in $[0, 1]$ such that

- a reflection occurs ($\Im^R$) if $u \leq \rho_p(\theta_1, \phi_1)$
- a transmission occurs ($\Im^T$) if $\rho_p(\theta_1, \phi_1) < u \leq \rho_p(\theta_1, \phi_1) + \tau_p(\theta_1, \phi_1)$
- an absorption occurs ($\Im^A$) if $\rho_p(\theta_1, \phi_1) + \tau_p(\theta_1, \phi_1) < u$
3.5. INTERACTION MODELS

Direction of scattering

The scattering direction is simulated on the basis of the knowledge of the incoming direction, the surface normal to the intersection point and the reflection or transmission scattering functions only. In the case of reflection, for instance, the scattering direction $\Omega_R^2$ is computed with

$$\Omega_R^2 = \mathcal{U}(\theta_1, \phi_1, u_1, u_2)$$ (3.14)

where $\mathcal{U}$ is a random variate generated with the normalized function $\rho(\theta_1, \phi_1; \theta_2, \phi_2)/\rho_p(\theta_1, \phi_1)$ and $u_1, u_2$ are uniformly distributed in $[0, 1]$. The various methods which exist to generate random variates from probability distribution functions have been described in Annex A. The scattering direction is computed in the coordinate system local to the point of intersection such that the normal is the vector $(0, 0, 1)$ which is then transformed to the world coordinate system (refer to section 3.2). Raytran relies on object oriented programming techniques such that the implementation of scattering distributions functions is very easy. Annex (C) contains the distributions which have been implemented so far.

Propagation in a HSM

The radiation transfer in a scattering medium of finite spatial extension is simulated with Monte Carlo procedures applied to track ray trajectories from their entrance to their possible exit. These media are characterized by a set of probability distribution functions and a process of sampling which is used to generate a Markov’s chain. Basically, these functions determine the structural properties of the medium (density and orientation of the scatterers) and the optical properties of the scattering elements. A discrete random walk process in this medium will therefore be completely specified by the simulation of the probability of collisions (interaction point) and the scattering directions.

1. Simulation of the interaction point. In a spatially constant medium, distances between interactions are exponentially distributed (Spanier and Gelbard 1969) such that the probability of covering a free path $d$ in the direction $\Omega_1$ is given by

$$p(\Omega_1, d) = 1 - \exp(-\tau(\Omega_1)d)$$ (3.15)

where $\tau(\Omega_1)$ is the optical thickness of the medium in the direction $\Omega_1$. The actual ray free path covered in that medium is calculated as

$$d_a = -\frac{1}{\tau(\Omega_1)} \ln u, \quad u \in [0, 1]$$ (3.16)

such that an interaction with the medium will occur if $d_a < d_m$. $d_m$ is the maximum distance that the ray can cover in the medium in direction $\Omega_1$. The position $P_2$ of the collision is calculated as

$$P_2 = P_1 + d_a \Omega_1$$ (3.17)

with $\| \Omega_1 \| = 1$ and $P_1$ is the position where the ray intersects the medium envelope. If the scatterers are of finite size and oriented, the normal to the intersection point $\Omega_L_1$
is simulated with a random variate based on the scatterer normal distribution function. Annex (D) gives the formulation of $\tau(\Omega_1)$ in the case of a finite-size oriented scatterers.

2. Simulation of the scattering direction The scattering direction can be simulated as previously described (equations 3.11 and 3.12) or with a phase function $\Gamma(\theta_1, \phi_1; \theta_2, \phi_2)$ when the scatterer size is small enough with respect to the wavelength. In this case, one simulates the scattering with an elementary volume. The ray will be absorbed if $\alpha(\theta_1, \phi_1) < u$ with $u \in [0, 1]$. $\alpha(\theta_1, \phi_1)$ is the so-called “single scattering albedo” and

$$\alpha(\theta_1, \phi_1) = \int_{4\pi} \Gamma(\theta_1, \phi_1; \theta_2, \phi_2) d\omega_2 \quad (3.18)$$

3.6 Extracting information from ray paths

The computed ray paths $\mathcal{R}_{k=1,\ldots,N}$ include the exact position of each collision point with the associated intercepted object identification and type of interaction. Formally, a ray path $\mathcal{R}_k$ can be expressed as a sequence of events as $\mathcal{R}_k = \varphi_{k_0}, \varphi_{k_1}, \ldots, \varphi_{k_Q}$. Each event $\varphi_{k_j}$ is defined by a set of information such that $\varphi_{k_j} = \{P_{k_j}; \Omega_{k_j}; \Im_{k_j}; \mathbb{A}_{l,k_j}\}$ where the index $k_j$ indicates the interaction $j$ of ray $k$, $P$ is the origin of the ray, $\Omega$ is its direction, $\Im$ is the type of interaction (\(\Im^E\), \(\Im^R\), \(\Im^T\) or \(\Im^A\)) and $\mathbb{A}_l$ is the intercepted object. It is therefore possible to extract very easily any kind of statistics from these trajectories, such as the mean free path distribution or the vertical extinction profile in the canopy. Different measurements may be defined simultaneously. Basically, two types of physical values or measurements are extracted from the ray paths: the radiation regime in the scene and the bidirectional reflectance factor (BRF). Furthermore, these measurements may be applied selectively to the ray trajectories.

3.6.1 Filtering ray paths

Specific sensitivity studies may require knowledge of the separate contributions of the different components of the scene (e.g., leaves, branches, soil), to differentiate the single and the multiple scattering or to extract statistics on the type of scattering. Virtual filters can be optionally associated with each measurement to select only rays which fulfil a set of conditions, such as the number of interactions, the collision with specific objects or the way rays terminate (absorbed or scattered out of the scene). For instance, to extract statistical information about rays which have interacted with the specific object $\mathbb{N}_{vuv}$ ($v \in [1, M]$), the filter $F_A$ can be defined as $F_A = \{\mathbb{N}_{vuv}, \forall j\}$. $\mathcal{R}_{k,F_A}$ defines the set of ray paths which have interacted with the object $\mathbb{N}_v$. More complex filter expressions can be defined combining basic filters with logical operators. For instance, let $F_B = \{j_Q = 1\}$ be the filter which defines the set of rays which have interacted only once with the scene, then the filter $F_C = F_A \cap F_B$ defines the set of rays which are single scattered by the object $\mathbb{N}_v$. Since different measurements can be defined simultaneously, these filters allow extraction of different information from a single execution of the program and thereby save computer time.
3.6.2 Estimation of the bidirectional reflectance

To estimate the BRF, the hemisphere above the scene is divided into \( n_e \) patches of equal area \( S_{i=(l,m)} = 2\pi/n_e \) (Figure 3.5A). To realize the division, the hemisphere is divided into \( k \) zones of face \( Z_m \) with \( m \in [1, k] \), each of which is divided into \( j(m) = Z_m/S_{i=(l,m)} \) elementary areas. The width \( \Delta \theta_m \) \((m = 1, \ldots, k)\) of a zone is adjusted in order that \( j(m) \) is an integer number and the azimuthal length \( \Delta \phi_l \) \((l = 1, \ldots, j(m))\) of an elementary area is approximately equal to \( \Delta \theta_m \). The BRF \( f_{i=(l,m)} \) of the elementary surface \( S_{i=(l,m)} \) is calculated according to (Ross and Marshak 1989)

\[
f_i(\theta_1, \phi_1; \Delta \theta_i, \Delta \phi_i) = \frac{\pi N_i}{N \Delta \Omega_i}, \quad i = 1, \ldots, n_e
\]

(3.19)

where \( N_i \) is the number of rays which cross \( S_i \), \( N \) is the total number of generated photons and \( \Delta \Omega_i \) is the projected solid angle corresponding to the elementary surface \( S_i \). If the hemisphere is located at infinity, only the direction of an escaped ray determines the outgoing solid angles \( S_i \) whatever the origin of the ray. Expression (3.19) is therefore useful for direct comparisons with other BRF models. However, for comparisons with observations, it is desirable to reproduce as faithfully as possible the actual measurement conditions, such as the detector aperture \( A_r \) and field-of-view (FOV) \( \psi \). To that respect, the possibility of simulating front-of-detector BRF \( g_i \) of a typical instrument located at a constant distance \( R \) from the center of the target (Figure 3.5B) has been added where \( g_i \) is equal to

\[
g_i(\theta_1, \phi_1; \theta_i, \phi_i) = \frac{\pi N^\psi_{A_r,i} R^2}{N A_r \cos \theta_i}.
\]

(3.20)

\( N^\psi_{A_r,i} \) refers to the number of rays hitting the detector of area \( A_r \) located in \((R, \theta_i, \phi_i)\) with a central direction included in the cone defined by the detector FOV (Figure 3.5C). Because the ray paths are computed without any probability weighting mechanism, it turns out that statistical estimations of target radiative properties, as given by equations (3.19) and (3.20), are fairly simple and straightforward to derive. In the same way, any kind of statistics on the radiation regime can be very easily implemented. In the next Section, we explain how to compute the vertical fluxes in the scene.

3.6.3 Estimation of the vertical ‘fluxes’ in the scene

To compute the vertical fluxes\(^2\) of radiation in the scene, the target is divided into \( m - 1 \) horizontal layers separated by \( m \) virtual detectors. Each time a ray crosses the upper face of the sensor \( p_+ \) \((p \in [1, m])\), the downward flux counter \( N^{\downarrow}_{p} \) associated with that sensor is incremented by 1. Conversely, the upward flux counter \( N^{\uparrow}_{p} \) is incremented when a ray crosses

\(^2\) A flux expresses an amount of energy crossing a unit area per unit time. The present model simulates ray propagation in a scene at a given instant, and does not consider the time evolution of the scene or of the light source. In this context, the term ‘flux’ therefore refers to the number of rays crossing a specified plane normalized by the total number of generated rays even though this is an abuse of language.
Figure 3.5: Bidirectional reflectance factor measurements. (A) Division of the hemisphere into equal area patches to estimate the BRF as observed at the infinity. (B) Simulation of goniometer observations of radius $R$ with a detector of aperture $A_r = \pi a_r^2$ and given FOV as shown in (C).

the lower face $p_-$. The relative upward $F_{p}^\uparrow$ and downward $F_{p}^\downarrow$ fluxes of sensor $p$, expressed as the fraction of the total number of generated rays, are defined as

$$
F_{p}^\downarrow = \frac{N_{p}^\downarrow}{N} \\
F_{p}^\uparrow = \frac{N_{p}^\uparrow}{N}
$$

If the actual irradiance of the energy source is known, it is possible to define the corresponding energy which is conveyed by each ray and hence to express the fluxes in physical units. An example of such a computation is given in Chapter (7). The net relative flux at level $p$ is simply defined as $F_{p} = F_{p}^\uparrow - F_{p}^\downarrow$. The divergence of $F_{p}$, which is reduced to a vertical derivative $\Delta F_{p}$ in the present case, gives the fraction of absorbed relative flux per unit length

$$
\Delta F_{p} = \frac{F_{p} - F_{p-1}}{z_{p} - z_{p-1}}, \quad p \in [2, m].
$$

3.7 Concluding remarks

Since ray paths are generated in a physically meaningful way, the extraction of any kind of information concerning the radiation regime in the target is straightforward. Furthermore, the
3.7. CONCLUDING REMARKS

filters which can be associated with each measurement allow very specific problems to be addressed. Due to this feature, Raytran is not a simple model which solves the radiative transfer equations but a powerful research tool. These advantages, in conjunction with the possibility of assigning elaborate ray-matter interaction models, whatever the structural complexity of the target, are definitively original features with regard to the previously developed radiative transfer models and justify the name virtual laboratory. It has been designed as a very modular platform using object oriented programming techniques where the latest developments in radiative transfer can be easily implemented as shown for instance in Annex (D). Specifically, the original characteristics of our model with respect to the existing canopy reflectance models may be summarized as:

- Each object in the scene may have different optical properties characterized by interaction models representing surface as well as volumetric (body) effects.
- It can address radiative transfer problems in relation with remote sensing studies over a wide range of spatial scales.
- Raytran can estimate not only the bidirectional reflectance, but also the radiation regime in the scene using advanced filtering mechanisms.
- It can simulate natural as well as laboratory lighting.
- Raytran includes the latest techniques of computer graphics to describe complex natural or artificial three-dimensional objects.
- It can account for sensor optical properties.
- The code is parallelized for computing efficiency.
- It is designed to be maintained and improved at low cost.

The various geometrical objects, illumination and interaction models allow very different problems to be addressed. Since no scene, illumination condition or virtual measurements are predefined, the relevance of the results rely principally on the accuracy with which the scenes are defined. In Annex (C), we suggest several distribution functions to represent object directional properties. However, none of these distribution functions are entirely satisfactory to describe the directional properties of a plant leaf. Further research efforts are needed to overcome this specific problem. Chapter (5) represents a first step in this direction and illustrate the potential of Raytran to address specific radiative transfer problems.
Chapter 4

Evaluation of Raytran accuracy

4.1 General strategy

The present Chapter aims at verifying the accuracy of Raytran and validating some of the assumptions inherent in the radiation transport model. According to Oreskes et al. (1994), the “verification”, \textit{i.e.}, the establishment of the truth) or the “validation” (\textit{i.e.}, establishment of the legitimacy) of a numerical model of a natural system is extremely difficult, if not impossible. These authors claim that the adequacy of a model to represent specific conditions can be at least confirmed by comparisons with laboratory tests. These direct comparisons simply demonstrate that a model matches observations over a particular range of conditions under consideration. Practically, the evaluation of the model can be divided into three steps:

- \textbf{Implementation of the equations in the model}. Before any evaluation of the model performance itself, it is necessary to ensure that the radiative transfer equations and the numerical scheme to solve them have been correctly implemented in the model. Thanks to the very modular design of Raytran, each element of the computation can be easily isolated and tested. Specifically, three main modules need to be tested: \textit{(1)} the computation of the intersection of rays with objects; \textit{(2)} the computation of the scattering events, including the emission by light sources and \textit{(3)} the extraction of relevant information of ray paths (measurements). The first point can be easily verified by visualization of the scene with \textit{Rayshade} since both models share the same routines for that purpose. The distribution functions which are used to computed the emission of the energy sources (refer to Section 3.4) and the scattering processes (refer to Section C) can be easily tested displaying the trajectories of the ray paths and counting the different scattering events for simple configurations such as a point light source and a single object. Raytran also allows a statistical representation of the structural properties of the scattering elements. This statistical representation requires more complex verification mechanisms because of the computation of the intersection points and the interaction events cannot be clearly separated as in the previous case. This specific verification is presented in Section (4.2). Finally, the extraction of information such as the BRF from the ray trajectories can be tested by representing a scene for which the analytical solution exists, such as a simple
Lambertian surface. However, it is desirable to verify the model in case of more complex scenes as explained in the next two paragraphs.

- **Legitimacy of the assumptions with respect to the model requirements.** This point concerns the evaluation of the potential of Raytran to simulate the reflectances of “real scenes”. In other words, the assumptions which have been made on the light transport and the representation of the scene structural properties need to be tested. This evaluation should be based on comparisons with observations but requires the precise knowledge of the position, size and shape of each element of the scene as well as the optical properties, simultaneously with the values of the bidirectional reflectance of the scene and the lighting conditions. Since such data sets are extremely difficult and costly to acquire for natural targets, observations have been done on a man-made target whose characteristics are precisely known, avoiding additional assumptions on the representation of the target structural properties. The bidirectional reflectance of the target has been measured in a goniometer under controlled illumination conditions (refer to Section 4.3).

- **Accuracy of the numerical scheme.** The first need with respect to that issue is to verify the “randomness” of the random number generator that is used in the Monte Carlo procedures. Our generator has been verified by lighting a Lambertian surface with millions of rays. No bias greater than the estimated error has been observed. In addition, the accuracy of the Monte Carlo scheme has been tested comparing Raytran with a model which relies on the same assumptions concerning the light transport and which permits the explicit representation of the structure of the scene. Consequently, any differences that should occur between the solution of the two models emphasize the relative accuracy of the numerical method. This comparison is presented in Section (4.4) and permits to evaluate Raytran in case of complex scene.

### 4.2 Evaluation of the HSM interaction model

The HSM interaction model (refer to Section 3.5.2) is based on a statistical representation of the medium’s structural properties. In Annex (D), we gave the formulation of the medium’s optical thickness in the case of finite-size and oriented scatterers. These equations have been partially derived from the parameterization of the hot spot effect developed by Verstraete et al. (1990) but adapted to account for the finite spatial extension in the three directions of the medium. The objective of this Section is to evaluate our adaptation to represent the radiative transfer in such a medium. The model developed by the above mentioned authors has been validated by inversion against field measurements (Pinty et al. 1990). However, their approach cannot be used in the present case since Raytran may not be inverted because of the large computer time required. The general principle of the present evaluation relies on the capability of Raytran to represent explicitly the position of each scatterer with an exact formulation of the multiple scattering. This advantage is used to generate a HSM-like scene composed of fixed radius discs, uniformly distributed in a space of finite dimension (referred to as the discrete canopy). The same scene
is generated but substituting every individual scatterer by a single HSM object (referred to as the pseudo-turbid canopy) as illustrated in Figure (4.1). The bidirectional reflectances of the two scenes are then compared assuming that the reflectances of the discrete canopy represent the reference values. This assumption relies on the fact that statistical representation of the medium's structural properties in the HSM model can be conceptualized as a collection of discs for which the hot spot effect and the multiple scattering can be explicitly calculated. Before comparing the two solutions, it is necessary to establish the correspondence between the parameters which represents the structure of the two different canopies.

\[ \text{Figure 4.1: “Discrete” versus “pseudo-turbid” representation of a canopy.} \]

### 4.2.1 Equivalence between the discrete and the pseudo-turbid canopy parameters

The HSM interaction model, in the case of finite-size oriented scatterers, is characterized by 5 structural parameters: the scatterer area density \((\Lambda)\), two parameters for the scatterer normal distribution \((\mu, \nu)\) and two parameters which define the mean horizontal \((a_h)\) and vertical \((a_v)\) areas between the scatterers. In the discrete canopy, we assume that each scatterer can be represented by a disc of given radius \(r_s\) and normal \(\Omega_L\). Let us now assume a parallelepipedic box of given height \(h\) and surface \(s\) filled with \(n_s\) discs uniformly located. The distribution of the disc normals \(\Omega_L\) is characterized by a distribution function \(g_L(\Omega_L)\). This discrete canopy can be therefore very easily generated, provided the parameters \(h, s, n_s, r_s\) and the function \(g_L(\Omega_L)\) are known, paying special attention to the fact that scatterers do not overlap. We now need to establish the correspondence between these parameters and the parameters \(\Lambda, a_h, a_v\) which characterize the structure of the HSM. The scatterer area density is simply given by

\[ \Lambda = \frac{\pi r_s^2 n_s}{sh}. \]  

(4.1)

Statistically, each scatterer occupies a mean elementary box whose volume is

\[ V_s = \frac{sh}{n_s} = d_h^2 d_v \]  

(4.2)

where \(d_h\) is the horizontal side of the parallelepiped and \(d_v\) the vertical one. A new parameter \(h_v\) is introduced to describe the ratio between the mean vertical and horizontal distance
CHAPTER 4. EVALUATION OF RAYTRAN ACCURACY

Figure 4.2: NIR reflectance factors in the principal plane for the “discrete” canopy (solid line) versus the “pseudo-turbid” canopy (dashed line). LND is planophile and IZA = 30°. Positive viewing angles indicate back-scattering.

between the leaves such that $d_v = d_h/h_v$ and

$$d_h = (h_v sh/n_s)^{1/3}.$$ (4.3)

This parameter controls the vertical density of the scatterers. The mean horizontal and vertical areas between the scatterers may now be expressed as

$$a_h(\theta = 0) = d_h^2 - G(\theta = 0) \pi r_s^2$$ (4.4)

$$a_v(\theta = \pi/2) = \frac{d_h^2}{h_v^2} - \sqrt{1 - G^2(\theta = \pi/2)} \pi r_s^2.$$ (4.5)

where $G$ is the Ross function.

To be independent of the absolute size of the scene, we normalize the horizontal distance between the scatterers $d_h$ such that $\hat{d} = d_h/d_h \equiv 1$. In the same way, $r_d = r_s/d_h$ and equation (4.3) may be rewritten as

$$\hat{d} = (h_v h_d/n_l)$$ (4.6)

where $n_l = n_s d_h^2/s$ is the mean number of scatterers along the vertical direction and $h_v = h_v/d_h$. The height of the canopy is equal to $h_d = n_l/h_v$ and equation (4.1) becomes $\Lambda = \pi r_d^2 h_v$. The main advantage of this new equation lies in the fact that the expression of the LAD does not depend anymore on the actual size of the boxes or the number of leaves. The LAI of the canopy is simply equal to $\text{LAI} = \pi r_d^2 n_l$. Clearly, small values of $r_d$ represent a discrete canopy more similar to the ideal case of the turbid medium than larger ones, for which the intershadowing effects are stronger. To confirm the correspondence between the two different canopy representations, we compute the corresponding reflectances using the optical data set BRT described in Table (4.2) for the soil and the leaves with an IZA = 30°. Moreover, we
4.2. EVALUATION OF THE HSM INTERACTION MODEL

Figure 4.3: Relative differences between the hemispherical reflectance of the pseudo-turbid versus the discrete canopy in the case of a planophile LND. Positive values indicate overestimation of the pseudo-turbid solution with respect to the discrete one. Isolines represent LAI values of 1, 3, 5 and 8.

assume that the box is horizontally surrounded by equivalent ones. The “discrete” canopy is generated with 40,000 circular scatterers. Both canopies are lit with $200 \times 10^6$ rays.

Figure (4.2) shows the reflectance factors of planophile canopies in the NIR for LAI=1, 3 and 8 and $\hat{r}_d = 0.17, 0.3$ and 0.5. These results demonstrate that the agreement between the two solutions increases as $\hat{r}_d$ decreases. To confirm this observation, the possible values of $\hat{r}_d$ between 0.15 and 0.55 and $n_l$ between 1 and 80 have been systematically explored. Figure (4.3) shows the relative difference between the hemispherical reflectance factor of the discrete versus the pseudo-turbid representation. In the red spectral region, the relative differences are proportional to the size of the scatterers. The hemispherical reflectances of the pseudo-turbid canopies are slightly overestimated in the case of small scatterers and underestimated in the case of large ones. Note that planophile LND represents the worse case. The analysis of the results for $\hat{r}_d = 0.5$ (Figure 4.2) reveals that the deviation of the pseudo-turbid representation results mainly from differences around the hot spot region and illustrates the limitation of the hot spot parameterization in the case of large scatterers. In the NIR spectral region, these deviations are of lesser importance because of the relatively lower contribution of the hot spot effect with regard to the multiple scattering contribution.

4.2.2 Evaluation of the HSM model in the case of finite spatial extension

So far, the correspondence between the discrete and pseudo-turbid representation has been established in the case of a horizontal infinite plane parallel medium. We now need to account for the finite spatial extension of the medium. The HSM model accounts for the hot spot only when the first interaction occurs in the medium. In other words, when a ray crosses an object
Figure 4.4: Reflectance factors in the principal plane of a row canopy with $LAI_{row} = 3$. Solid line: discrete canopy; dashed line: pseudo-turbid canopy. SZA=30° for an azimuth angle perpendicular to the rows.

without interaction and is reflected by the soil or another object in a direction close to the incoming direction, no hot spot effect is simulated in the HSM object. This simplification is motivated by the need to save computer time. It has been estimated that spending the extra processing time, that would be necessary to verify this specific situation, is not worthwhile in terms of accuracy improvement. To evaluate the effect of this assumption, canopies with different macro-structures have been generated. The first one is a simple rectangular row structure defined with three parameters: the height $h$ and width $v$ of the rows and the distance $t$ between them. The simplicity of this canopy is advantageous since the number of parameters needed to describe the macro structure is very low. The height of the rows depends on the meso-structure properties of a row and is given by $h_d = LAI_{row} / \left(\pi r_d^2 h_d\right)$. Distances $v$ and $d$ may be normalized in the stand $v_h = v/h_d$ and $t_h = t/h_d$. The total LAI of the canopy is simply given by $LAI_{tot} = LAI_{row} v_h / (v_h + t_h)$. It is expected that the hot spot will be underestimated for small $v_h$ values, especially when $LAI_{row}$ is low. For canopy A (wide row), $v_h = 1.0$ and $t_h = 0.5$. For canopy B (thin row), $v_h = 0.5$ and $t_h = 1.0$. Both canopies are generated with a $LAI_{row}$ of 3 and 8 with $r_d = 0.3$. ($LAI_{tot} = A: 2$ and 5.33; B: 1 and 2.67). Optical properties are those of the data set BRT. The illumination azimuth angle is perpendicular to the rows.

Results are presented in Figures (4.4) and (4.5). The general shape of the BRF is fairly well simulated with the HSM interaction model. As expected, in the case of thin rows (canopy B), the hot spot is correctly represented when $LAI_{row} = 8$ but underestimated for low LAI values. However, the hot spot contribution is not very significant with respect to the angular variation of the reflectance. In fact, most of the anisotropic reflectance comes from the macro structure rather than the meso structure.
To confirm this result, more complex scenes, composed of randomly located spheres or cylinders, were generated with a fractional cover of 40% and a LAI of 3. Figure (4.6) illustrates the discrete representation of the scene with spherical objects which define the macro structure. Figure (4.7) shows the reflectance factors in the principal plane in the red and NIR spectral region for the two different, non overlapping, macro objects (cylinders and spheres). The good agreement between the discrete and pseudo-turbid representation is confirmed and illustrate the potential of the HSM model to represent the bulk canopy structural properties. In Chapter (6), we discuss in more detail the problem of representing plant or canopy shape with HSM objects.

4.3 Comparisons with laboratory measurements

The goal of these comparisons is to demonstrate the capability of Raytran to reproduce the reflectance of a given target by direct comparison with bidirectional reflectance factors of a simple artificial surface measured in a “real” laboratory. All observations have been carried out by the Advanced Technology unit of the Institute of Remote Sensing Applications in the new goniometer facility.

4.3.1 Description of the goniometer

The European Goniometer facility is a double T angle iron structure composed of a platform that is to receive the sample target, and two rotating arcs, a half one for the light source and the other one for a detector (Koechler et al. 1994). The system allows the independent positioning of the light source and the detector anywhere on a 2 m radius hemisphere above the target.
and thereby measurement of bidirectional reflectances. The azimuthal angular movement is insured by the rotation on two horizontal circular rails on which the arcs are mounted on motorized sledges. Each arc supports a mobile sledge that can receive a laser or a detector and realize the zenith movements. The azimuthal range varies between 0 and 360° while zenith displacements are possible between 0–90° for the light and −90–90° for the detector. The angular positioning resolution is better than 0.1°. The system is mechanically centered on the ceiling and the floor of the laboratory (Figure 4.8). A Personal Computer automatically controls the observation geometry as well as the acquisition of the detector measurements. The structure and all laboratory walls are painted in matt black.

For the present experiment, the target is illuminated with a compact self-contained HeNe laser (\(\lambda = 0.6328 \, \mu m\)) with a 0.5 mm diameter beam. A beam expander provides a beam with a diameter of 48 mm whose intensity decreases as a Gaussian from its center. The detector is a simple silicon photodiode with an active area of 100 mm². The temporal stability of the laser–detector system is better than 0.2% over a period of several days. To control the field of view (FOV) of the detector, a 100 mm long tube with a diameter of 50 mm is placed in front of it, insuring a FOV of 28°. The laser beam footprint on the target is thereby totally included within the FOV of the detector.

4.3.2 Description of the targets

The choice of the target is a critical issue for this comparison. As explained in the introduction of the chapter, the structural properties of a natural scene would be difficult to characterize. Therefore, for the purpose of this verification, we worked on simple man-made surfaces, whose geometrical and optical properties can be characterized \textit{a priori} in the laboratory and represented explicitly for Raytran simulations. Specifically, the choice of the target has been motivated by the following requirements:
4.3. COMPARISONS WITH LABORATORY MEASUREMENTS

Figure 4.7: Reflectance factors in the principal plane of three-dimensional canopies made of cylinders (top) and spheres (bottom) in the NIR and red spectral regions. Solid line: discrete canopy; dashed line: pseudo-turbid canopy. SZA=30°.

- The material should be inexpensive and easy to manufacture.
- The geometry of the rough surface should be relatively easy to characterize and simple to represent in Raytran.
- The bidirectional reflectance anisotropy of the target must be clearly observed.
- The optical properties of the material should be known or independently measurable. The anisotropic behavior of industrial solid surfaces derives from the main part from the physical structure and from the optical properties of the material. It is therefore necessary to work with a rough surface of homogeneous optical properties.

The target has accordingly been designed as a matrix or lattice of cubes over a plane surface (Figure 4.9A) made of duralumina A-U4GUN13579. To ensure uniformity of properties, the rows of cubes have actually been carved out of a thick plate (Figure 4.9B). All vertical and horizontal exposed faces have been sanded to get an average surface micro-roughness $\sigma_r$ of 1.65 $\mu$m. The shape factor, i.e., the ratio between the sides $s_c$ of the cubes and the distance $d_c$ between the cubes, which is the main factor responsible for anisotropy has been estimated from simulation. The optimal value is equal to $s_c = (5/3)d_c$. The choice of the actual distances $d_c$ and $s_c$ results from a trade-off. On one side, the process of manufacturing this lattice structure involves the use of equipment which can deliver products with a given finite tolerance. Sanding tends to soften the sharp edges at the top of the cubes. The larger the cubes, the more accurate the cube dimensions can be made in relative terms. On the other hand, the light beam diameter is limited to 4.8 cm. To generate useful data, the illuminated spot should contain a large number of cubes, even for an illumination near zenith. A $25 \times 25$ cm
duralumin plate, with a lattice of cubes such that \( d_c \approx 2 \text{ mm} \) and \( s_c \approx 3.3 \text{ mm} \) was prepared to meet these requirements. The tolerance of the cut is \( \pm 0.1 \text{ mm} \).

Fundamentally, the detector measures a radiance, i.e., the number of photons entering the sensor within the FOV of its optical system in a given period of time. Due to the technical difficulty of calibrating radiometers in absolute terms, these measurements are usually converted into reflectance factors by normalizing them by similar measurements acquired over a reference panel illuminated and observed under identical geometrical conditions. A Spectralon\(^1\) panel was used for that purpose. Finally, to assess the purely optical properties of the target, it is also necessary to prepare a third target consisting simply of a flat panel of duralumin with the same finishing process. This is required in order to assign the intrinsic characteristics to the surfaces.

In summary, to document the respective contributions of the structural and optical properties of the material, three surfaces must be observed under essentially the same measurement protocol: one with a well defined structure (the target \( T \) of interest), one composed of the same material but completely flat (the reference target \( R \)), and finally the Spectralon panel \( (S) \).

### 4.3.3 Measurement protocol

An arbitrary direction is chosen as reference for the azimuth angle \( \phi \). The lattice of cubes of plate \( T \) is then aligned with this direction. The requirements for alignment on the other two targets is not an issue since both are supposed to be azimuthally uniform targets. This has been verified by rotating the radiometer along \( \phi \) with constant zenith angles of observation

---

\(^1\)Spectralon is a near-Lambertian white material often used as reference, especially in space-borne experiments (Flasse et al. 1993).
4.3. COMPARISONS WITH LABORATORY MEASUREMENTS

Figure 4.9: Man-made target for comparison with goniometer measurement. (A) View of the target. (B) Detail of the lattice of cubes.

and illumination. A standard set of measurements on any one of the three targets comprises all measurements which can be obtained by combining

- 3 illumination zenith angles (IZA): 3, 26, 56°;
- 4 illumination azimuth angle: 0, 15, 30, and 45° for T, while only the direction 0° and 45° have been considered for the azimuthally symmetric targets R and S;
- viewing azimuth angles every 15°, but only in half of the hemisphere for R and S;
- 8 viewing zenith angles: 0, 10, 20, 30, 40, 50, 60, and 70°.

or a total of $3 \times 4 \times 24 \times 8 = 2304$ measurements for T and $3 \times 2 \times 13 \times 8 = 624$ measurements for R and S.

4.3.4 Observational data processing

To compute the radiance $L_T(\Omega_1, \Omega_2) \text{[Wm}^{-2}\text{sr}^{-1}\mu\text{m}^{-1}]$ which is reflected by the target T, the gain $\gamma_T \text{[V/Wm}^{-2}\text{sr}^{-1}\mu\text{m}^{-1}]$ of the photodiode needs to be know such that

$$L_T(\Omega_1, \Omega_2) = \frac{A_T(\Omega_1, \Omega_2) - \beta_0}{\gamma_T}$$  \hspace{1cm} (4.7)

where $A_T$ is the analog output of the detector [V] and $\beta_0$ is the black light offset. Since both the gain and the irradiance of the laser are unknown, the reflectance cannot be directly estimated. Instead, the reflectance factor $R_T$ of T could be estimated and only requires a
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Figure 4.10: Bidirectional reflectance of the Spectralon panel normalized by the nadir radiance for IZA = 3° (left) and 56° (right). Values are represented in cylindrical coordinates. The distances from the origin of the horizontal axes represent the cosine of the zenith viewing angle.

relative calibration procedure. Indeed, if \( A_S \) is the analog output of the reference Spectralon panel, then

\[
R_T (\Omega_1, \Omega_2) = \frac{(A_T(\Omega_1, \Omega_2) - \beta_0) / \gamma_T}{(A_S(\theta_1, \Omega_2) - \beta_0)} / \gamma_S
\]

(4.8)

If we assume that the photodiode response is linear according to the intensity of the received light, then \( \gamma_T = \gamma_S \) and equation (4.8) may be simplified to

\[
R_T (\Omega_1, \Omega_2) = \frac{A_T(\Omega_1, \Omega_2) - \beta_0}{A_S(\theta_1, \Omega_2) - \beta_0}
\]

(4.9)

The hemispherical reflectance of the Spectralon at the wavelength of the laser is 0.99. However, as mentioned by Flasse et al. (1993), the Spectralon is not a perfect Lambertian surface and suffers from anisotropic reflection at high illumination zenith angles. This has also been observed on the present Spectralon panel (Figure 4.10). Moreover, since the detector footprint is larger than the laser spot on the target, it is not necessary to light the Spectralon panel with the same zenith angle. Indeed, with this configuration, the detector observes always all the radiation which light the target, whatever the illumination zenith angle. Therefore, to avoid the specular effects of the Spectralon panel, all the observations over \( T \) have been normalized with the values over \( S \) for an irradiance zenith angle of 3° and

\[
R_T (\Omega_1, \Omega_2) = \frac{A_T(\Omega_1, \Omega_2) - \beta_0}{A_S(\theta_1 = 3^\circ, \Omega_2) - \beta_0}
\]

(4.10)

This procedure is applied to compute the reflectance factors \( R_R \) of target \( R \).

4.3.5 Modeling strategy

Modeling the bidirectional reflectance of \( T \) first requires the characterization of the bidirectional properties of the cube sides. The Torrance and Sparrow model (Torrance and Sparrow 1967) has been specifically designed to simulate surface reflectances for which \( \sigma_r/\lambda > 1 \) where \( \sigma_r \) is the surface roughness. This constraint is verified in the present case since this ratio
4.3. COMPARISONS WITH LABORATORY MEASUREMENTS

Figure 4.11: Observations (left column) of the reflectance factors of the reference duralumin target, and simulations (center column) with the Torrance Sparrow model, and relative differences (right column) in percent between simulations and observations for three different IZA: 3° (first row), 26° (second row) and 56° (third row). Positive values of the relative differences indicate overestimation of the simulations with respect to the observations. The values are plotted in cylindrical coordinates. The distances from the origin of the horizontal axes represent the cosine of the zenith viewing angle.
The main feature of the aluminium plate bidirectional reflectance is correctly reproduced. The relative difference between simulations and observations clearly shows that the surface model overestimates the reflectance at the nadir and underestimates the specular peak as the illumination zenith angle increases. Moreover, observation at IZA=56° shows backscattering effects which may be due to the hot spot or coherent backscattering (Hapke et al. 1993) that are not represented in the Torrance-Sparrow model. This model can correctly fit the reflectances corresponding to a specific IZA for a given set of parameters as has been shown by the authors, but it fails to fit the reflectance of different geometries of observation with a single set of parameters. In Annex (C), we already underlined the limitation of this model. It has been designed to represent a specific effect, i.e., the off-specular peak resulting from the distribution of micro-facets but not to account for the angular dependencies of the multiple scattering.

We also tried to fit the SOILSPEC model presented in the same Annex but the agreement was even worse. An empirical formulation with a sufficient number of parameters can certainly fit the reflectances corresponding to one angle of illumination. In the present case, we need a model which can reproduce the reflectances of an artificial surface for all the possible angles of illumination but simple enough to be implemented in a Monte Carlo ray tracing code. We therefore decided to use the Torrance and Sparrow model. Clearly, further investigations are required with respect to that problem and we already know that part of the difference that could be observed between the measured and simulated reflectance may be due to the inaccuracy of the representation of the directional properties of the material. Raytran has been primarily designed to study the reflectances of natural surfaces. The choice of an artificial material such as the duralumin results mainly, as we already said, from economic reasons. Generally speaking, the problem of representing the directional properties of scattering elements in canopy reflectance models has been underestimated. These points are emphasized in the final discussion of this Chapter.

The structural properties of the target T are simulated with boxes laid out on a square polygon base. The laser beam is simulated with a circular energy source whose normal is oriented through the center of the target. The emitted rays are parallel to that normal. The origin of the rays are uniformly distributed in the energy source area. The scene is lit with $200 \times 10^6$ rays. The reflectance factor is computed with equation (3.20).
Figure 4.12: Idem Figure (4.11) but for the lattice of cubes (target T) illuminated with an azimuth angle of $45^\circ$ with respect to the rows.
4.3.6 Results

Figures (4.12) and (4.13) show the simulated reflectance factors in comparison with the observed ones for illumination azimuth angles of 45° and 0° respectively with respect to the rows. Simulations reproduce correctly the reflectance variations due to the rows, although the relative differences between simulations and observations may reach 15% in some places. Most of these differences are probably due to the inaccuracy of the representation of the cube side optical properties as appears from the discussion of the previous section. Moreover, Raytran does not simulate the diffraction effects which may occur at the edges of the cubes. To control as precisely as possible the structure of the target, we were obliged to use a material which does not exhibit the same directional properties as biological surfaces. In addition, the regularity of the target macro structure (there are only five different normal directions) makes the target reflectance anisotropy particularly sensitive to the material directional properties. In natural media, the angular dispersion of the scattering elements is much wider so that the effects of
4.3. COMPARISONS WITH LABORATORY MEASUREMENTS

Figure 4.14: Unnormalized measurements of target $T$ of the left side versus the right side of the hemisphere for an illumination zenith angle of 56° and azimuth angle aligned with the rows of cubes. The different symbols represent the different zenith angle of observation: (+) = 0°; (∗) = 10°; (·) = 20°; (△) = 30°; (△) = 40°; (□) = 50°; (∗) = 60°; (∇) = 70°.

their directional properties are averaged. Besides, a careful observation of the target with a light microscope reveals small imperfections in the lattice of cubes. Unfortunately, we have only one standard data set of measurements as defined in Section (4.3.3) for target $T$ such that we were not able to quantify these effects by comparing the measurements corresponding to a 90° rotation of the target.

Among the other possible sources of difference, the problem of measurement inaccuracies must be pointed out. In Section (4.3.4), we underlined the issue of data calibration. The Spectralon reference panel is not a perfect Lambertian surface, even for an IZA of 3° as can be seen from Figure (4.10). As a result, normalized measured reflectances should be overestimated at large zenith angle of observations and underestimated at lower ones. Moreover, with only one data set, the estimation of the errors due to the geometry of observation accuracy (0.1°) and target misalignment in the goniometers were limited. Hence, to assess potential errors due to observation geometry inaccuracies, we compared the left and right sides of the measured reflectances when the illumination azimuth angle is row-aligned (Figure 4.14). The analysis clearly shows a bias in the data. To identify the origin of the differences, we simulated the reflectances for the same geometries of observation but rotating the target by 2° in Raytran. The modeled differences between the left and right sides of the reflectances were both positive and negative and not that large even for a misalignment of 2°. Detailed analyses (Figure 4.15) indicate that the differences mainly occur at observation azimuth angles larger than 60° with respect to the the laser position. This may be due to a defect in the goniometer structure. Further investigations are required to determine exactly its origin. To the extent that such defect can be identified and quantified, it will be possible to simulate it also with Raytran. Correct it.
CHAPTER 4. EVALUATION OF RAYTRAN ACCURACY

Figure 4.15: Relative differences of the reflectances between the left and right side of the hemisphere of target \( T \) The azimuth illumination angle is aligned with the rows of cubes. The different symbols represent the different zenith angle of observation: (+) = 0°; (∗) = 10°; (·) = 20°; (∆) = 30°; (□) = 40°; (×) = 50°; (∧) = 60°; (∇) = 70°.

Nevertheless, these comparisons have to be further investigated in order to detect any possible conceptual error in the Raytran model. To achieve this objective, we explored systematically the differences between simulated reflectance factors and the observations for different illumination geometries. We noticed that these differences depend on the zenith angle of observation as shown in Figure (4.16), as can be expected from the observation geometry inaccuracies. We divided the hemisphere into three zones. For observations close to the nadir (0 – 30°), the simulated reflectance factors are overestimated, especially for an IZA of 3°. This may be explain by the overestimation by the Torrance-Sparrow model of the duralumin plate reflectance for these observation geometries as can be seen on Figure (4.11). The poor fit of the Torrance-Sparrow model may also be due to this goniometer structural defect. As the zenith angle of observation increases, the reflectances corresponding to the different IZA are mixed. In the (30 – 60°) zone, the simulations match the observations, although reflectances corresponding to nadir illumination are systematically overestimated. For high observation zenith angles (60 – 90°) corresponding to high zenith angles of illumination, the effects of observation geometry inaccuracies appear clearly. The differences between observations and simulations are much more spread out. From this analysis, it turns out that our model results do not produce systematically biased reflectances. In brief, Raytran simulates correctly the qualitative variations of the reflectance due to the row effects and should therefore be able to document bidirectional reflectance effects due to plant canopy architecture, one of the main objectives of our model.
4.3. COMPARISONS WITH LABORATORY MEASUREMENTS

Figure 4.16: Observed versus simulated reflectance factors of the lattice of cubes for all the geometries of observation. The upper plot contains the viewing directions within the range 0 – 30\(^\circ\), the middle one the range 30 – 60\(^\circ\) and lower one the range 60 – 90\(^\circ\). The red points correspond to an IZA of 3\(^\circ\), the green ones to 26\(^\circ\), and the blue ones to 56\(^\circ\).
4.4 Comparison with another Monte Carlo code

4.4.1 Motivation

The comparisons with laboratory measurements have shown that, even in the case of a very simple man-made target, the number of uncontrolled parameters remains important. As a result, it is difficult to perform sensitivity analyses to explain the differences between observations and simulations. Moreover, the artificial target was composed of opaque cubes such that transmission scattering processes do not occur. Plant leaves are characterized by high transmissivity in the NIR spectral region. We therefore need to evaluate Raytran in the case of a scene composed of both reflecting and transmitting scatterers. As stated above, direct comparisons with natural target reflectances is almost impossible because of the large number of parameters which need to be controlled. We wanted to verify only a specific feature, i.e., the accuracy of our Monte Carlo scheme in the case of more complex scenes. In this case, the objective is not anymore to test the capability of representing the structural and optical properties of a real target. For that specific purpose, we compared Raytran with another radiative transfer Monte Carlo model developed by Ross and Marshak (1988) (referred below as RM), which is very similar to Raytran in its principle. The RM model relies on the same assumptions concerning the physical description of light propagation. In addition, the same scene may be represented in both models. Therefore, a favorable comparison between the solutions of the two models strongly suggests that the Monte Carlo scheme may be correct. However, important differences between the two models remain:

- In the RM model, rays are traced using a weighting mechanism adjusted after each
4.4. COMPARISON WITH ANOTHER MONTE CARLO CODE

collision, where the contribution to the bidirectional reflectance is estimated for every viewing angle. A ray path is stopped when its weight becomes too small according to a random cut-off technique of the trajectory.

- The RM model permits the simulation of only one type of plant canopy architecture (see Figure 4.17) which has been generated for the Raytran simulation.

- The RM model computes only the BRF as observed from an infinite distance. As a consequence of the Monte Carlo technique, the two models do not compute the BRF in exactly the same way. For a given viewing direction, Raytran accounts for all the rays in the solid angle defined by the patch corresponding to that direction (Figure 3.5A) while RM accounts only for the rays in the direction of observation.

<table>
<thead>
<tr>
<th>name</th>
<th>LAI</th>
<th>$H$</th>
<th>$a_L$</th>
<th>$r_{st}$</th>
<th>$a_h$</th>
<th>$\sigma_h$</th>
<th>$N_L$</th>
<th>$\phi_g$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SPARSE</td>
<td>1</td>
<td>50</td>
<td>5.00</td>
<td>0.2</td>
<td>4.0</td>
<td>1.0</td>
<td>6</td>
<td>80°</td>
</tr>
<tr>
<td>MEDIUM</td>
<td>3</td>
<td>60</td>
<td>3.81</td>
<td>0.2</td>
<td>5.0</td>
<td>1.5</td>
<td>6</td>
<td>90°</td>
</tr>
<tr>
<td>DENSE</td>
<td>5</td>
<td>100</td>
<td>2.50</td>
<td>0.2</td>
<td>10.0</td>
<td>3.0</td>
<td>8</td>
<td>100°</td>
</tr>
</tbody>
</table>

Table 4.1: Parameters for the different canopies. $H$ is the canopy height. $a_L$ is the leaf radius. $r_{st}$ is the stem radius. $a_h$ the mean height of the first leaf and $\sigma_h$ its normal variance. $N_L$ is the number of leaves per stem. $\phi_g$ is the azimuth angle of the genetic spiral. All linear dimensions are reported in cm.

4.4.2 Description of the scene

In the RM model, the architecture of the canopy is defined by vertical cylindrical stems of radius $r_{st}$ and height $H$ with round leaves of radius $a_L$ over a flat soil (Figure 4.17). The height of the first leaf above the soil $z_{l1}$ follows a normal distribution of mathematical expectation $a_h$ and variance $\sigma_h$. There are $N_L$ leaves per stem with a constant azimuth angle $\phi_g$ between the successive leaves. The distance $A_r$ between the stems is the same in both the X and Y directions and is controlled by the LAI such that

$$A_r = \sqrt{\frac{\pi N_L a_L^2}{LAI}} \quad (4.11)$$

The leaf normal distribution (LND) is characterized by a Beta ($\mu, \nu$) distribution (Goel and Strebel 1984). The soil, the stems and the leaves are assumed Lambertian surfaces. To explore the effect of the LAI, three different canopy types have been generated, their parameters are summarized Table 4.1. The optical values of the different elements are given Table 4.2. For simulation with RM, as many as 1000 rays have been generated for each simulation. The scene is composed of $5 \times 5$ stems. To ensure a good statistical distribution of leaf position, a new generation of the plant canopy is carried out every 20 rays. The same canopy structure has been generated in the Raytran syntax for simulation with this code but for a $12 \times 12$ plant stand. $400 \times 10^6$ rays have been generated for each simulation and a new occurrence of
the canopy is generated every $40 \times 10^6$ rays. The difference in the number of rays which are generated between the two models is very large. However, for each intersection point, the RM model traces rays in each viewing direction such that the efficiency of the method is directly proportional to the number of these directions.

### 4.4.3 Comparisons

For each type of canopy, comparisons have been carried out for two SZA ($31^\circ$ and $61^\circ$), for a planophile LND ($\mu = 2.531, \nu = 1.096$) and an erectophile LND ($\mu = 1.096, \nu = 2.531$) and the DRK and BRT optical data set of Table (4.2) in the red and near-infrared (NIR) spectral regions which represents a total of 48 simulations. Figure (4.18) shows the comparisons in the case of the SPARSE canopy in the red (top) and the NIR (bottom) for the indicated soil brightness and leaf normal distributions. The relative difference $\varepsilon_r$ between the BRF calculated with Raytran $\rho_1$ and RM $\rho_2$ is estimated with $\varepsilon_r = (\rho_2 - \rho_1)/\rho_1$. Both in the red and NIR spectral region, whatever the soil brightness and LND, a systematic difference between the negative and positive viewing angles can be observed. The reflectances in the hot spot direction (positive view), where the number of interactions is lower, agree generally better than the negative directions. Figure (4.19) summarizes the comparisons for all the different cases. The agreement between the two models are confirmed for these specific conditions. However, for the dense canopy (LAI = 5), Raytran overestimates by 15% the RM reflectances in the NIR spectral region. In this region, the multiple scattering is important, especially in the case of a dense canopy. Consequently, some systematic bias may result from the random cut-off technique which is applied to stop a ray in the RM model. In Raytran, since no weighting mechanism is applied to trace ray paths, the model is not conceptually sensitive to the multiple scattering. Clearly, the differences between the two models for the dense canopy are related to the higher number of interactions and may be explained by:

- The random cut-off technique of the RM model;

- The accuracy of the computations: single precision for the RM model, double precision for the Raytran model;
4.5 DISCUSSION

Figure 4.18: BRF in the principal plane for a SZA of 30° for the SPARSE canopy. Raytran values are indicated with solid lines and RM with dotted-dashed lines. Positive viewing directions indicate backward scattering. The dashed-dotted lines represent the mean relative differences of the positive and negative viewing directions.

However, the difference cannot be explained by the way the BRF is computed otherwise it would occur for every scene. The good agreement (a relative different less than 10%) between the two models for sparse and medium canopies shows that Raytran does not have major conceptual errors, or, if an error is present in the model, it must also be present in the RM one.

4.5 Discussion

The evaluation procedures performed in this Chapter have permitted the establishment of the accuracy of Raytran for computing the radiation transport in given three-dimensional structures and in controlled environments. Raytran has been specifically designed to account for the structural complexity of the canopies spatial organization and to document the resulting bidirectional reflectances. With regard to these objectives, these evaluations have clearly shown the very good accuracy which can be achieved. However, the correct representation of the scatterer optical properties remains a major issue, in order to achieve good quantitative accuracies, as has been demonstrated by comparison with laboratory measurements. The
lack of a meaningful surface reflectance model that can be implemented in a Monte Carlo ray tracing code constitutes a limitation of the approach. The consequences of an inaccurate characterization of object’s optical properties on the simulation of the scene BRF can be of two types:

- **The amount of radiation scattered by the individual objects is correct but its angular distribution is inaccurate.** In this case, the error on the final BRF of the scene depends mainly on the distribution of the normal of the scattering surfaces in the scene. This error will be minimal when the scene is composed of uniformly distributed scattering faces, especially when the multiple scattering is important.

- **The angular distribution of radiation scattered by the individual objects is correct but the total amount of scattered radiation is inaccurate.** In this case, the BRF of the scene will be erroneous, whatever the complexity of the scene and the error will be enhanced by the multiple scattering.

However, once scattering distribution functions are assigned to the objects of a scene, there is no systematic numerical error in the BRF of the scene associated with the complexity of the spatial arrangement of the objects, provided a sufficient number of rays are generated.

The meaningful representation of surface properties is currently limited by the lack of information on the different physical processes rather than their formulation. For instance, equations to describe the propagation of the phase and polarization of electromagnetic waves do exist but only very limited information is available on how these characteristics are modified when light interacts with leaves or other natural surfaces. The fundamental problem of light interaction with plant leaves is investigated in the next chapter. The capacity of Raytran to represent realistic canopy reflectances is constrained by the accuracy with which the scene’s structural and optical properties can be described rather than by its conceptual formulation. The different possibilities of representing the plant canopy architecture are investigated in Chapter (6).
Chapter 5

Modeling the optical properties of a leaf

5.1 Introduction

In Chapter (2), we saw that at the scales involved in space-borne remote sensing observations over the optical spectral region, plant leaves may be considered as basic absorbing and scattering elements. It is therefore necessary to accurately represent the optical characteristics of the leaves as a function of their physiological and morphological properties. However, none of the distribution functions described in Annex (C) describe correctly the directional properties of a leaf. The development of a meaningful leaf reflectance model which accounts for parameters such as the water and chlorophyll content is highly desirable. Observations have revealed a high variability in the directional behavior of leaves of the same species. To this end, it is crucial to understand first the mechanisms involved in radiation transfer processes in order to include them properly in canopy reflectance models.

The attenuation of light inside plant leaves results from complex absorption and scattering processes controlled by the biochemical composition and morphological features of the various tissues. The epidermis plays an important role in determining the overall bidirectional reflectance of the leaf while the chlorophyll amount in the parenchyma and spongy mesophyll control the level of light absorption. Although the leaf spectral properties of various plants are relatively well described in the literature, only very few measurements of the directional dependency of leaf reflectance and transmittance have been reported, and then only for a handful of species.

Over the last fifty years, various authors have examined the influence of biochemical composition and anatomical features on leaf optical properties (Vogelmann 1993). However, the rapid development of computer-based models since the late sixties has allowed significant quantitative progress in the understanding of the interaction of light with plant leaves. The range of models that have been developed to address this scientific problem has been recently reviewed (Verdebout et al. 1994). Of the various models that have been proposed so far, the ray tracing approach is the only one that can account for the full three-dimensional complexity of
the internal leaf structure as it appears in a photomicrograph. The method requires a detailed
description of the structure and properties of individual cells, as well as their particular spatial
arrangement inside tissues. Once each of the leaf constituents (cell walls, cytoplasm, pigments,
air cavities, etc.) has been assigned specific optical properties, it is possible to simulate the
propagation of individual light rays incident on the leaf surface on the basis of classical phys-
ical laws such as reflection, refraction, and absorption. Statistically representative values of
the leaf radiative properties of interest are estimated from an analysis of a sufficiently large
number of rays.

This ray tracing technique has already been applied at a number of scales. The first
studies were performed at the cell level (Haberlandt 1914; Gabrys-Mizera 1976), in particular
to investigate the role of epidermal cells on the path of the incident radiation beam: the convex
cells of some plants appear to act as lenses to focus light within the upper region of the palisade
parenchyma, which contains many chloroplasts adapted to high light levels. This feature has
been largely understood as an adaptation to the low light environment on the tropical forest
floor (Bone et al. 1985), although it has also been suggested that epidermal lenses could
increase the absorption of light at low sun angles among cultivated plants (Medicago sativa)
(Martin et al. 1989). At a larger scale, research has been pursued to better understand the
transmission of light through entire leaves. In one such case, the complete leaf structure was
described by 100 circular arcs, while leaf composition was restricted to two media: intercellular
air space and cell walls, each characterized by their refractive index (Allen et al. 1973). This
model was used to simulate the specular and diffuse reflection of light at the cell walls, but
led to an underestimation of the reflectance and an overestimation of the transmittance in
the near-infrared spectral region. It was later found that the estimation of leaf reflectance
and transmittance was improved by adding two more media to the model (the cytoplasm and
chloroplasts), thereby increasing the internal scattering of light (Kumar and Silva 1973).

In all these cases, the absorption phenomena that characterize leaf optical properties out-
side the near-infrared region have been ignored. Moreover, all these models described leaves
as two-dimensional objects, although the three-dimensional structure of these organs is very
important to their physiological function (e.g., for CO₂, H₂O, O₂ diffusion) and to light scat-
tering (Parkhurst 1986; Vogelmann and Martin 1993). As a matter of fact, three-dimensional
radiation transfer models are the only ones capable of describing the heterogeneity of the me-
dia and its effect on the propagation of light. In this chapter, we used a recently developed
three-dimensional light scattering model to describe the transfer of radiation inside a dicotyle-
don leaf as a function of its internal structure and morphological properties. This model aims
at:

1. representing as faithfully as possible the internal structure of the leaf to improve the
   interpretation of reflectance measurements in terms of vegetation biophysical properties;

2. evaluating whether the representation of leaves as layers of cells, together with the clas-
   sical principles of optics, is sufficient to account for the available measurements of leaf
   optical properties.

In the next section, we develop a general method to build a virtual plant leaf which fullfils
the constraints of plant anatomy and physiology, as well as those of the ray tracing model.
The following section explains the construction of a typical dicotyledon leaf with its structural and optical properties. The last section compares different model outputs of leaf spectral and bidirectional properties with observations.

5.2 Concept and methods

Ray tracing techniques require a detailed description of the leaf geometrical properties, as well as the knowledge of the mechanisms involved in the scattering and absorption of light at different levels of organization and at different wavelengths. While modeling leaf anatomy in two dimensions was relatively easy, the generation of a three-dimensional leaf structure is much more challenging. One major issue is the general lack of information on the structure of leaf tissues (Parkhurst 1982). First, in real tissues, cells present a great diversity of shape, size, and arrangement. They are generally enclosed in leaf tissues, which are agglomerates of neighboring cells in close contact (Gibson and Ashby 1988). Second, compared to other cellular solids, plant cells do not completely fill the available space: intercellular air may occupy a significant volume fraction, which varies with plant species, leaf tissue, as well as environmental conditions (e.g., sun-illuminated or shaded leaves, hydrophytic or xerophytic leaves). Only three-dimensional models could provide a meaningful representation of the spatial structure of the leaf.

Various assumptions must be made on the shape and size of the cells and on their spatial arrangement in tissues, if efficient numerical computations are to be performed repetitively. In particular, cells will be represented through simple geometrical objects, and tissues by juxtapositions of such objects. The implications of these representations at the cell and tissue levels are now discussed.

5.2.1 Schematic representation of a leaf cell

Although plant leaves may present numerous anatomical structures, and leaf cells may vary largely in shape and size according to the foliar tissue type (protective tissue such as the cuticle, conductive tissue such as veins, parenchyma, etc.), basic cell structures are relatively uniform because of common cell functions (Mohr and Schopfer 1995). Cells are surrounded by a wall and a plasma membrane containing the cytoplasm with several organelles (nucleus, mitochondria, chloroplasts, amyloplasts, endoplasmic reticulum, etc.) and a central vacuole which may occupy up to 90% of the cell volume. Chloroplasts are found within the cytoplasm of all photosynthesizing cells (Figure 5.1A). All these elements scatter or absorb the light penetrating a plant cell. At all scales where the size of the scattering particles is much greater than the wavelength, refractive index differences between two different media create optical boundaries. When the particle size is less than or about equal to the wavelength, Rayleigh and Mie scattering may occur. While the dimensions of plant cells with respect to solar wavelengths is too large to induce such phenomena (Gates et al. 1965; Sinclair et al. 1973), the cytoplasmic organelles, such as chloroplasts, whose size is comparable to optical wavelengths, and large molecules like proteins, do scatter light. Absorption results essentially from electronic transitions and vibrations of poly-atomic molecules. Electronic transitions
mainly involve porphyrin rings in photosynthetic pigments such as chlorophyll; they act as photoreceptors to convert sunlight into chemical energy for the reduction of CO\textsubscript{2} into carbohydrates (Lichtenthaler 1987). Vibrations of poly-atomic molecules involve another category of chemical compounds: the most common is water, which fills the vacuole and represents from 40 to 90\% of the fresh leaf by weight. Cellulose, hemicellulose, and lignin are other compounds mainly located in the cell walls of all plants, where they act to strengthen and protect plant structures.

![Figure 5.1](image)

**Figure 5.1:** (A) Schematic representation of a mesophyll leaf cell which shows the complexity of the different membrane. (B) For modeling purpose, the internal cell structure is represented by three homogeneous membranes.

Plant cells have been classically modeled as polyhedra (Hulbary 1944; Thompson 1961). The rhombic dodecahedron (10 parallelogram faces) or the tetrakaidecaahedron (8 hexagonal faces and 6 square faces), which fill space when assembled as shown in Figure (5.2), are commonly used. Although these forms are closely approached or even attained in certain simple and homogeneous plant tissues, they can hardly represent cells of leaf tissues that are not made of regularly packed identical units, but instead contain cells of different sizes and shapes with differing numbers of faces and edges. In theory, it should be possible to simulate actual cells by defining polyhedra with faces varying in number from 4 to 50 or more (Romberger et al. 1993). However, multiplying the number of faces tends to smooth the cell shape until it converges to a sphere-like volume. Consequently, we decided to simulate cells with primitive objects (spheres, ellipsoids, cylinders, etc.) that can be carved out and assembled using the Constructive Solid Geometry (CSG) method. The current model defines a typical cell as a set of concentric objects, filled with three different media: cell wall material (cellulose, hemicellulose, and lignin), chlorophyll, and water (Figure 5.1B). The number of media may be changed. For instance, except for stomatal guard cells, cells of the epidermis have only two media instead of three due to the absence of chlorophyll. Each modeled medium is homogeneous: its physical properties are assumed constant in space, and isotropic (independent of the direction). Each cell constituent is therefore characterized by a volume, a refractive index and an absorption coefficient to describe the partitioning of light among the reflected, transmitted, or absorbed contributions. This simplified representation still permits to take into account the basic cell functions.
5.2.2 Schematic representation of a leaf tissue

In real tissues, cells are not isolated but are bounded to neighboring cells in multiple directions and are separated by intercellular air spaces. Although the internal structure of plant leaves varies from species to species, the following model is based on the representation of a typical dicotyledon leaf with a palisade and a spongy mesophyll sandwiched between two layers of epidermal cells as illustrated in Figure (5.3).

The epidermis is made up of a single layer of colorless cells, with few if any chloroplasts and entirely covers both faces of the leaf. Leaf surfaces play a crucial physiological role in protecting these organs from various environmental conditions, such as heat and water stresses, biological threats, *etc.* As far as radiation transfer is concerned, the main effect of these surfaces is to reflect light unequally in various directions. For instance, many leaves exhibit rather strong specular reflectance under specific conditions. This non-Lambertian behavior has been well documented in the literature, especially at oblique incidence angles (Breeze and Holmes 1971; Brakke et al. 1989; Walter-Shea et al. 1989). The light reflected by surfaces in general and by leaves in particular is also often polarized (Grant et al. 1993).

Contrary to monocotyledon leaves characterized by a homogeneous parenchyma with few
intercellular air spaces, the mesophyll of dicotyledons is characteristically differentiated into a palisade and a spongy mesophyll. Palisade cells are elongated, densely packed, and arranged in one to several layers which contain the largest proportion of chloroplasts. The spongy mesophyll is made up of cells of irregular shape and size, separated by large intercellular air-filled spaces which facilitate the circulation of gases (CO$_2$, H$_2$O, O$_2$) inside the leaf (Parkhurst 1986). Why natural selection has led to this differentiation is still unclear, but the arrangement of cells in space appear to follow precise rules. Specifically, the structure of leaves strongly influences the efficiency of light absorption in plants (Vogelmann and Martin 1993). The model described in this chapter permits the study of particular questions, such as the role played by the palisade cells in controlling the distribution of light within the leaf. The volume fraction of air-filled spaces, which varies from one leaf tissue to another, may also play an important role in gas diffusion and light scattering. Clearly, the representation of leaf tissues as assemblages of cells made up from elementary volumes should take these elements into account.

5.3 Construction of a typical dicotyledon leaf

It results from the previous section that the leaf internal structure and the optical properties of each of the media constituting the cell elements must both be carefully simulated if the reflectance and transmittance properties of a typical bifacial mesophytic dicotyledon leaf are to be accurately estimated.

5.3.1 Cell membrane optical and physical properties

The spectral variation of the refractive index and the absorption coefficient of each medium (cell wall, chlorophyll, and water) are both necessary to simulate the scattering and absorption events inside the leaf. The \textit{in vivo} specific absorption coefficient of water (Jacquemoud et al. 1996) has been used; it is very similar to that of pure water (Curcio and Petty 1951). Values of the refractive index of water have also been published (Palmer and Williams 1974). For cell walls, the refractive index of leaf material derived by the PROSPECT model (Jacquemoud and Baret 1990) and the specific absorption coefficient of cellulose, hemicellulose and lignin for dry leaves (Jacquemoud et al. 1996) were used. The specific absorption coefficients determined by the same authors for photosynthetic pigments (primarily chlorophyll), were also used. Although pigment molecules attached to the thylakoid membranes have very clumped distributions, we considered a homogeneous distribution within the layer. For practical purposes, as hypothesized before (Richter and Fukshansky 1994), we assumed that chlorophyll had the same real part of the refractive index as its environment, \textit{i.e.}, as water.

5.3.2 Description of the leaf internal structure

The requirements are first, to define the cell shapes, sizes, and their spatial arrangement in different tissues, and second, to derive the equations which characterize the volume of each membrane. These equations are then used to compute the total amounts of the various media.
5.3. **CONSTRUCTION OF A TYPICAL DICOTYLEDON LEAF**

in each of the different tissues. The dimensions of the leaf cells have been determined by observations. For instance, typical dimensions are $15 \times 15 \times 60 \, \mu\text{m}$ for palisade cells and $18 \times 15 \times 20 \, \mu\text{m}$ for spongy mesophyll and epidermal cells (Gates et al. 1965; Ma et al. 1990). These characteristics have been selected to ensure realistic values of the cell density, i.e., the number of cells per unit area, and thereby the air-space volume. The thickness of the cell membranes is fixed for the cell wall (cellulose and lignin) and the remaining volume is assigned to water and chlorophyll in such a way that these constituents occur in the correct concentrations. The shape, size and position of the cells have been empirically adjusted to ensure that the gross structural and biochemical properties of the leaf are realistic.

### The epidermis

We modeled both the upper and lower epidermis as layers of compact ellipsoidal cells. No intercellular spaces are normally present in this particular tissue, which controls gas exchanges between the leaf and its environment through stomatal pores. These openings have been ignored in this radiation transfer study. As seen in Figure (5.4A), the epidermal cells fit one another like pieces of a jigsaw puzzle (Niklas 1992). Although very different arrangements can be created by varying the way cells are located in space, we tried to define a simple but realistic epidermal layer (Martin et al. 1989). Let $a_e$ be the half-axis of the ellipsoid in the plane of the leaf (in two directions) and $b_e$ the half-axis of the ellipsoid in the direction perpendicular to the leaf. The roughness of the leaf surface can be easily controlled by the oblateness $a_e = b_e/a_e$ of the ellipsoid. The distance between the centers of two cells along a row is $L_e = \sqrt{3}a_e$, and the distance between two rows of cells is given by $R_e = 3a_e/2$. Each cell is carved out at three symmetric points to leave space for the surrounding cells (Figure 5.4B). The volume of one cutout is expressed as follows:

$$2 \pi a_e \int_{L_e/2}^{a_e} \left( a^2_e - x^2 \right) \, dx = \frac{16 - 9\sqrt{3}}{12} \pi a_e^3 o_e$$

(5.1)
and the volume $V_e$ of an epidermis cell is given by

$$V_e = \frac{4}{3} \pi a_e^3 o_e - 3 \left( \frac{16 - 9 \sqrt{3}}{12} \pi a_e^3 o_e \right) = \frac{27 \sqrt{3} - 32}{12} \pi a_e^3 o_e. \quad (5.2)$$

The dashed rectangle in Figure (5.4A) indicates the size of an elementary lattice. Its surface is equal to $S_e = 3\sqrt{3}a_e^2$ and contains $N_e = 2$ cells. It is therefore possible to define the volume per unit area $V_e = N_e V_e / S_e$ and the fraction of intercellular air spaces in this tissue, i.e., the fraction of space between the epidermis insides and the palisade parenchyma:  

$$\xi_e = 1 - \frac{V_e}{2a_e o_e}. \quad \xi_e = 25.6\% \text{ and is independent of the cell size. To define the volume of water } V_{we}, \text{ the same reasoning is applied. The vacuole membrane has a radius of } a_e - e_{ce} \text{ and is carved out with ellipsoids of radius } a_e + e_{ce} \text{ where } e_{ce} \text{ is the cell wall thickness. The cell wall volume } V_{ce} \text{ merely equals } V_{cc} = V_e - V_{we}. \text{ It is also easy to express the cell wall volume per unit area } (V_{ce}) \text{ and the water volume per unit area } (V_{we}).$$

The palisade parenchyma cells

As seen before, palisade cells are narrow, cylindrical cells oriented perpendicular to the leaf surface and usually arranged in one or two layers subjacent to the epidermis. Although compactly arranged, they have little mutual contact due to the long, narrow, intercellular voids along their anticlinal walls as shown in paradermal sections of palisade mesophyll (Esau 1965; Martin et al. 1989; Niklas 1992). The palisade cells have been modeled by cylinders with spherical caps (Figure 5.5A). The volume of a single palisade cell $V_p$ is

$$V_p = \pi a_p^2 \left( h_p + \frac{4a_p o_p}{3} \right) \quad (5.3)$$

where $a_p$ is the radius of the palisade cell, $o_p$ is the oblateness of the cylinder cap, and $h_p$ is the height of the cylinder. The oblateness $o_p$ is defined as $o_p = b_p / a_p$ where $b_p$ is the half-axis of the cap in the direction perpendicular to the cylinder radius. The triangle in Figure

![Diagram](A) (B)
(5.5B) indicates the elementary lattice of area \( S_p = \sqrt{3}a_p^2 \) which contains \( N_p = 1/2 \) cell. The volume per unit area \( V_p \) can be expressed as in the case of the epidermis and the fraction of intercellular air spaces \( \xi_p \) is

\[
\xi_p = 1 - \frac{\sqrt{3}3h_p + 4a_p}{18h_p + 2a_p}.
\]  

The cell wall volume \( V_{cp} \) is determined, as described above, by defining a smaller object whose dimensions are reduced by the cell wall thickness \( e_{cp} \). To evaluate the thickness \( e_{pp} \) and volume \( V_{pp} \) of the layer containing chlorophyll, we assume that a typical palisade cell contains \( n_{pp} = 40 \) chloroplasts, each occupying a volume of 85 \( \mu m^3 \) (Fukshansky et al. 1993). \( e_{pp} \) is numerically estimated using the analytical formula of \( V_{pp} \). The remaining volume \( V_{wp} = V_p - V_{cp} - V_{pp} \) is filled with water. The volumes per unit area \( V_{cp}, V_{pp}, \) and \( V_{wp} \) are easily deduced.

<table>
<thead>
<tr>
<th>Tissue</th>
<th>Characteristic</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>epidermis</td>
<td>cell radius</td>
<td>( a_e )</td>
<td>12.5*</td>
</tr>
<tr>
<td></td>
<td>cell oblateness</td>
<td>( o_e )</td>
<td>0.7</td>
</tr>
<tr>
<td></td>
<td>cell wall thickness</td>
<td>( e_{ce} )</td>
<td>1.0*</td>
</tr>
<tr>
<td>palisade parenchyma</td>
<td>cell radius</td>
<td>( a_p )</td>
<td>7.5*</td>
</tr>
<tr>
<td></td>
<td>cell cap oblateness</td>
<td>( o_p )</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td>cell wall thickness</td>
<td>( e_{cp} )</td>
<td>1.0*</td>
</tr>
<tr>
<td></td>
<td>chloroplast membrane thickness</td>
<td>( e_{pp} )</td>
<td>1.53</td>
</tr>
<tr>
<td>spongy mesophyll</td>
<td>basic cell radius</td>
<td>( a_s )</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>fraction of air spaces</td>
<td>( \xi_s )</td>
<td>0.45*</td>
</tr>
<tr>
<td></td>
<td>tissue thickness</td>
<td>( h_s )</td>
<td>50</td>
</tr>
<tr>
<td></td>
<td>basic cell wall thickness</td>
<td>( e_{cs} )</td>
<td>1.0*</td>
</tr>
<tr>
<td></td>
<td>basic chloroplast membrane thickness</td>
<td>( e_{ps} )</td>
<td>1.32</td>
</tr>
</tbody>
</table>

Table 5.1: Structural parameters to define the generic dicotyledon leaf. Distances are given in \( \mu m \). Values found in the literature are indicated with an asterisk.

The spongy mesophyll cells

In contrast to the other two tissues, the shape of spongy mesophyll cells is complex and intercellular air spaces may occupy up to 50% of the tissue volume. This tissue is consequently somewhat difficult to represent. We defined spheres of different sizes, located at random, such that the occupied volume corresponds to observations. Such a statistical approach seems appropriate to describe an irregular tissue which, at first sight, does not obey any simple rule. We first consider a box of height \( h_s \) and base \( S_s = 300 \ \mu m \times 300 \ \mu m \), and assign the volumetric fraction of air spaces \( \xi_s \) to 45%. The spongy mesophyll is generated by filling the box at random with spheres of initial radius \( a_s \) without overlapping. When no more space is available, this radius \( a_s \) is reduced by 10% and the filling process continues with smaller spheres. This iterative process stops when \( 1 - \xi_s \) of the space is occupied by cells. A total of
1139 spheres of eleven different sizes allow us to fill the space available at the required density. The thicknesses of all internal membranes of the smaller spheres are similarly decreased. To compute the chloroplast layer thickness of the initial spheres, we assume that the latter contain \( n_{ps} = 25 \) chloroplasts, each occupying a volume of \( 85 \ \mu m^3 \), and estimate \( e_{ps} \) numerically as for the palisade parenchyma. The remaining volume is then filled with water. This process is repeated for each class of spheres.

<table>
<thead>
<tr>
<th>Cell membrane</th>
<th>Parameter</th>
<th>Epidermis</th>
<th>Palisade parenchyma</th>
<th>Spongy mesophyll</th>
<th>Whole leaf</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>h ((\mu m))</td>
<td>17.5</td>
<td>65</td>
<td>50</td>
<td>150</td>
</tr>
<tr>
<td></td>
<td>(\xi) (%)</td>
<td>25.6</td>
<td>16.3</td>
<td>45.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>N (cm(^{-2}))</td>
<td>246,336</td>
<td>513,200</td>
<td>1,265,556</td>
<td>2,271,428</td>
</tr>
<tr>
<td>cell wall</td>
<td>(\alpha_c) (%)</td>
<td>27.0</td>
<td>26.6</td>
<td>23.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>V ((\mu m^3))</td>
<td>1427.51</td>
<td>2815.91</td>
<td>1662.95</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(C_c) (g.cm(^{-2}))</td>
<td>0.00052</td>
<td>0.00213</td>
<td>0.00093</td>
<td>0.00410</td>
</tr>
<tr>
<td>pigments</td>
<td>(n_p)</td>
<td>40</td>
<td>25</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(\alpha_p) (%)</td>
<td>32.1</td>
<td>29.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>V ((\mu m^3))</td>
<td>3400.00</td>
<td>2125.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(C_p) ((\mu g.cm^{-2}))</td>
<td>41.1</td>
<td>19.0</td>
<td>60.1</td>
<td></td>
</tr>
<tr>
<td>water</td>
<td>(\alpha_w) (%)</td>
<td>73.0</td>
<td>41.4</td>
<td>47.7</td>
<td></td>
</tr>
<tr>
<td></td>
<td>V ((\mu m^3))</td>
<td>3857.44</td>
<td>4386.96</td>
<td>3450.28</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(C_w) (g.cm(^{-2}))</td>
<td>0.00095</td>
<td>0.00225</td>
<td>0.00131</td>
<td>0.00546</td>
</tr>
</tbody>
</table>

Table 5.2: Statistics for the leaf biophysical properties.

### Generation of the leaf

The cross-section of the leaf appears like a bifacial slab structure, in which the blade is represented as two layers of epidermal cells surrounding a palisade parenchyma and a spongy mesophyll. This organization is of course an idealization of actual leaf structures, which exhibits a rather large natural diversity in the number, shape, and orientation of cells in the various tissues. For instance, it has been shown that the palisade cells of Medicago sativa leaves do not follow any regular pattern in their arrangement below the epidermal cells:Martin et al. 1989 they can be located directly in line with the transverse axis of an epidermal cell, anywhere along the inner periclinal wall, or below a junction of two or more epidermal cells. The boundary between the palisade and spongy mesophyll is also undefined; the small intercellular voids of the palisade mesophyll are continuous with the much larger voids in the subjacent spongy mesophyll, thereby promoting CO\(_2\) diffusion through the whole leaf.

The leaf internal structure is thus fully defined by 13 parameters summarized in Table 5.1. The previous formulæ allow us to control the fraction of intercellular air spaces, the fractional
5.3. CONSTRUCTION OF A TYPICAL DICOTYLEDON LEAF

Figure 5.6: Perspective view of the artificial dicotyledon leaf

The volume of the different media, as well as the number of cells per $\mu$m$^2$ ($N_l$) which is given by

$$N_l = \frac{N_e}{S_e} + \frac{N_p}{S_p} + \frac{1}{S_s} \sum N_s + \frac{N_e}{S_e}.$$  \hspace{1cm} (5.5)

Assuming that $\alpha_c$, $\alpha_p$, and $\alpha_w$ are the fractional volumes of cell walls, chlorophyllian pigments, and water respectively, we can also calculate $C_c$, $C_p$, $C_w$, which are the corresponding contents expressed in g cm$^{-2}$ or $\mu$g cm$^{-2}$. The density of water being $v_w = 1.0$ g cm$^{-3}$, the water content is

$$C_w = v_w \left( \alpha_{we} V_e + \alpha_{wp} V_p + \alpha_{ws} \sum V_s + \alpha_{we} V_e \right).$$  \hspace{1cm} (5.6)

Table 5.2 shows that $C_w$ is within the range of laboratory measurements acquired in the LOPEX93 experiment (Hosgood et al. 1995). The case of cell walls is somewhat less straightforward, due to the lack of information about their biophysical properties. Cellulose (including hemicellulose) and lignin are the main constituents of the cell wall, in proportion to 3/4 and 1/4 (Jacquemoud et al. 1996), and they have densities of 1.52 and 1.34 (Stamm and Sanders 1966). The cell wall density has accordingly been set to $v_c = 1.47$ g cm$^{-3}$. The biochemical composition of cell walls is almost constant and so is its density. As for cell walls, the water content is expressed as follows

$$C_c = v_c \left( \alpha_{ce} V_e + \alpha_{cp} V_p + \alpha_{cs} \sum V_s + \alpha_{we} V_e \right).$$  \hspace{1cm} (5.7)

As previously, $C_c$ agrees with experimental observations of cellulose + hemicellulose + lignin content (Jacquemoud et al. 1996). Finally, the total leaf chlorophyll content ($C_p$) is given by

$$C_p = c_p \left( n_{pp}N_p + \sum n_{ps}N_s \right).$$  \hspace{1cm} (5.8)

where $(n_p)$ is the average number of chloroplasts in a cell and the chlorophyll content of a chloroplast is $c_p = 2 \times 10^{-6}$µg. The value of $C_p$ for this modeled leaf is given in Table 5.2 and appears reasonable (Hosgood et al. 1995). This Table also exhibits the other properties of our virtual leaf. For a given set of parameters, a program automatically computes the position of each cell as shown in Figure (5.6), and another the statistics developed above. The next step consists in simulating the path of rays through a 300 $\mu$m$^2$ sample of this virtual leaf.
5.4 Radiative transfer simulations

Although the leaf structure described above is greatly simplified compared to that of actual leaves, it nevertheless allows the representation of a fair degree of complexity. The computation of the radiation regime in such a complex medium is not particularly difficult with a ray tracing model. The number of emitted rays and their initial angular distribution can be set individually for each experiment. The leaf is generated with the parameters shown in Table 5.1. In addition, to study the effect of the epidermis roughness, we also generated a leaf with an epidermal oblateness \( o_e = 0.2 \), which represents a smoother surface. In this case, we also increased \( a_e \) in order to keep the leaf water content unchanged. We now investigate the spectral behavior and the directional reflectance of this leaf.

5.4.1 Spectrum

To evaluate the adequacy of the description of leaf internal structure and optical properties, we calculated the leaf bi-hemispherical reflectance \( R_{bh} \) and transmittance \( T_{bh} \) in the 400 to 2500 nm spectral region at a resolution of 25 nm. The upper (adaxial) face of the leaves is illuminated by an isotropic point light source with a conical angular aperture of 90°. One million of rays are generated for each simulated wavelength. The absorptance \( A_{bh} \) is derived from the reflectance and the transmittance through the simple relationship \( A_{bh} = 1 - (R_{bh} + T_{bh}) \). In Figure (5.7), one recognizes classical absorption features in the visible (chlorophyll) and the middle infrared (water); the NIR plateau attributed to leaf internal structure is also well represented. By inversion of the PROSPECT model (Jacquemoud et al. 1996) against these spectra, we estimated the original leaf biophysical parameters. While the retrieved water content (0.00659 g cm\(^{-2}\)) is very close to the value of Table 5.2 (0.00546 g cm\(^{-2}\)), the estimated chlorophyll content (18.6 µg cm\(^{-2}\)) strongly differs from its actual value (60.1 µg cm\(^{-2}\)). This disagreement reveals the limits of a purely refractive scattering approach. Since
increasing the absorption by the chlorophyll pigments does not improve the output of the model, we hypothesized that the discrepancy may be due to an overestimation of the leaf surface reflectance. These effects will be discussed in more detail in Section (5.4.3). The reflectance and transmittance levels in the NIR are more characteristic of a monocotyledon than a dicotyledon: $R_{bh}$ is underestimated and $T_{bh}$ overestimated. This bias has been observed before with other models (Allen et al. 1973). Decreasing the epidermis roughness to $\alpha_e = 0.2$ mainly affects the transmittance, while the reflectance remains almost unchanged. By smoothing out the epidermis, we increased the transmittance of the leaf, except in the spectral region around the peak of water absorption (i.e., $\approx 1930$ nm). In the NIR spectral region, the slightly higher reflectances associated with the rough epidermis are due to the contribution of the multiple scattering. This simulation underscores the role of the epidermis in controlling the internal distribution of light in the leaf structure. These features are investigated further in the next Section.

5.4.2 Vertical light attenuation

To illustrate the effect of the shape of the epidermis on light scattering, we computed the relative upward (transmitted), downward (scattered), and net fluxes using twenty virtual sensors regularly positioned along a vertical axis between the two epidermal layers for the same illumination conditions (refer to Section 3.6.3). Figure (5.8) shows the light gradients within the leaf at 675 nm. The extinction of the relative downward flux is greater in the case of a convex epidermis cell ($\alpha_e = 0.7$). As already observed by many authors (e.g., Bone et al. 1985; Lee 1986; Poulson and Vogelmann 1990), an epidermis with a convex shape, i.e., with a rough surface, acts as lens which focuses the light on the palisade tissue and therefore increases the absorption. The distribution of light reveals other notable features in accordance with experimental results. For instance, Vogelmann et al. (1989), using a fibre-optic probe, observed small increases in the profiles when a transition between two different tissues occurred; these increases, which were probably due to optical discontinuities, can be seen in Figure (5.8). The
CHAPTER 5. MODELING THE OPTICAL PROPERTIES OF A LEAF

attenuation of transmitted light is exponential, indicating significant amounts of absorption. 80% or more of the light is absorbed in the palisade, i.e., within the initial 90 µm or so of the leaf.

The relative downward flux in the upper epidermis is higher than 100% because the same ray may be scattered several times inside an epidermal cell and hence be counted more than once by a given detector. This concentration of light has already been reported in the literature for various leaves (Vogelmann 1993). Figure (5.8) also shows that the amount of scattered light falls to less than 10% of its initial level within the upper epidermis, as observed experimentally (Vogelmann et al. 1989).

5.4.3 Hemispherical reflectance and transmittance

The relationship between the hemispherical reflectance $R_h$, or transmittance $T_h$, and the illumination zenith angle $\theta_i$ assuming direct radiation has also been investigated. Results are presented in Figure (5.9) for $\lambda = 675$ nm and 1000 nm for $\phi_e = 0.7$. In the red, only $R_h$ significantly varies with $\theta_i$. In the NIR, both $R_h$ and $T_h$ present an angular dependence which is symmetric so that the hemispherical absorptance $A_h$ is constant. As also observed by Brakke (1994), the specular reflection component is independent of the wavelength. Using the Fresnel equations and an average refractive index of 1.45 that is characteristic of leaf material, Allen (1973) calculated the reflection of light by a dielectric surface in three dimensions and found similar results for $R_h^r$. As the hemispherical single scattering reflection only results from the surface, it should be also comparable with experimental measurements of the polarized reflectance of plant leaves such as those performed by Grant et al. (1993). Because Raytran ignores, for the moment, the effects of the cuticular waxes and leaf pubescence (which may produce diffraction and increase $R_h$), our values are relatively low, but still consistent. McClendon (1984) observed that the “specular” reflection in the red spectral region rarely exceeds the “diffuse” reflection. Typical reflectance values in the red are close to 0.05, with a very weak diffuse component (Brakke 1994). In the present simulation, the diffuse reflection

![Figure 5.9: Hemispherical reflectance $R_h$, transmittance $T_h$, and single scattering reflection $R_h^r$ (dashed line) for various IZA. $\phi_e = 0.7$](image-url)
5.4. RADIATIVE TRANSFER SIMULATIONS

originating from the multiple scattering is overestimated. Too much of the light transmitted in the epidermis tissue can be scattered back to the upper side. This may be due either to the fact that the epidermis absorbs more than what we assumed or to the negligence of diffraction phenomena.

5.4.4 Bidirectional reflectance and transmittance

Finally, we calculated with equation (3.19) the bidirectional reflectance and transmittance for various illumination zenith angles \( \theta_i \) in the near-infrared. The leaves are lighted by a collimated beam generating 5 million rays for each of the three illumination directions (Figure 5.10). Leaves with a rough epidermis have an almost Lambertian reflectance and transmittance. Such Lambertian leaf reflection has already been observed (Brakke 1992), but most of the leaves exhibit a specular reflection peak (Brakke et al. 1989; Brakke et al. 1993). To investigate this issue, we experimented with values of \( o_e \) varying continuously from 0.7 to 0.2. As the epidermis becomes smoother, the reflectance becomes more specular, especially for high illumination zenith angles. At large \( \theta_i \), the transmittance is also affected by the illumination direction as can be seen Figure (5.10) and reported elsewhere (Brakke 1994). For oblateness values around 0.3 and for the particular leaf being modeled here, the specular component exhibits an off-specular peak as predicted by the theory (Torrance and Sparrow 1967). However, more realistic simulations of the leaf bidirectional reflectance will require a careful description of the roughness of the epidermis.

![Figure 5.10: Bidirectional reflectance and transmittance in the principal plane in polar co-ordinates for an illumination angle of 30° (left) and 60° (right). The rough epidermis means \( o_e = 0.7 \) and the smooth one \( o_e = 0.2 \).](image)

The relation between the reflectance of the leaf and the structure of its epidermis needs to be further investigated. For instance, it would be useful to understand why various leaves adopt
a particular roughness, and how the structure (and hence the radiation transfer characteristics) evolves in space and time. As seen above, convex epidermis cells tend to focus light on the subjacent palisade cells, but also tend to reflect light relatively isotropically. This type of leaves is often found in the lower part of the canopy (Bone et al. 1985), where direct solar radiation does not easily penetrate. These leaves exhibit a larger absorptance than those with a smoother epidermis, and have rather Lambertian bidirectional reflectance. Conversely, leaves with smooth epidermis exhibit a more specular reflectance and absorb less radiation; they are expected to be found in the upper part of the canopy, where direct sunlight is predominant. Through this mechanism, leaves may protect themselves against excessive direct solar radiation and transmit light to the lower layers of the canopy. This mechanism could be ascertained through appropriate field observations.

5.5 Discussion

This study reported on an innovative attempt to simulate light scattering and absorption in a three-dimensional leaf with a ray tracing model. The leaf biophysical properties of a typical dicotyledon leaf are reasonably described by its structure, defined as an assemblage of simple geometric volumes filled by three different media: cells wall materials, chlorophyll pigments, and water. The position, size and shape of each cell in the simulated leaf section are explicitly defined. These specifications were selected to yield reasonable concentrations of biochemical components. The Raytran model is capable of simulating the spectral and bidirectional reflectance properties of such a leaf. Although the model is still in an early stage of development, the results obtained so far agree fairly well with reflectance and transmittance observations. This approach allows us to confirm and improve our understanding of leaf optical properties.

The structure and optical properties of the various leaf tissues have been assigned to conform to the information available in the published literature. The transmittance, reflectance and absorptance of the leaf were computed with the ray tracing model, without allowing any further ajustments. In other words, the radiative properties of the simulated dicotyledon leaf described here result exclusively from the geometrical description of the leaf tissues, their optical characteristics, and the physical principles of classical optics. Although the general factors controlling absorption and reflection have been understood for a long time, it had never been shown before that a spatially detailed description of leaf structure would yield optical properties as close to the measured ones as those obtained here. Through this rigorous approach, we succeeded to show, for the first time, that specific biochemical concentrations in different leaf layers and cell structures could be modeled and to predict actual wavelength-specific light absorption and scattering patterns that closely match observations.

In retrospect, it is interesting to see how important the shape of the epidermis cells is for the transfer of radiation in leaves. The model described above is capable of simulating subtle aspects of this problem, including the focusing of light by these cells on the subjacent tissues. In addition, these initial results suggest new laboratory measurements, for which the leaf bidirectional reflectance should be observed simultaneously with the leaf internal structure, in
order to investigate the relationships between these two properties. Such an approach would be very helpful to improve the representation of leaf directional properties in canopy reflectance models.

The current model has excluded a number of leaf tissues and cell types that would make it more physically realistic but would require descriptive information not readily available. For example, conductive tissues are not included, nor are various specialized cells, \textit{e.g.} schlerids, glands, trichomes and others. Additionally, the assumption of an homogeneous chlorophyll membrane may reveal some limitation if finer detail on the absorption by chloroplasts is desired to investigate the photosynthesis mechanism. Original approaches recently published in the literature (Fukshansky et al. 1993; Richter and Fukshansky 1994) are worth further investigations. Also of potential interest is the suggestion that the chloroplasts near the upper face of the palisade tissue receive more light than those located near the lower side (Martin et al. 1989). Consequently, chloroplasts may develop different strategies to trap light (Poulson and Vogelmann 1990). We also saw that an accurate estimation of the bidirectional reflectance requires accounting for the irregularities in the shape of the epidermis cells. From a physiological point of view, it would also be interesting to examine the light collecting capabilities of various leaf anatomies and chemical compositions. Several authors have already investigated the relationships between leaf spectra and chemical content, but these studies exploit only a limited number of observations (Baret et al. 1992; Danson et al. 1992). Our approach opens the way for new sensitivity studies, which may prove very useful in the understanding of ecological processes.

From a physiological point of view, it would be also interesting as a next step to examine the light collecting capabilities of various leaf anatomies and chemical compositions. Several authors (\textit{e.g.}, Baret et al. 1992; Danson et al. 1992) have already investigated the relationships between leaf spectra and chemical content but these studies exploit only a limited number of observations. Our approach opens the way for new sensitivity studies, which may prove very useful in the understanding of ecological processes and helpful in the design of new spectral indices for upcoming high spectral resolution instruments such as MERIS and MODIS. In addition, these results can be used to develop a simple physically-based leaf reflectance model which should account for both the effects of the epidermis roughness and the internal structure.
Chapter 6

Representation of the canopy architecture

6.1 Introduction

In the previous chapter, we investigated the spectral and directional properties of a plant leaf with an explicit representation of the internal structure. In particular, we illustrated the role of the epiderm roughness on both the spectral and directional behavior. This study shows the importance of the structural properties of the interacting media, even at the scale of the single plant leaf. In any case, further efforts are required to develop an accurate analytical leaf reflectance model which can be included in canopy reflectance models, such as Raytran.

We now explore the role of the canopy architecture on the radiation transfer. To this end, the first issue is the representation of the structural properties of the vegetation in a way suitable for radiation transfer modeling. This chapter discusses the problem of representing the structural properties of plant canopies. In the next section, we define the concept of plant architecture and briefly review the approach commonly used in canopy reflectance models. In the rest of the chapter, we investigate different methods to describe the spatial organization of the canopy according to the spatial scale of interest and the complexity of the scenes.

6.2 Background

Ross (1991; page 9) defines the plant community architecture (PCA) as “the set of features delineating the shape, size, geometry and external structure of a plant community”. Although plants of a given species present obvious architectural similarities, they exhibit a myriad of spatial and temporal differences due to self-adaptations to local environmental conditions. Hence, the level of detail with which the canopy needs to be described will have to be adjusted to the particular application at hand. For instance, biological plant studies would rather stress the representation of the organs which ensure the species’ reproduction while in the case of
the radiative transfer, one is more interested by the representation of the foliage arrangement. The quantitative formulation of PCA is divided into two conceptually different approaches. On the one hand, a plant can be considered as a purely architectural realization, in which the external form of the plant community is determined by the geometry of individual organs and their spatial arrangement (Myneni et al. 1989). On the other hand, a plant may be viewed as a living organism characterized by its vital functional activities (i.e., reproduction, nutrition) and the corresponding organs (i.e., roots, stomates) that interface with the external environment. A purely structural description of plant morphological properties should be, in any case, consistent with the physiological functioning responsible for its growth and development under specific nutritional and climatological conditions such as the soil water content, the available solar radiation, the wind or the air temperature.

Two main structural parameters are relevant from a radiative transfer point of view: the leaf area density (LAD) and the leaf normal distribution (LND) (Myneni and Asrar 1991). These parameters are first used to define the optical thickness of the medium as given by equation (D.1) and thereby the interception of the solar radiation. In turn, these equations allow the estimation of the mean free path of the rays, i.e., the mean distance they can cover without interaction with phyto-elements. In fact, most of the numerical sophistication of radiative transfer models in vegetation comes from the difficulty of properly accounting for the finite size of the scatterers and the multiple scattering process. To reduce the complexity of the radiation transfer equations, the spatial distribution is most often assumed homogeneous, to the detriment of an exact representation of the foliage aggregation (Sampson and Smith 1993; Andrieu and Sinoquet 1993). Although leaf position is primarily determined by the basic structure of the plant, the morphogenetic response of the leaf-bearing branches to the external environment (i.e., quantitative change in growth) is strongly dependent on the light availability (Jones 1983). Therefore, the assumption that leaves are locally uniformly dispersed is to some extent consistent with a plant optimal photomorphogenic adaptation. However, as one moves up to a higher level of organization, the homogeneity of this local organization decreases and spatial variability increases (Levin 1993). These findings suggest the definition of a “locally uniform dispersion” of leaves in a canopy. In the context of radiation transfer in vegetation, an elementary radiative unit may be defined as a region occupied by “uniformly” dispersed phyto-elements in which the variability of the ray mean free path length is smaller than the size of the considered region. In other words, the “relative homogeneity” or the tolerance in the “uniformity” of the distribution of the sampled region of the canopy is directly linked to its size such that the smaller the region, the smaller the allowed variability of the interception coefficient. This concept does not rely on the definition of an absolute dimension of an elementary radiative unit but on its relative size with regard to the scale of interest. It emphasizes the radiative meso-scale introduced in Chapter (2). Hence, from a radiative point of view, the plant canopy structure may be conceptualized as an assemblage of elementary radiative units in which the scattering phyto-elements are uniformly distributed and separated by gaps. The representation of these radiative elementary units is investigated in the next section.

Only a limited number of radiative transfer models in vegetation account for the spatial dispersion of these elementary radiative units. Basically, four different approaches have been followed so far.
6.2. BACKGROUND

1. The scene can be divided into a number of cells of equal size of different optical thickness (e.g., Kimes and Kirchner 1982; Goel and Grier 1988; Knyazikhin et al. 1992; Myneni and Asrar 1993; Gastellu-Etchegorry et al. 1994). The advantage of this technique lies in the accurate representation of radiation transfer inside each cell but suffers from the large number of grid cells required as soon as a high level of detail is desired. Furthermore, the choice of the cell size with regard to the heterogeneity of the scene is a critical issue.

2. Another approach consists of describing the elementary radiative unit with geometrical objects (e.g., Norman et al. 1985; Li and Strahler 1985; Li and Strahler 1992; Bégué 1992; Franklin et al. 1994). These models represent each individual plant as a single geometrical object but fail to account correctly for the effect of individual scatterers.

3. The next technique is based on statistical approaches which account for gap probabilities in the radiation mean free path (Li et al. 1995) or for stochastic representation of the gaps (Peltoniemi 1993).

4. Finally, the last method consists of describing explicitly the position of each individual scatterer as permitted by computer based techniques.

In the first three approaches, the description of the three-dimensional structure is driven by a nicely integrable formulation of the radiative transfer equation rather than by an accurate representation of the geometrical heterogeneities of the medium. Raytran includes most of these different representations and allows the association of different optical properties to each scatterer. The description of the scene geometry is in fact completely independent from the computation of the radiative transfer. The constraint is no longer the representation of the scene heterogeneities in a way that fits the way the radiation transfer equations are formulated but to have an accurate representation of the optical and structural properties of the medium with respect to the addressed problems. However, as mentioned above, whatever the method used to describe the vegetation, the representation should be consistent with the physiological functioning of the plant. For instance, the foliage arrangement does not result exclusively from an optimized strategy to absorb sunlight for the photosynthesis processes but also from a need to efficiently release thermal energy (Gates 1980).

The most explicit and accurate way to describe plant architecture is to define explicitly the position, size, shape and orientation of the scattering phyto-elements as they would be observed in the field. However, this kind of deterministic representation would require a large amount of measurements, which would be a difficult and time-consuming proposition. For practical purposes, methods of measuring the canopy architecture involve simplifications which limit the number of parameters to be measured (Vanderbilt 1985). These assumptions are based on statistical properties of canopy organization. In turn, these measurements may be used to compute the corresponding optical thickness or to “reconstruct” instances of a plant with the same statistical properties as the observed ones. Formally, an architecturally-based representation may be defined as a deterministic or non-deterministic system characterized by a set of structural variables and associated probabilities which should be ideally conceptualized as an adaptive system. The definition of such a system requires the following steps: (1) the identification of the relevant structural parameters and their statistical properties; (2)
the sampling of these parameters with field measurements; (3) the definition of a process to “reconstruct” explicitly the observed plants.

Alternatively, vegetation models are based on the representation of the physiological mechanisms of plant growth with an explicit representation of the environmental conditions. Martin (1993) reviewed the different methods which have been developed so far. The dynamics of plant growth may be described in terms of simple statistical rules or by very elaborate mechanistic approaches which simulate the life cycle of individual trees as a function of light and nutrient availability and climatic disturbances. Such models can predict the production of biomass for different species and at a larger scale, their assemblage. The main advantage of this approach lies is that the response to environmental changes can be predicted and it is therefore appropriate for the study and understanding of the environmental consequences of global changes (Nikolov and Fox 1994; Smith et al. 1994) although it does not provide enough information to explicitly represent the resulting canopy architecture.

In brief, methods to describe the plant canopy properties can be categorized in two different approaches: an architectural-based approach which aims at representing the structural properties as a set of distribution functions and associated parameters and a functional-based approach which relies on the description of physiological growth processes and their adaptation to a changing environment. In the rest of this section, we focus on the representation of the canopy architecture at different scales, presenting techniques that are directly suitable to generate scenes for Raytran simulations.

6.3 Representation of an elementary radiative unit

As mentioned above, the two main parameters which characterize the structural properties of an elementary radiative unit are the LND and LAD. The LAD is merely the ratio between the scatterer surface and the volume of the region which encompasses the scattering elements. The angular orientation of a leaf is defined by the normal to the upper face, i.e., its zenith and azimuth angles. The leaf normal distribution describes the proportion of leaves whose normals fall within a unit angle around any particular direction (Myneni et al. 1989). In practice, the azimuthal distribution is most often characterized by a uniform distribution. Bunnik (1978) observed that foliage angular distributions could be categorized into specific angular distribution (erectophile, planophile, etc.). These distributions can be represented as a sum of cosines (Bunnik 1978), with Beta functions (Goel and Strebel 1984) or with elliptical distributions (Nilson and Kusuk 1989). To simplify the resolution of the radiation transfer equations, this distribution can also be approximated by polynomials (Reyna and Badhwar 1985). However, the definition of the LND and LAD are not strictly sufficient to characterize the structure of the medium since a huge number of small leaves may have exactly the same area density as a few big leaves but the backscattering probability, which is responsible for the hot spot effect, may not be the same in the two cases. To account for the size of the scatterers, a new parameter is required to represent either the sun fleck area or the surface of the scatterers. An example of the relationship between the scatterer’s surface and the sun fleck area is given in Chapter (4). Finally, one has to specify the shape and the spatial extent of the
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elementary radiative unit. Note that in the case of Raytran, the shape of these units is not limited to a box but may have any kind of shape as permitted by CSG techniques introduced in Section (3.2).

Myneni et al. 1989 reviewed the theoretical development, interpretation and measurement methodologies of each of these structural parameters. Methods for acquiring data on foliage distribution have been classified as direct and indirect methods (Vanderbilt et al. 1990). Direct methods rely on destructive or non-destructive observations, they aim at determining with a compass, inclinometer and meter stick the position of each component of the canopy (e.g., Ustin et al. 1991). These methods may provide accurate measurements but data availability is often limited to individual plants or small areas. In the case of indirect methods, the architecture of the canopy is retrieved from remote observations in several viewing directions (e.g., Sinoquet et al. 1991; Webb and Ungs 1993), which need to be processed to extract the desired statistical information (e.g., Lang 1991).

6.4 Representation of leaf shape and foliage aggregation

In Chapter (4), we gave examples of the generation of clouds of discs with specified LAD, LND and disc radius. Clearly, leaves exhibit an extraordinary variety in size, shape and aggregation. To assess the importance of these geometrical features on the transport of radiation in vegetation, it is important to describe them as accurately as possible. Because of the high diversity of plant architecture and leaf organization, it is not in the scope of this work to represent all types of plant canopies or a subset of the most important ones. Instead, the study has been focused on two different cases to illustrate different techniques to represent these effects. We focus first on the representation of leaf shapes by investigating a grassland prairie. The potential of L-systems to represent tree branching patterns is then explored.

![Figure 6.1: Grassland. (A): Wireframe representation of a generic gramineaceous plant. The dashed line circle defines the area in which no other clumps may grow. (B): Angular distribution of the polygon normal forming the leaves (solid line, $\mu = 0.82, \nu = 1.37$) in comparison to the standard erectophile distribution (dashed line, $\mu = 1.172, \nu = 2.77$). (C) Top view of the grass for LAI=2.8. Ground cover is 70%.]
6.4.1 Modeling gramineous leaf aggregation

Grassland represents a dominant land cover type in every continent. According to the International Institute for Environment and Development, natural grassland and pasture occupied 24% of the terrestrial surface in 1983. The larger grassland regions are the Russian steppe and the North American prairies. The annual productivity in terms of biomass is very high (several tons per ha under favorable climatic conditions) and over half of livestock feed supply is furnished as forage and legumes. Grassland is essentially composed of grasses (*Graminae*), and constitute the world’s most universally distributed plant. Gramineous plant structures are easy to recognize with their long leaves composed of the sheath surrounding the stem and the blade with a curvilinear central vein. There are thousands of different species of grasses. Most of the effort to model their structure has been limited to the representation of grass crops such as maize (e.g., Prévot et al. 1991). Here, we focused on the representation of the leaves and their aggregation in tufts, as appears commonly in natural grassland. The number of leaves per tuft and their orientation at the base depends on the horizontal space available which, itself is function of the clump density and the amount of dry material on the ground (Deering et al. 1992; Friedl et al. 1994). Our model is based on a statistical description of a fully-developed generic gramineous tuft characterized by the following parameters:

- The number of leaves per tuft;
- The mean length of a leaf and its variance;
- The ratio between the maximum width and the length of a leaf;
- The mean zenith angle at the base of the tuft blade;
- A tropism vector responsible for the blade central vein curvature.

Each blade of grass is represented by a set of isosceles trapezoids whose top is smaller than the base (Figure 6.1). The leaf length varies according to a Gaussian distribution. The azimuth angle of the first polygon is randomly selected between 0 and $2\pi$. The zenith angle of this first polygon is adjusted according to the actual length of the leaf such that longer blades have larger inclinations. To ensure leaf continuity, the length of the top of each trapezoid corresponds to the length of the base of the next one. The normals to the successive trapezoids are adjusted according to the intensity of the tropism vector.

To artificially “sow” the grasses, we used the following technique: Each clump base is surrounded by a circle in which no other clump can grow. The radius of this circle is a function of the number of leaves and the horizontal extension of the clump. The clumps are uniformly distributed in a given square until the requested LAI value is reached. Tufts are sequentially positioned, checking each time that the newly sown clump does not overlap with the existing one. Figure (6.1B) shows the polygon mean LAD of the zenith direction ($\mu = 0.82, \nu = 1.37$). Figure (6.1C) represents a prairie with a LAI of 2.8 which corresponds to a ground cover of 70%. This canopy is not exactly homogeneous since the polygons close to the soil are more vertical than the polygons of the upper part of the canopy (Figure 6.1A).
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Figure 6.2: View of the generation of the artificial grassland with a LAI of 2.8. Each tuft is composed of 7 leaves divided into 8 trapezoids. The scene is composed of 208 tufts which represents 11649 objects including the soil.

Moreover, the horizontal distribution of the polygons is not uniform as a result of the clumping effects (Figure 6.1C). In spite of its empiricism and simplicity, this model represents grassland rather realistically as illustrated in Figure (6.2) where the clumping effects and the variations in the leaf angular distributions are correctly represented. This methods demonstrates the potential of statistical descriptions to represent simple leaf aggregations.

6.4.2 Modeling woody plant geometry

Branching pattern is a fundamental constraint on plant architecture, especially in the crowns of woody plants. Several methods have been proposed so far to represent branching patterns based on the underlying principle that biological objects exhibit self-similarities and deterministic behavior throughout their growth process. In the seventies, Hallé et al. (1978) suggested that each individual species has a precisely determined structure or architectural model. They found that by using a set of simple growth characteristics it was possible to categorize all trees into 23 architectural models which encompass the total diversity of tree forms. Each of these models is identified by the name of a botanist. For a detailed description of the laws of branching mechanisms, see for instance Fisher (1986). Basically, branching patterns are determined by the functioning of meristem. The primary direction of a branch depends on the gravitropic response of the bud and the orientation of the parent axis. Here, we investigate the potential of L-systems to generate architecturally consistent trees.

Fractals have been used to describe simple plant architectures represented with one type of geometrical object (Mandelbrot 1983). de Reffye et al. (1991) have developed a very detailed
model of tree growth, based on an accurate representation of the functioning of the meristem, growth unit (shoot) and mortality processes. An alternative approach lies on L-systems, initially introduced by Lindenmayer (1968), which constitute a mathematical representation of plant structure. Their principles are explained in Annex (E). We illustrate below the generation of a typical tree species with L-systems.

L-systems are very easy to use to model the growth and structural complexity of the vegetation. This technique requires information on the actual structure of canopies, and in particular field observations of the frequency and angles of branching, the average length of shoots, etc.. The potential of L-systems to generate realistic-looking plants has been shown by many authors (e.g., Goel et al. 1991). More recently, Goel and Rozehnal (1991) have also explored some non-biological applications of the L-systems. However, when L-systems are used to generate plants for the purpose of canopy reflectance modeling, the requirement is not so much to represent realistic-looking plants as to produce plant architectures with realistic morphological properties. For example, a given L-system may produce a very realistic-looking tree but with a completely unrealistic LAI value. In the present case, the objective is not to reproduce explicitly a specific existing tree species but rather to create a generic tree obeying classification criteria corresponding to one of the 23 standard architectural models, i.e., Rauh’s model, which includes, among others, poplar trees, birch trees, pine trees and fruit trees of temperate regions (de Reffye et al. 1988). This model represents rhythmic orthotropic monopodial growth. Rhythmic growth results from seasonal climatic changes and produces shoots with an articulated branching process as shown in Figure (6.3A). The angular behavior of a branch or axis with respect to the bearing axis is an important parameter. It is plagiotropic if the development is mainly horizontal and orthotropic if the development is mainly vertical. A monopod is a ramified system which includes a unique main axis: the trunk.
the trunk produces two (in the middle part) or three (in the upper part) mother branches at each branching process

the mother branches produce two (in the middle part) or three (in the upper part) daughter branches at each branching process

the length of the trunk segments are shortened by a constant ratio with respect to the first segment

the sum of the mother branch diameters at every branching point is equal to the diameter of the trunk at this point

the growth of the trunk stops when the height defined by the growth function is reached

the growth of the mother branches stops when the length defined by the growth function is reached

the angle between the trunk and the mother branches decreases with height

the length of the daughter branches increases with respect to the distance from the trunk

the daughter branches produce a twig at each branching process

the twig produces a clump of 5 leaves at each branching process

Table 6.1: List of production rules used to define the L-system of the generic Rauh tree.

To take full advantage of parametric table oriented L-systems in our growth model, we divided our generic tree into three parts (Figure 6.3B). The lower one is composed of the bare trunk. The middle one is composed of sparse rather horizontal mother branches, and the upper one is composed of dense mother branches which become more vertical as we reach the top of the tree. Each part has its own growth unit which defines the frequency of the branching processes. The rhythmic growth of the tree is determined by the number of iterations used to derive the trunk (first order axis), the middle and upper part mother branches (second order axis), the daughter branches (third order axis) and the twigs (fourth order axis). The twigs produce the stems (fifth order axis) which bear the leaves with a plagiotropic phyllotaxy (Figure 6.3C). The production rules, summarized in Table (6.1), used to define the L-system have been established from observations of birch trees and adjusted in order to provide consistent LAI values and number of leaves. The branches are defined with cylinders and the leaves with triangles. Moreover, growth functions delimit the maximum horizontal and vertical development of the tree. The simplest, but quite arbitrary, way to represent plant growth is to use a sigmoidal function. The term *sigmoidal* refers to a function with a plot in the shape of the letter S. Such functions are commonly found in biological processes (Charles-Edwards et al. 1986). However, since we are more interested in producing adult plants than in modeling their actual growth mechanism, we have used logarithmic functions. These functions control the height of the three parts of the trunk (Figure 6.4A, solid line), the bottom radius of the trunk...
(Figure 6.4B), the vertically projected area of the tree (Figure 6.4C, solid line) and the area of the leaves (Figure 6.4D). The resulting number of leaves and LAI of our generic Rauh tree are given in Figure (6.4E and F). Figure (6.5) shows the silhouette of the tree at different ages.

Figure 6.4: Growth functions of the artificial Rauh’s tree. The solid lines represent free tree development, the dashed lines are for a tree in a medium tree density environment, the dotted-dashed ones are for a high tree density environment.

So far, the morphological properties apply to trees whose development may proceed with a minimum of disturbance. In contrast, in natural environments such as forests, tree growth may be modified due to stress conditions such as storms, climatic events, fires or crown density (Tomlinson 1983). To generate more complex scenes including several trees, their adaptation to the surrounding environment must be accounted for in the growth simulation processes. We introduced a new empirical parameter, $d_c$, to take into account the effects of surrounding trees: the denser the forest, the smaller the parameter. This parameter aims at empirically simulating the effect of changes in lighting conditions as a function of the density of the trees. When $d_c = 1$, the tree can grow without any constraint. The main effects of this parameter are to reduce the horizontal development of the tree and the total number of leaves (Figure 6.4C and E, dashed lines for a medium density; dotted-dashed line for a high density), as well as to increase the length of the bottom part and the growth unit in the middle part. We are thus able to control the effects of the tree density on the development of the individuals. Figure
(6.6) shows the effect of this parameter on different tree densities.

Despite its simplicity, such a model is capable of generating trees with realistic size, shape, LAI and number of leaves. Hence, L-systems can produce architecturally consistent trees. However, L-systems do not permit the evaluation of the functional significance of these trees. In the future, the implementation of mechanistic growth functions could represent a first step in this direction.

![Figure 6.5: Silhouette of the artificial Rauh’s tree at different ages.](image)

![Figure 6.6: Empirical representation of the effect of the tree density on the tree development.](image)

**6.5 Discussion**

These examples have demonstrated that it is conceptually possible to represent the architecture of an individual plant with a high level of realism. This kind of representation also permits the exploration of the contribution of the different plant components (trunk, branches, etc.) in a realistic environment where the soil properties can also be accurately described. In this context, L-systems offer attractive possibilities because of their flexibility and ease of implementation. However, the number of objects generated per tree is quite high, typically a few hundred thousand. The spatial extent of such scenes will therefore have to be limited. Clearly the heterogeneity, the number of structural parameters and the complexity of the environment increases with the size of the observed area. New techniques must be investigated in order
to represent canopy structural properties at a larger scale. A rational approach would consist of identifying elementary radiative units to represent the bulk plant canopy architecture at various scales, such as tree crowns, gaps, rows, plant shapes, or species arrangements, including the topography and landscape morphologies at larger scales. One of the main difficulties in describing a large scale canopy lies in the lack of parameterizations suitable for radiative transfer purposes. At the scale of a landscape, vegetation patterns can be characterized in terms of the statistical distribution of patch sizes and shapes, and by the spatial configuration of patches. With each spatial pattern, it is possible to associate quantitative measures, based on geometric indicators (e.g., fragmentation indices, distance metrics), fractals (e.g., perimeter/area indices), spectral analysis (Fourier transform), information theory (e.g., entropy, diversity, dominance or contagion indices), spatial statistics (e.g., autocorrelation tests, nearest neighbor probabilities), geostatistics (e.g., semivariograms), moving window operations (e.g., means, standard deviation), or mathematical morphology (Mayaux and Lambin 1995).

Only indirect methods can be used in practice to measure the canopy organization at this scale; they are based on different techniques according to the scale of investigation. At the scale of individual trees or plants, gap probability has recently generated a lot of interest (see for instance Andrieu et al. 1994; Chen et al. 1993; Martens et al. 1993; Smith et al. 1992; Whitmore et al. 1993). At the scale of species aggregation, fractal dimension measurements (e.g., Rigon et al. 1994; Vedyushkin 1994), or landscape fragmentation (e.g., Mayaux and Lambin 1995) have been explored. The representation of these geometrical arrangements is based either on a narrative description or, as we saw in the first section of this chapter, on functional vegetation models. The former methods rely on a detailed description of the vertical and horizontal distribution of the various plant canopy elements (see for instance Clinton et al. 1993; Koike and Syahbuddin 1993; Bourgeron 1983) and is limited to a specific studied area.

In summary, the accurate representation of the spatial organization of the canopy, as required for radiative transfer simulations with Raytran, is a very important issue, which needs further investigations and synergies between different fields to validate, from a morphological and physiological point of view, the generated plant architectures. The type and accuracy of the representation vary as a function of spatial scale. Although architectural models exist, they can provide fully consistent plant structure descriptions only if they correctly account for the physiological processes and their adaptation to the environmental conditions. In that respect, coupling of plant functional models with radiative transfer will permit the exploration of new avenues.

We have developed a three-dimensional radiative transfer model, evaluated its accuracy, and elaborated techniques to represent the canopy architecture. We therefore have a very powerful tool to address specific issues concerning the quantitative exploitation of remote sensing observations. In the next two chapters, we perform sensitivity studies to investigate the importance of the canopy architecture on the radiation transfer. We first explore an original method to measure the vertical biomass profile (Chapter 7). Next we suggest a strategy to evaluate the accuracy and suitability of retrieval procedures. This study is motivated by the problems resulting from the direct comparisons between ground measurements and satellite observations.
Chapter 7

Modeling new techniques of observation

7.1 Introduction

Remote sensing data on continental surfaces has been extensively exploited for target discrimination on the basis of classifications of linear combinations of spectral observations. A more ambitious utilization of radiometric measurements aims at quantifying one or more state variables of the observed systems, but this requires dedicated sensors and observations. For instance, the ATSR (Along Track Scanning Radiometer) instrument which flies on the ERS platforms has been specifically designed to measure the sea surface temperature using both the split-window and dual viewing angle technique to correct for the atmospheric scattering and absorption effects (Prata et al. 1990). On land surfaces, the design of relevant radiometers is much more difficult because of the complexity of the medium and the diversity of variables of interest at different spatial and temporal scales. The land use/cover change (LUCC) programme of the IGBP (IGBP 1992) typically requires low spatial ($\approx 10^6$ m$^2$) and temporal resolution data, but with a global coverage, while agricultural monitoring requires rather high spatial ($\approx 10^3$ m$^2$), spectral and temporal data on specific areas.

So far, the quantitative evaluation of vegetation properties from remote sensing data has largely been limited to the exploitation of detectors not specifically designed for land observations (e.g., NOAA-AVHRR) or which have been dedicated to target identification (e.g., Landsat). The spatial organization of the canopy is one of the crucial variables of interest in characterizing terrestrial environments. Indeed, canopy architecture is largely responsible for the anisotropy of the observed reflectances due to mutual shadowing effects. It should therefore be possible to retrieve canopy structure information from bidirectional reflectance measurements. In the case of homogeneous canopies, the inversion of physically-based models against bidirectional reflectance observations may provide some structural information such as the LAI or (LND) (e.g., Privette et al. 1994). However, this approach can be used only if the number of observations is much larger than the number of variables which characterize the state of the system (Pinty and Verstraete 1991). In practice, this technique may be
particularly difficult to apply in the case of complex canopy architectures because of the high number of parameters required to define the vegetation structure.

**In this chapter, we simulate the scattering of a laser pulse in the vegetation to investigate the potential of the laser altimetry technique to infer the spatial organization of the canopy.** Indeed, as suggested by Harding et al. (1994), the analysis of laser altimeter echo recovery (LAER) data should provide more straightforward information on canopy spatial organization, soil slope and roughness, at a global scale. The recent technological developments which have been carried out in this direction raise several questions, such as the effect of multiple scattering, the reliability of detecting canopy closure, the analysis of the returned pulse to retrieve physical parameters, etc. Indeed, as the reflecting medium becomes more complex, it becomes difficult to interpret the shape of the received signal. Consequently, the design of a high performance altimeter, as well as the prediction of its accuracy, are challenging. Modeling both the instrument response and the relevant radiative processes constitute the most rational approach to overcome these limitations. So far, most of the laser altimetry simulation efforts focused on a realistic representation of the instrument characteristics (e.g., Sun et al. 1993; Abshire et al. 1994) but neglected the accurate modeling of the laser pulse scattering processes at the reflecting surface. To investigate this specific aspect of the problem, we simulated, with Raytran, laser pulses reflected by a vegetated scene of different fractional covers. These sensitivity studies permit:

1. the exploration of the relationship between the altimeter performance, the canopy height and closure, and the vertical vegetation distribution;

2. the development of retrieval procedures to extract meaningful biophysical parameters.

**More generally, this study aims at demonstrating the role of accurate modeling activities in relation to instrument and retrieval algorithm design.** In that sense, our case study is an illustrative example of a modeling strategy to design a new instrument and the associated retrieval scheme, rather than a complete investigation of the LAER simulation problem. We first briefly describe the concept of the LAER instrument (Section 7.2) and how it has been modeled with Raytran (Section 7.3). The artificial scenes we used for this study are described in Section (7.4). In Section (7.5), we assess the performance of our simulated instrument to discriminate different forest types. Finally, we analyse the information conveyed by the reflected pulse to infer quantitative data on the structure of the canopy in Section (7.6).

### 7.2 Concept of laser altimeter echo recovery

The general principle of a laser altimeter (LA) is to measure the round trip travel time between the emission of a short-duration pulse and its detection by an instrument after reflection by a surface (Bufton 1989). A traditional LA detects the centroid of the received pulse without recording the actual echo resulting from the full backscattering history. Laser altimetry has been used to measure important geophysical phenomena, such as solid Earth tides (Gardner 1982) and planetary surface topography (e.g., Zuber et al. 1992; Zuber et al. 1994). An
improvement on this technique consists of digitizing the complete time distribution of the returned pulse energy (or waveform) that results from the reflection of the laser pulse from multiple scatterers located at varying heights within the canopy, as illustrated in Figure (7.1) (Blair et al. 1994). This waveform conveys information on the vertical distribution of vegetation canopy components and the underlying ground height distribution (Harding et al. 1995). The accuracy of the echo recovery method is governed by the characteristics of the laser pulse, the observation geometry and the performance of the detector (Gardner 1992).

1. *The laser source.* The laser provides the radiation flux to generate the pulse. Significant parameters include the laser energy and wavelength, the beam divergence and the pulse shape. Laser energy depends mainly on the available on-board power supply and the laser pulse rate. The typical surface roughness and reflectivity dictate the required pulse intensity which, in any case, must be greater than the detected solar radiation if the instrument is to be used during the day. The divergence of the beam is an important parameter that controls, for a given instrument altitude, the laser beam footprint size on the soil. Ideally, the transmitted pulse should be square-shaped to facilitate the measurement analysis and very short in time to ensure a high accuracy estimation of the photon travel time. In practice, gain switched solid-state lasers can generate nearly Gaussian-shaped pulses with a duration of a few nanoseconds\(^1\). High peak power and the fast rise time of the front edge are the key performance features of a laser transmitter (Blair et al. 1994). When emitted in the visible spectral region, a pulse is strongly absorbed by the vegetation, but the reflected signal results almost exclusively from single scattering. On the contrary, in the NIR spectral region, a pulse may penetrate deeper into the canopy but the returned waveform is affected by multiple scattering.

2. *Measurement geometry.* The instrument altitude and the pointing angle are the relevant parameters of the observation geometry. Both control the footprint size. In the case of small footprints, the waveform is very sensitive to individual tree crowns. Conversely, for large footprints, the soil and the top of canopy signal may be mixed up, due to local topography or slope effects. Any error in laser pointing angles shifts the round-trip time and therefore the estimated distance between the sensor and the surface. This error can be positive or negative according to the relative offset of the pointing direction and the surface slope (Harding et al. 1994). However, the canopy height retrieval should not be significantly affected by this inaccuracy.

\(1\)One nanosecond corresponds to a distance of 29.97925 cm for photons travelling in the vacuum.
3. *The receiver.* Important features for the receiver design concern the telescope aperture and field-of-view, the detector filter bandwidth, gain, noise and the sampling rate of the digitizer (Sun et al. 1992). The reflected pulse is received by the telescope whose field-of-view should include the laser footprint. The waveform is focused onto a bandpass filter which transmits it to a detector. The detector output current is sampled at regular time intervals by the digitizer. The detected signal is affected by several different sources of noise: The reflected pulse (optical waveform) is contaminated by the ambient solar radiation while the detector output is contaminated by the dark current and thermal noise (Robinson and DeWitt 1983). Finally, the analog/digital (A/D) converter which delivers the "digitized waveform" may introduce quantization noise.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Units</th>
<th>Symbols</th>
<th>SLICER</th>
<th>LASIM</th>
<th>Raytran</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulse energy</td>
<td>mJ</td>
<td>$E_l$</td>
<td>350</td>
<td>40</td>
<td>–</td>
</tr>
<tr>
<td>Leading-edge rise time</td>
<td>ns</td>
<td>$T_l$</td>
<td>1.5</td>
<td>1.5</td>
<td>2.</td>
</tr>
<tr>
<td>Footprint diameter</td>
<td>m</td>
<td>$D_l$</td>
<td>10</td>
<td>–</td>
<td>25</td>
</tr>
<tr>
<td>Footprint area</td>
<td>m$^2$</td>
<td>$A_l$</td>
<td>79</td>
<td>–</td>
<td>491</td>
</tr>
<tr>
<td>Laser beam divergence</td>
<td>mrad</td>
<td>$F_l$</td>
<td>1.5</td>
<td>–</td>
<td>0.67</td>
</tr>
<tr>
<td>Telescope diameter</td>
<td>m</td>
<td>$D_t$</td>
<td>0.38</td>
<td>0.5</td>
<td>200</td>
</tr>
<tr>
<td>Telescope area</td>
<td>m$^2$</td>
<td>$A_t$</td>
<td>0.11</td>
<td>0.196</td>
<td>31416</td>
</tr>
<tr>
<td>Telescope altitude</td>
<td>m</td>
<td>$H_t$</td>
<td>6,700</td>
<td>250,000</td>
<td>30,000</td>
</tr>
<tr>
<td>Telescope solid angle</td>
<td>psr</td>
<td>$W_t$</td>
<td>2,525</td>
<td>3.14</td>
<td>34906</td>
</tr>
<tr>
<td>Telescope FOV</td>
<td>mrad</td>
<td>$F_t$</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Digitizer resolution</td>
<td>ns</td>
<td>$T_d$</td>
<td>1.54</td>
<td>1.33</td>
<td>–</td>
</tr>
<tr>
<td>Digitizer dynamic range</td>
<td>bits</td>
<td>$R_d$</td>
<td>0.22</td>
<td>0.2</td>
<td>0.2</td>
</tr>
</tbody>
</table>

Table 7.1: Laser altimeter sensor characteristics. See text for explanations regarding the characteristics of the Raytran simulator.

Aircraft altimetry has a long history of development and applications. The first space-borne LA flew successfully on the APOLLO 17 Command and Service Module in Lunar orbit in the early seventies. Geophysical applications such as volcano monitoring, ice sheet topography or sea state monitoring are always based on returned pulse centroid detection. Aldred and Bonnor (1985) pioneered measurement of the canopy structure with the LAER method. Since 1992, a SLICER (Scanning Lidography of Canopies by Echo Recovery) instrument has been developed at the NASA Goddard Space Flight Center and allows a very high resolution recovery of the backscattered pulse (Harding et al. 1994, Blair et al. 1994). It is a multiple shot LAER system, based on an in-house designed Q-switched laser which provides a 1.5 ns leading edge. The laser delivers a 350 mJ pulse at 1.064 µm (NIR). The internal detector electronics measure the clock time with a precision of 156.25 ps (2 cm). The reflected pulse, received by a 38 cm diameter telescope, is focused through a 2nm bandpass filter onto a 1 mm diameter Silicon Avalanche photodiode (Si APD). The waveform digitizer records the returned signal with a
7.2. CONCEPT OF LASER ALTIMETER ECHO RECOVERY

A sampling interval of 1.5 ns which provides a 22 cm spatial vertical resolution. The digitizer is started when the received energy exceeds a predefined threshold value. The characteristics of the altimeter are summarized in Table (7.1).

![Image](figure7.2.jpg)

Figure 7.2: April 1995 view of the test site in Edgewater, Maryland, managed by the Smithsonian Environmental Research Center.

The instrument has already produced successful airborne measurements on different test sites at an altitude of 6700 m. These observations have established the feasibility of measuring the canopy height and assessing the effects of the slope and roughness of the soil. Canopies with more than 90% coverage showed clear double-pulsing waveforms, as well as canopies with a greater fraction of exposed underlying terrain. The instrument is able to accommodate a large dynamic range of return signals with a sufficiently short and powerful laser output pulse, such that small amounts (< 5%) of exposed ground beneath a dense canopy can be detected (Harding et al. 1994). Due to the vertical uncertainty of 1 m resulting from the pulse width, the LAER method is limited to rather high canopies. Weltz et al. (1994) investigated the potential of using a classical LA to measure the canopy height of low vegetation, with a resolution < 0.3 m. The observations were carried out from a small aircraft flying at an altitude of 150 m. The altimeter operated with a very small footprint such that the laser fired either at a plant or at the soil. This technique provides a detailed canopy height profile along the airplane trajectory where each plant appears individually.

In January 1996, the Shuttle Laser Altimeter (SLA-1) instrument is to be flown on the Space Shuttle (STS-72): it will be the first space-borne instrument with complete waveform digitization. An improved version of this first orbital LAER is scheduled to fly on the Space Shuttle in 1997 and will include two wavelengths, one in the visible and one in the NIR spectral region. These two short duration experimental flights will be followed by the GLAS.

\[\text{Dave Harding, personal communication.}\]
(Geoscience Laser Altimeter System) instrument, a two wavelengths LA which is foreseen on a polar orbiting EOS platform (Cohen et al. 1987; Abshire et al. 1994).

Figure 7.3: Waveform profile measured with the SLICER instrument over a deciduous forest. The dashed line represents the noise level.

The LA technique has been originally developed to assess the range of the instrument from the observed surface, considering the soil roughness or the vegetation as undesirable perturbations. Consequently, the actual possibilities of extracting quantitative information on vegetation structure from waveform analysis has not been intensively investigated and only limited efforts have been undertaken to develop algorithms to retrieve meaningful biophysical parameters from the LAER method. The Laboratory for Terrestrial Physics at the NASA Goddard Space Flight Center has planned several airborne observations, on well documented sites, in order to study the relationship between the waveform shapes and the corresponding vegetation parameters. In April 1995, we participated in a Global Postioning System (GPS) field measurement campaign on one of these forest sites in Edgewater, Maryland, managed by the Smithsonian Environmental Research Center (Figure 7.2). Figure (7.3) shows a waveform recorded on this site in September 1995. The dash-dotted line indicates the level of the noise recorded before the increase due to the detection of the top of the canopy. The peaks due to the tree crowns and the ground appear clearly and illustrate the potential of the method for forest monitoring.
7.3 Raytran simulation of the LAER principle

Further investigations are needed to analyze precisely the relationship between the waveform shapes and the canopy LAD profiles as well as the possibility of using this method from a space-borne platform. To answer these questions, the LAER principle has been modeled over different forest densities. Raytran is used to model the reflection of a Gaussian-shaped laser pulse and its successive interception by a telescope. The simulated optical waveform is used to estimate the number of photons that would be detected by the LA instrument electronics on a space-borne platform. Next, we studied the effects of the multiple scattering on the waveform and then the type of algorithm that should be developed to extract quantitative information from these waveforms. The Raytran simulations are based on the following configuration.

- **Laser.** We assume a point source laser with a divergence of 0.67 mrad such that the footprint illuminated area is large enough to avoid the effects of local horizontal heterogeneities due to the fractional cover. The beam section is assumed uniform with respect to the beam center and its origin is located in the center of the telescope’s mirror. The laser pulse has a Gaussian shape corresponding to a length of 1.2 m when seen over a dynamic range of 200:1.

- **Geometry.** The laser is nadir pointing. The instrument altitude is arbitrarily located at 30,000 m above the soil. The main reason for this configuration is to avoid dealing with numbers too large or too small with respect to the scatterer size (typically $\approx 10^{-2}$ m) which may introduce inaccuracies in the computation of the ray-object intersection points.

- **Telescope.** Raytran is primarily designed to compute the BRF of the whole hemisphere and its Monte Carlo scheme is not optimized to simulate very small instrument apertures. To capture enough reflected rays, we had to increase the simulated telescope’s aperture. Sensitivity studies which decrease the aperture down to a few meters and increase the number of emitted rays to $3.5 \times 10^9$, show that, with an aperture of 200 m and a FOV of 2 mrad, the computed reflectance is underestimated by about 10% and the contribution of the multiple scattering in the NIR is overestimated by 5%. The maximum increase of ray travel time due to the telescope aperture being to large is 0.5 ns. The optical waveform is simply conceptualized as an array of fixed length. Each time a reflected ray reaches the telescope mirror and within its field-of-view, a vector element is incremented by one. The index of the vector element is calculated by dividing half of the total ray path length in the canopy by $R_d$.

Orbital laser altimeters for Earth observation could basically fly at three different altitudes depending on the type of space-borne platform: the Space Shuttle (250 km), the space station (400 km), or a sun-synchronous polar satellite (800 km). The characteristics of a typical orbital LA, referred to here as LASIM (Table 7.1), have been considered and correspond to mean standard values for a space-borne altimeter (Gardner 1992).

The telescope mirror receives a radiant flux $\Phi = dQ/dt \text{ [W]}$ which is the radiant energy $Q \text{ [J]}$ arriving within a unit of time $\text{[s]}$ in front of the mirror and within the field-of-view. The
total radiant energy which is intercepted by the mirror in the time interval $\Delta t_n = t_n + \Delta t$ is

$$Q_{\Delta t_n} = \int_{t_n}^{t_n+\Delta t} \Phi(t_n') \, dt$$

(7.1)

and corresponds to the number $N_{\Delta t_n}$ of rays which are reflected within the solid angle $W_t$ during this time interval. $t_n'$ is the mid-time of the time interval and is equal to $t_n + \Delta t/2$. If $N$ is the total number of emitted rays used to simulate the transmitted pulse, the corresponding number of photons $N_w$ originating from the reflection of the emitted pulse, which reach the telescope during the time interval $\Delta t_n$ may be estimated as

$$N_{w\Delta t_n} = \frac{E_l}{h\nu} \frac{N_{\Delta t_n} \tau_{atm}^2}{N}$$

(7.2)

where $E_l$ in the laser pulse energy and $\tau_{atm}$ is the atmospheric transmissivity, neglecting the contribution of the sky radiance. The radiant energy may be expressed per unit solid angle as $M_{\Delta t_n} = Q_{\Delta t_n} H_l^2 / A_t$. Hence, this relationship can be used to estimate the number of photons which would reach the LASIM telescope

$$N_{ph(LASIM)\Delta t_n} = \frac{E_l}{h\nu} \frac{N_{\Delta t_n} \tau_{atm}^2}{N} \frac{W_t(LASIM)}{W_t(Raytran)} \gamma$$

(7.3)

where $\gamma = 1.1$ accounts for the large aperture effects of Raytran.

A simple, relative representation of the recorded signal consists of dividing the received energy during each time interval $\Delta t$ by the total energy received between the time $t_0$ corresponding to the detection of the top of the canopy and a predefined record time duration $t_r$

$$\bar{Q}_{\Delta t_n} = \frac{\int_{t_n}^{t_n+\Delta t} \Phi(t_n') \, dt}{\int_{t_0}^{t'} \Phi(t_n') \, dt}$$

(7.4)

Such an expression is useful to study the distribution of the received energy.

### 7.4 Description of the test scenes

The sensitivity studies we want to carry out require the description of scenes for which the vertical and horizontal spatial distribution of the scatterers is known for different fractional covers $\sigma_f$ and vertical LAD. L-system trees described in Chapter (6) have been used to generate an artificial forest. Four different forest densities with fractional cover ranging from 0.45 to 0.9 have been simulated. The fractional cover is simply the ratio of the projected area of the plant on the soil to the area of the soil. For a given forest fractional cover, the empirical density coefficient $d_c$ which accounts for the space and light available for the tree growth has been adjusted in order to set the forest LAI to the desired value. To generate forest scenes, trees are randomly located in a square sampling area until the requested fractional cover is reached. The process starts with the oldest trees (25 years in this case), decreasing progressively the age of the trees, in order to better occupy the space between them with younger and hence smaller ones. The resulting fractional cover is controlled with a $z$-buffer algorithm (Foley et al.
7.5. ESTIMATION OF THE SIMULATED LA PERFORMANCES

<table>
<thead>
<tr>
<th>Name</th>
<th>Side</th>
<th>$\sigma_f$</th>
<th>$d_c$</th>
<th>LAI$_{tree}$</th>
<th>LND</th>
<th>Trunks$/10^4$m$^2$</th>
<th>Height</th>
</tr>
</thead>
<tbody>
<tr>
<td>F45</td>
<td>50.</td>
<td>0.45</td>
<td>1.</td>
<td>2.15</td>
<td>erectophile</td>
<td>128</td>
<td>17</td>
</tr>
<tr>
<td>F60</td>
<td>40.</td>
<td>0.60</td>
<td>0.9</td>
<td>2.90</td>
<td>erectophile</td>
<td>219</td>
<td>19</td>
</tr>
<tr>
<td>F75</td>
<td>30.</td>
<td>0.75</td>
<td>0.8</td>
<td>3.05</td>
<td>erectophile</td>
<td>344</td>
<td>20</td>
</tr>
<tr>
<td>F90</td>
<td>25.</td>
<td>0.90</td>
<td>0.6</td>
<td>3.60</td>
<td>erectophile</td>
<td>1010</td>
<td>20</td>
</tr>
</tbody>
</table>

Table 7.2: Characteristics of the different test scenes. LAI$_{tree}$ represents the LAI of tree leaves. The side length of the different scenes and the corresponding maximum height are given in meters. $d_c$ is the empirical density effect coefficient. $\sigma_f$ is the fractional cover.

1990). The side length for each forest type has been chosen such that the sample area has more than 30 trees. We assume a horizontally infinite scene. The values corresponding to the different forest densities are given in Table (7.2).

Graphtal$^{3}$ has been used to generate the trees from the production rules we defined in Chapter (6). It permits the definition of context-free, table-oriented L-systems with stochastic production rules. This software produces an output compatible with Raytran geometric primitives. For example, a 20 year old tree, described following the rules of Table (6.1), is represented with 289,280 different geometric primitives. To save memory space and computer time, we reduced the number of objects used to describe each tree: Daughter branches, twigs and stems were not included in the scene and the clumping of 5 leaves has been replaced by a single leaf of equivalent area. Sensitivity tests have shown that the difference between the hemispherical reflectance of the original tree and the simplified one is less than 1%. The accuracy of the representation of the artificial canopy has not been fully investigated but it offers the realistic clumping effects required for this study. Figure (7.4A) shows the vertical LAD of the different generated scenes.

The ground is assumed to be a “green soil” for forests with fractional cover between 0.45 and 0.75 and a bare soil for scene F90. In order not to complicate the scenes and the number of possible parameter combinations, we did not include any understory and assumed that all surfaces are Lambertian. The values of the spectral parameters of the soil, branches and leaves are given in Table 7.3. Figure (7.4B and C) show the dependence between the absorbed radiation for scene F45 and F90 and the SZA and illustrate clearly the importance of complex canopy architecture in plant radiation regimes. Such features are not observed over homogeneous canopies (Pinter 1993).

7.5 Estimation of the simulated LA performances

Previous LAER airborne observations have clearly shown the possibility of retrieving the canopy height over forested areas (Harding et al. 1994), even for fractional covers up to 90%, using a laser oscillating at 1.06 $\mu$m. In Section (7.2), we saw that a LA with a full echo recovery

$^{3}$Graphtal is a public domain software developed by C. Streit in 1992, available on the anonymous ftp server iamsun.unibe.ch.
CHAPTER 7. MODELING NEW TECHNIQUES OF OBSERVATION

<table>
<thead>
<tr>
<th>Element</th>
<th>RED</th>
<th></th>
<th></th>
<th></th>
<th>NIR</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Ground under F45</td>
<td>0.08</td>
<td>0.0</td>
<td>0.35</td>
<td>0.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ground under F60</td>
<td>0.08</td>
<td>0.0</td>
<td>0.35</td>
<td>0.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ground under F75</td>
<td>0.08</td>
<td>0.0</td>
<td>0.30</td>
<td>0.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ground under F90</td>
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<td>0.0</td>
<td>0.20</td>
<td>0.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Trunk and branches</td>
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<td>0.0</td>
<td>0.3</td>
<td>0</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Leaves</td>
<td>0.06</td>
<td>0.05</td>
<td>0.5</td>
<td>0.45</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 7.3: Spectral values for the various elements of the scenes ($\rho =$ reflectance; $\tau =$ transmittance).

will fly for the first time on the Space Shuttle. Only rough estimations of the intensity of the reflected pulse on the vegetated surfaces have been used to design this instrument.

7.5.1 Estimation of the energy which reaches the LA

Before studying in detail the radiation transfer processes of the propagation of a laser pulse in the vegetation, we will to assess as precisely as possible the actual number of photons which would reach a space-borne LA, in order to estimate the sensitivity of the measurements needed to discriminate different types of forest closure. Since the soil of the test scenes is perfectly flat, it represents an ideal situation for which we should get the best possible results. Raytran simulations have been carried out in the red and NIR spectral region with a nadir looking altimeter.

A first look at the results (Figures 7.5 and 7.6) shows the differences in the dynamics of the recorded signal. In the red spectral region, the waveform conveys a clearer return peak from the soil even for scene F90. This is due to the fact that the soil is generally relatively brighter than leaves in the visible spectral region. In the NIR region, the signal is smoothed by the multiple scattering and the peak returned by the soil is weaker due to its relatively lower reflectance. Raytran reproduces the double-pulsing waveforms as observed from real measurements (7.3).

As explained in Section (7.2), the waveform digitizer data stream starts when the received flux exceeds a threshold value $\iota$. Obviously, this detection does not correspond to the reflection of the laser pulse by the very highest leaf sticking up above the canopy but by the region where the LAD rapidly rises as can be seen on Figure (7.4A). For fractional covers greater than 0.5 the signal is very clear, while for scene F45 the detection of the tree’s presence will strongly depend upon the altimeter performance. Referring again to Figure (7.3), it can be seen that the level of noise in the waveform is relatively high with respect to the effective signal. In the rest of this section, we will investigate in more detail the relationship between the signal noise and the effective signal.

Equation (7.3) estimates the number of photons reaching the telescope as a function of the pulse energy, footprint area, telescope aperture and altitude. One-way atmospheric transmissivity in the NIR spectral region typically varies between 0.45 and 0.8 (Vermote et al.
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Assuming a transmissivity of 0.5 (Harding et al. 1994), the total number of photons in the returned pulse, received during the period $t_0 - t_r$, is approximately 4000 for the different forests in the case of the Space Shuttle orbit. This figure is consistent with values generally estimated for space-borne LA (see e.g., Cohen et al. 1987). Assuming a 1.3 ns digitizer integration time $T_d$, the maximum echo returned by the trees of scene F45 is equal to $N_{w\Delta t} = 45$ photons for the Space Shuttle orbit but drops to less than one in the case of a polar orbit. Increasing the digitizer sampling time by a factor of 5 and the laser pulse energy by a factor of 10, the number of received photons on a polar orbit remains less than 5, even in the case of dense forest. Therefore, we will exclusively consider the Space Shuttle orbit, focusing on the possibility of detecting the peak in the laser pulse reflected from a low forest closure in the NIR spectral region.

The number of photons which effectively illuminate the detector depends on the solar radiation background (external noise) and the optical system transmissivity $\tau_{sys}$. The number of photons originating from solar radiation is a function of the time, the location on the Earth and is controlled by the bandwidth $B_{\lambda}$ of the instrument filter. The number of photons due to background solar radiation reaching the telescope during the time interval $\Delta t$ may be estimated as (Cohen et al. 1987)

$$N_{s\Delta t} = \frac{E_s}{h\nu} A_l \tau_{atm}^2 B_{\lambda} \frac{r_{surf}}{\pi} \frac{A_t}{H^2} \Delta t. \quad (7.5)$$

The exo-atmospheric solar spectral irradiance $E_s$ in the NIR region is approximately $10^{-2}$ Wm$^{-2}$nm$^{-1}$. The surface reflectance $r_{surf}$ is given by Raytran and is about 0.4 for the F45 scene. In the case of the space shuttle orbit, $N_{s\Delta t}$ is about 0.15 photons per nanosecond. The value we estimated is in agreement with previously estimated values (Cohen et al. 1987; Bufton 1989; Harding et al. 1994). $N_{s\Delta t}$ defines the theoretical minimum possible detectable optical echo. Therefore the number of photons from the solar radiation which illuminate the telescope is much smaller than the number of photons originating from the reflection of the pulse and is obviously not the main source of noise.

If a detector is irradiated with a constant flux, the output current is not constant but presents unpredictable fluctuations which are referred to as noise and this limits the accuracy of the detector. We now need to compare the value $N_{w\Delta t}$ with the typical noise level of a LA instrument electronics.

7.5.2 Estimation of the probability of an echo detection

The LA detector responsetivity is defined as the ratio between the incoming radiation flux and the output analog signal strength that gets recorded by the digitizer. The detector responsive quantum efficiency $\eta$ determines the ratio between the number of detected and received photons (Slater 1980). The efficiency of the detector and the linearity of the response over the dynamic range of the return energy depends on the type of detector; typically a photomultiplier tube or a photodiode. In the first case, collected photons are emitted into a vacuum or gas and multiplied by successive electrodes while in the second case, incident photons interact directly with the electronic energy levels of the detector material to produce free charges carriers. Since photomultipliers are more sensitive to the recent history of the input signal (Robinson
and DeWitt 1983) and have a lower efficiency at the 1.06 µm wavelength, Silicon avalanche photodiodes (Si APD) are generally used in laser altimetry.

The total number of photons which will effectively be transformed into free electrons (now referred to as “photo-electrons”) during the elementary integration time is $N_{wd\Delta t} = N_{w\Delta t}\tau_{sys}\eta$ for the waveform and $N_{sd\Delta t} = N_{s\Delta t}\tau_{sys}\eta$ for the solar radiation contribution. Typical values for the system optics transmissivity is 0.5 and 0.4 for the detector quantum efficiency which gives $\sim 10$ photo-electrons in the case of the Space Shuttle orbit. The 10 photo-electrons will be detected by the digitizer data stream if the corresponding output current is above the receiver threshold value $\iota$. This threshold value is determined according to the signal-to-noise ratio (SNR) of the instrument. Hence, estimation of the noise is necessary in order to establish the sensor’s performance in detecting a small variation in the incoming flux. This noise is responsible for erroneous detections of the echo, namely false alarm detection and miss detection. A false alarm occurs when the noise produces a peak in the output signal whose intensity exceeds the value $\iota$. A detector contributes both to the dark current (output current when the incoming radiation flux is equal to zero) and the multiplicative excess noise due to the randomness of the detector gain $G$ (Sun et al. 1992). The Si APD dark current is composed of the surface leakage current and the bulk leakage current. The first one occurs before the gain and is due to surface irregularities and contact noise. The second one results from quantum effects i.e., current pulses produced by individual electrons and/or holes when an electric current flows across a potential barrier (Slater 1980). In addition, the random motion of charge carriers in a resistive element (the pre-amplifier) gives rise to a random electrical voltage called the thermal noise. Detailed descriptions and formulations of these different effects can be found in Gardner (1992) and Sun et al. (1993). These noise effects can be expressed in a number of equivalent electrons (or electrical charges) as

\begin{align*}
N_{surf\Delta t} &= \frac{I_{s\Delta t}}{q} \quad \text{surface leakage current} \\
N_{bulk\Delta t} &= \frac{I_{b\Delta t}}{q} \quad \text{bulk leakage current} \\
N_{thi\Delta t} &= \frac{2K_BT_e\Delta t}{q^2R_L} \quad \text{thermal noise}
\end{align*}

(7.6)

where $K_B = 1.380658 \times 10^{-23}$ [JK$^{-1}$] is the Boltzman constant and $q$ is the electron charge 1.60$\times$10$^{-19}$ C. The other parameters are given in Table (7.4). Several models have been proposed to approximate the forms of the output current produced by a Si APD detector (Sun et al. 1992). For the present analysis, we will assume that the output signal of the detector has a Gaussian random variation resulting from the noise. Therefore, the mean number of electrical charges which account for the detector output current after the gain is

\begin{equation}
\langle N_{G\Delta t} \rangle = (N_{wd\Delta t} + N_{sd\Delta t} + N_{bulk\Delta t}) G
\end{equation}

(7.7)

and the corresponding standard deviation is

\begin{equation}
s_{\langle N_{G\Delta t} \rangle} = \sqrt{\text{Var}(\langle N_{G\Delta t} \rangle)} = \sqrt{(N_{wd\Delta t} + N_{sd\Delta t} + N_{bulk\Delta t})FG^2 + N_{surf\Delta t} + N_{thi\Delta t}}
\end{equation}

(7.8)

where $F$ is the Si APD multiplicative excess noise factor. The probability $P_{\text{ms}}$ that the signal $\langle N_{G\Delta t} \rangle$ is not detected is (Bufton 1989)

\begin{equation}
P(\langle N_{G\Delta t} \rangle < N) = \frac{1}{\sigma_{\langle N_{G\Delta t} \rangle}\sqrt{2\pi}} \int_{-\infty}^N \exp \left[ -\frac{1}{2} \left( \frac{t - \langle N_{G\Delta t} \rangle}{\sigma_{\langle N_{G\Delta t} \rangle}} \right)^2 \right] dt
\end{equation}

(7.9)
7.5. ESTIMATION OF THE SIMULATED LA PERFORMANCES

### Table 7.4: Typical values for a Si APD after Sun et al. (1992).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si APD surface leakage current</td>
<td>$I_s$</td>
<td>12 nA</td>
</tr>
<tr>
<td>Si APD bulk leakage current</td>
<td>$I_b$</td>
<td>0.1 pA</td>
</tr>
<tr>
<td>Si APD load resistance</td>
<td>$R_L$</td>
<td>2000 Ω</td>
</tr>
<tr>
<td>Equivalent noise temperature</td>
<td>$T_e$</td>
<td>400°K</td>
</tr>
</tbody>
</table>

or

$$P_{ms} = 1/2 + \frac{\text{erf}}{2} \left( \frac{N_i - \langle N_{G\Delta t} \rangle}{\sqrt{2\sigma_{\langle N_{G\Delta t} \rangle}}} \right)$$  \hspace{1cm} (7.10)

where $N_i$ is the threshold value expressed as the number of electrical charges. In the same way, the probability $P_{fa}$ of a false alarm triggering due to the noise is

$$P(N_{G\Delta t} = 0 > N_i) = \frac{1}{\sigma_{\langle N_{G\Delta t} \rangle} \sqrt{2\pi}} \int_{N_i}^{\infty} \exp \left[ -\frac{1}{2} \left( \frac{t}{\sigma_{\langle N_{G\Delta t} \rangle}} \right)^2 \right] dt$$  \hspace{1cm} (7.11)

or

$$P_{fa} = 1/2 - \frac{\text{erf}}{2} \left( \frac{N_i}{\sqrt{2\sigma_{\langle N_{G\Delta t} \rangle}}} \right)$$  \hspace{1cm} (7.12)

The threshold value $N_i$ is generally chosen such that $N_i$ is few percent greater than the mean value of the instrument noise. Using the values given in Table (7.4) and assuming that $N_i$ is 10% greater than the mean instrument noise, forest F45 will be missed with a probability of $P_{ms} = 11\%$. According to Bufton (1989), a value of $10^{-3}$ for $P_{ms}$ is acceptable in laser altimetry operations. To detect scene F45 by applying this criterion, it is necessary to increase the digitizer resolution up to 6 ns, a value very close to the actual performance of the SLA altimeter. As noted by Sun et al. (1992), the assumption of a Gaussian distribution of the noise is not very accurate and predicts rather optimistic results. Consequently, even at this vertical resolution, the probability of getting a double-pulsed waveform for scene F45 is not ensured.

The received signal of the red waveform over the F45 forest rises rapidly from a relatively low level up to a very high level due to the soil return. So far, we have not included the effect of the dynamics of the digitizer. Consider an A/D converter which provides a digitized output of $n_d$ bits and $N_{mx}$ the maximum number of electrical charges outputs by the detector. Then, the minimum theoretical detectable echo is given by $N_{mx}/2^{n_d}$. The ratio between the maximum signal of the trees and the maximum of the soil return for this waveform is about 20:1 but only 12:1 in the case of the NIR waveform. For scene F60, the ratio is 10:1 in the red and 4:1 in the NIR. Scene F45 and F60 have the same optical properties and the difference in LAI values is 0.75. The difference in the ratio of scene F45 and F60 in the red is high with respect to the difference in the LAI values. This difference results mainly from horizontal clumping effects as will be investigated in Section (7.6.2).

The LAER method on vegetated surfaces should be envisioned as a potential tool to monitor forests. We saw that the amount of energy which needed to be detected is extremely low,
CHAPTER 7. MODELING NEW TECHNIQUES OF OBSERVATION

in the range of a few tens of photons. This method requires therefore very efficient detectors. Moreover, the design of a good LA is extremely complex due to the very high number of different parameters which can be controlled: laser shot frequency, laser pulse energy, laser beam divergence, telescope mirror radius, detector gain, digitizer sampling time, etc. The optimal settings for these parameters depend on the type of surfaces, e.g., ocean, ice, vegetation, which are observed. The return pulse shape and intensity is indeed completely different for these different media. In this section, we shown how Raytran can be used to simulate waveforms corresponding to different forest densities. In addition, we performed a very simple analysis to estimate the corresponding number of photons which would reach our simulated instrument.

7.6 Analysis of the waveform signal

We now investigate the possibility of extracting relevant parameters on the spatial organization of the canopy by interpreting the waveforms. The airborne observations have clearly shown the sensitivity of the waveform shape to the vertical profile of the vegetation density as it appears in Figure (7.3). This study explores how this information is exactly conveyed by the waveform and analyses the method to be developed to extract this information. The waveform provides a time distribution of the reflected pulse at varying heights in the canopy. Therefore, this temporal information should first be converted into a spatial information, establishing the relationship between the photon travel time and the depth of the last interaction in the canopy. Next, we explore the potential of radiation transfer theory to describe the propagation of the pulse in the canopy and thereby extract relevant parameters by inversion of a physically-based radiative transfer model. This latter analysis assumes a perfect instrument.

7.6.1 Space - time correspondence

We analyse now the relation between a photon travel time and its depth of interaction in the canopy. The waveform profile gives the number of intercepted photons as a function of their trajectory duration. To infer information on the vertical biomass distribution in the canopy, the photon travel time has to be converted into a path length. Consider a photon reaching the telescope after reflection from a leaf located at a height $z_l$ from the soil level and at a horizontal distance $x_l$ from the center of the footprint. Assuming that the photon path in the canopy is limited to a single interaction, the round trip time $t_{ps}$ between the altimeter and the interaction point is given by

$$t_{ps} = \frac{2\sqrt{(H_t - z_l)^2 + x_l^2}}{c}.$$  

(7.13)

where $H_t$ is the canopy height. The estimated height $z_l'$ assigned to the photon interaction in the canopy is given by

$$z_l' = H_t - \frac{ct_{ps}}{2}.$$  

(7.14)

In the case of a nadir observation with the LASIM instrument, the difference between $z_l$ and $z_l'$ is of the order $10^{-3}$ m such that $z_l \simeq z_l'$ is a very good approximation. If the photon
Table 7.5: Total multiple scattering contribution as percent of the returned waveform.

<table>
<thead>
<tr>
<th>Scene</th>
<th>VIS</th>
<th>NIR</th>
</tr>
</thead>
<tbody>
<tr>
<td>F45</td>
<td>1.6</td>
<td>30</td>
</tr>
<tr>
<td>F60</td>
<td>2.8</td>
<td>38</td>
</tr>
<tr>
<td>F75</td>
<td>3.3</td>
<td>40</td>
</tr>
<tr>
<td>F90</td>
<td>2.6</td>
<td>42</td>
</tr>
</tbody>
</table>

Table 7.5: Total multiple scattering contribution as percent of the returned waveform.

has interacted several times before escaping from the canopy in the direction of the telescope, the total travel time \( t_{pt} \) is increased to \( t_{pt} = t_{ps} + t_{pm} \), where \( t_{pm} \) is the extra time due to the multiple scattering. Therefore, \( z'_l \) may now be written as

\[
    z'_l = H_t - \frac{c(t_{ps} + t_{pm})}{2}.
\]

(7.15)

Clearly, as \( t_{pm} \) increases, \( z'_l \) decreases. As a consequence, the photon seems to originate from a shifted height \( \Delta z'_l = c t_{pm} / 2 \) deeper in the canopy. In fact, whatever the direction of the instrument, the telescope is always observing the hot spot, as is shown in Figure (7.7A). This observation geometry is optimum for LAER measurements since the hot spot corresponds to the viewing direction where the number of interactions is a minimum (Figure 7.7B). The mean number of ray interactions in the hot spot direction is estimated as 2.5 for the denser scene (F90). The corresponding increase in path length will depend on the mean distance between the scatterers and the heterogeneity of the canopy structure. Basically, vegetation with high LAD generates more multiple scattering in the NIR but with relatively short photon mean free paths. Conversely, in sparse canopies, the multiple scattering contribution will be relatively lower but with longer photon mean free paths. In addition, the presence of gaps in the canopy tends to increase tremendously the path length between two interactions. To estimate the importance of \( \Delta z'_l \), we calculated, with Raytran, the contribution due to the multiple scattering in the optical waveform, for the different forest fractional covers. These computations show that, in the red spectral region, the waveforms result almost exclusively from the single scattering (Table 7.5). In the NIR spectral region, it turns out that about 40% of the received signal originates from the multiple scattering. Waveforms from low fractional cover forests are less contaminated by the multiple scattering since more rays have interacted only once with the ground.

To evaluate the resulting shift in the waveform, the canopy has been divided into horizontal layers of thickness \( R_d \). For each layer, we computed the number of rays which reach the telescope for each order of scattering. Figure (7.8) illustrates these measurements for the first, second and all orders of scattering. We next compared these observations with the received optical waveform transformed into the corresponding depth from the top-of-canopy (TOC) \( f_l \) with the following formula

\[
    f_l = \frac{c t_{pt}}{2} - H_t + z_{toc}
\]

(7.16)

where \( z_{toc} \) is the height of the TOC above the soil. The shift effect appears clearly (Figure 7.8) and results in a 30% underestimation of the maximum canopy returned signal. Within the
first 5 to 10 m from the TOC of the canopy, the waveform intensity is close to the contribution of the first and second order of scattering (70% of the signal) which means that most of the observed radiation path length increase may result from multiple interactions between the soil and the vegetation. As a result, more radiation seems to appear from the lower part of the canopy. Note that the smoothing effect of the multiple scattering is somewhat difficult to see on actual measurements because of the noise of the detector.

This study has clearly emphasized how the waveform shape is affected by the multiple scattering. In the red spectral region, this effect is not very large and the waveform conveys direct information on the vertical biomass distribution. In the NIR, the multiple scattering decreases the signal originating from the upper part of the canopy and increase the one in the lower part. The design of an accurate algorithm to quantify vertical biomass distribution with a NIR waveform should account for this effect.

7.6.2 Extracting parameters from waveform analysis

We investigate now the type of approach which can be used to extract meaningful biophysical parameters such as the biomass vertical distribution. A physically-based radiative transfer model can be inverted against a waveform provided the number of independent variables of the model is smaller than the number of observations as will be seen in Chapter (8). To address this issue, we first consider the propagation of a steady-state radiative flux in a horizontally homogeneous but vertically heterogeneous canopy. These hypotheses will be discussed in due course. We assume that the canopy is composed only of leaves of finite-size, simulated as plates. This canopy may therefore be represented as a stack of layers characterized by an area density \( u_i(z) \) and a normal distribution \( g_{L_i}(z,L_i)/2\pi \) and a thickness \( \vartheta_i \) chosen such that leaves do not overlap in a layer. Let \( F_\downarrow^i(\Omega_1) \) be the radiant flux density incident at the TOC in the direction \( \Omega_1 \). The optical thickness \( \tau_i(z,\Omega_1) \) of layer \( i(z) \) is given by \( u_i(z)\vartheta_i(z)G(z,\Omega_1) \) (Verstraete 1987) where \( G(z,\Omega_1) \) is the Ross function (refer to Annex D).

The probability that the beam passes through that layer is equal to \( 1 - \tau_i(z,\Omega_1) \). From this equation, we can derive the intensity of the uncollided beam through the layer \( i(z) \)

\[
F_\downarrow^i(z,\Omega_1) = F_\downarrow^0 \prod_{j=1}^{i} (1 - \tau_j(z,\Omega_1)).
\]  

(7.17)

The flux intercepted by the layer \( i(z) \) is equal to \( \tau_i(z,\Omega_1) \left( I_{i-1}^\downarrow + I_D \right) \) where \( I_D \) is the diffuse radiation originating from previous scattering of the direct beam in the vegetation. For the time being, the contribution of this term is neglected. Part of this intercepted radiation will be scattered. Since a laser altimeter is always observing in the hot spot direction, we assume that all the reflected radiation in the incidence beam direction is able to exit without further interaction (Verstraete et al. 1990). Consequently, and neglecting the effects of the multiple scattering, the radiance \( L_\uparrow^i(z,\Omega_1) \) which is scattered from layer \( i(z) \) in the direction \( \Omega_1 \) is equal to

\[
L_\uparrow^i(z,\Omega_1) = \tau_i(z,\Omega_1) I_{i-1}^\downarrow \Gamma_i(z,\Omega_1)
\]  

(7.18)
where $\Gamma_i(z, \Omega_1)$ [sr$^{-1}$] is the probability that the radiation is scattered in the solid angle $d\Omega_1$ centered in the direction $\Omega_1$. Assuming a nadir pointing observation, the flux $\Phi_i(z)$ [W] which would reach the telescope from the layer $i(z)$ in the absence of the atmosphere is equal to

$$\Phi_i(z) = \tau_i(z, \Omega_1) I_{\downarrow, i-1} \Gamma_i(z, \Omega_1) \frac{A_i}{H_i^2}.$$  (7.19)

It turns out that, in a first approximation, each registered echo is proportional to

$$u_i(z) \vartheta_i(z) G(\Omega_1) I_{\downarrow, i-1} \Gamma_i(z, \Omega_1).$$  (7.20)

The leaf area density $u_i(z)$ of the corresponding layer $i(z)$ should be retrieved from this signal. We assume bi-Lambertian leaves of reflectance $\rho_l$ and transmittance $\tau_l$ such that the single scattering albedo $\omega_l_i(z)$ is equal to $\rho_l(z) + \tau_l(z)$. $\Gamma_i(z)$ may now be rewritten as $\omega_l_i(z)/4\pi$. The Ross function $G(z, \Omega_1)$ which represents the projection of the scatterer surfaces in the direction $\Omega_1$ is a function of the leaf normal distribution as has been discussed in Chapter (6) and it requires a minimum of one or two parameters. Obviously the problem is ill-posed since, for each layer, the number of variables (minimum 3) is greater than the number of observations ($I_{\downarrow, 0}$ and $\Phi_i(z)$). Several solutions may be envisioned to solve this problem. A simple solution assumes a uniform LND, for which $G(\Omega) = 1/2$ and a fixed value for $\omega_l(z)$ to a constant value. Another possibility could be, if technically feasible, to use several pointing directions to increase the number of observations. Alternatively, if the altimeter flies on a space-borne platform in conjunction with a spectral imaging instrument such as the MISR (Multi-angle Imaging SpectroRadiometer) sensor, combined use of waveform analysis and bidirectional reflectance data may open up new research avenues.

We now discuss several effects which have not yet been taken into account:

- **Atmospheric effects.** The correct estimation of the radiance observed by the telescope requires that we account for the attenuation of the transmitted laser pulse by atmospheric water vapor and aerosols. Several models have been developed for this purpose (e.g., Kneizys et al. 1988; Vermote et al. 1995; Rahman and Dedieu 1994) and operational solutions require multi-spectral or bidirectional observations over dark or contrasted areas (Engelsen 1995).

- **Multiple scattering.** Section (7.6.1) emphasized the importance of the multiple scattering in the NIR spectral region. The diffuse term $I_D$ cannot therefore be neglected. Verstraete (1988) computed the contribution of the diffuse radiation for the upward and downward hemispheres. While giving rise to complex mathematical expressions, no new canopy structural parameters are required to describe them. The effects of the multiple scattering mainly concerns the inversion scheme and the shift in the observed waveform. The inversion procedure must account simultaneously for all recorded echoes. The photon mean free path length should be estimated and its effects included in equation (7.18).

- **Horizontal heterogeneities.** To assess the importance of horizontal heterogeneities, the relative downward flux estimated by Raytran in the different scenes has been compared with the relative downward flux corresponding to the case where the same value of leaf
area density is uniformly distributed in each horizontal layer for the same LND. Figure (7.9) shows these differences in the case of a nadir direct illumination in the red spectral region. For sparse forests, the relative downward flux in the homogeneous case is underestimated because the regions free of scattering elements, between the trees, are no longer represented. For dense forests, however, the relative downward flux is overestimated in the horizontally homogenous scene because an exact homogeneous distribution of the leaves is more efficient at intercepting the radiation than clumped tree leaves (Sampson and Smith 1993). In the case of sparse forests, it is therefore necessary to introduce additional parameters to account for the fractional cover. In summary, a horizontally uniform canopy is more efficient at intercepting a vertical laser pulse than the canopy with horizontal clumping effects, provided the scatterer density is not too high. This explains why, although the LAI values are quite similar for scene F45 and F60, the shapes of the received echoes are so different. It illustrates also the necessity to represent correctly the horizontal and vertical clumping effects, as permitted by Raytran, when analyzing the information conveyed by the waveforms.

- **Non steady-state illumination.** So far, we have only considered steady-state illumination of the canopy. The finite duration and Gaussian-shaped features of the laser pulse make the analysis of the waveform somewhat more complex. In the case where the detector sampling time is smaller than the laser pulse duration, the incident energy $F_0(\Omega_1)$ has to be represented as a function of the time, because only the leading edge part of the pulse actually accounts for the reflection of the first few layers.

### 7.7 Discussion

In this chapter, we investigated the potential contribution of Raytran to design a new instrument to infer the spatial organization of the canopy. Sensitivity studies have shown that the LAER technique is particularly suited for retrieving canopy height of rather tall vegetation over flat soil, even in the case of open forest. We also saw that a LA flying on a sun-synchronous polar platform would require quite large transmitted energy pulses or rather long integration times. A two wavelength (visible and NIR) instrument offers additional prospect to the extent that the relative soil/vegetation reflectance contrast is different in the visible and NIR spectral region. The vertical biomass distribution could be retrieved with a physically-based approach only if observations were acquired from multiple directions or if the measurements were analyzed simultaneously with BRF observations. Indeed, LAER does not provide the same information as BRF measurements. LAER observations are sensitive to the vertical distribution of the vegetation density in the hot spot direction of the incident laser pulse, while BRF measurements are sensitive to the angular variation of the reflected solar radiation. The simulation of the laser pulse reflection from the vegetation requires therefore an accurate description of the hot spot phenomenon, as permitted with the Raytran model.

Moreover, with respect to the Raytran model, this study has shown that:

- Raytran would need to be improved before it can be considered an operational laser
altimeter echo recovery (LAER) simulator. Specifically, the Monte Carlo procedures should be optimized to simulate efficiently small aperture instruments.

- It should be useful to integrate the computation of the atmospheric attenuation directly in Raytran to better represent all effects due to the multiple scattering at the atmosphere - vegetation interface. Since Raytran can represent turbid media, the main issue is to implement suitable scattering phase functions.

- The meaningful simulation of advanced observation techniques requires accounting for the sensor characteristics. In this respect, the principal requirement is an accurate representation of the side effects at the detector level, which requires only the knowledge of the order of magnitude of the reflected pulse.

Our analysis has shown that the vertical biomass profile would be easier to retrieve from more horizontally homogeneous canopies. In brief, the LAER method could be considered a valuable way to monitor vegetated surfaces, such as forests. In addition, more empirically-based approaches could also be envisioned for retrieving qualitative information from the waveform shape analysis. For instance, the increase rate of the waveform from the TOC could provide useful information on the canopy roughness, a relevant parameter in energy exchange efficiency at the vegetation - atmosphere interface. However, an empirical estimation of the vertical biomass distribution based on some sort of vertical vegetation index combining the visible and NIR waveform would be systematically biased because of the multiple scattering effect in the NIR.

The development and validation of algorithms to retrieve information from remote sensing observations is a key issue. Indeed, remotely sensed data are useful only if appropriate exploitation tools are available. We hope that the strategy which has been developed in this chapter will open new avenues for the design of more efficient radiometers and the associated retrieval algorithms to monitor vegetated surfaces.

In the next Chapter, we suggest a modeling strategy to evaluate the performance of retrieval procedures.
Figure 7.4: (A) Vertical leaf area density in m$^{-1}$ of the different scenes. (B) Radiation absorption in percent for scene F45 at different SZA. The solid line corresponds to the total absorption, the dashed line to the leaf absorption. (C) Idem but for scene F90.
Figure 7.5: Normalized echo recovery energy with a laser wavelength in the visible spectral region.

Figure 7.6: Normalized echo recovery energy with a laser wavelength in the NIR spectral region.
Figure 7.7: (A) Bidirectional reflectance factor of a NIR nadir pointing laser pulse over scene F90. (B) Mean number of interactions per escaped ray as a function of the viewing angle in the principal plane.

Figure 7.8: Effect of the multiple scattering on the waveform in the NIR spectral region. Thin solid lines represent the contribution of the single scattering for each layer. Medium thickness solid lines are for the contribution of the first and second order. Thick lines correspond to the total contribution. Dashed lines show the corresponding waveform as measured by Raytran.
Figure 7.9: Effects of horizontal heterogeneities on the vertical relative downward flux in the canopy in the red spectral region. Solid lines represent the relative downward flux computed by Raytran in the different scenes assuming a nadir direct illumination in the red spectral region. Dashed lines correspond to the case where the leaf area density is horizontally uniformly distributed.
Chapter 8

Strategy to evaluate retrieval procedures

8.1 Introduction

In the previous chapter, we investigated the contribution of our radiative transfer model as a support to the design of new observation techniques and retrieval procedures to exploit these observations. In this chapter, we suggest an original strategy to evaluate these procedures, based on the capability of Raytran to simulate the reflectance of scenes with a high level of realism. The main advantage of our strategy in to overcome the problem of comparing directly remote sensing observations with ground measurements. Indeed, direct comparisons require synchronous observations at consistent spatial scales. Our method is explained in the next section. The rest of the chapter is dedicated to practical applications.

8.2 Problem statement

The mathematical tools which have been developed to analyze TOA remote sensing observations can be categorized in two different classes. The first set of tools relies on combinations of radiometric values referred to as Vegetation Indices (VI) or, more generally, Spectral Indices (SI). They take advantage of spectral features exhibited by the parameters of interest. This approach is used either to discriminate different land cover types on the basis of supervised or unsupervised classification procedures (Ehrlich et al. 1994), or to infer some coarse geophysical properties. SI are usually simple to implement operationally but their quantitative interpretation stumbles against their sensitivity to the various perturbing factors that affect the reflectances. Indeed, VIs are dimensionless quantities, spectrally sensitive to the parameters of interest, they are not geophysical parameters by themselves. This point will be further discussed in Section (8.4) below. The second class of methods is based on an explicit empirical or physically-based modeling of the radiation transfer processes in the atmosphere, vegetation and underlying soil. The variables of interest are retrieved by inversion of these models against measured bidirectional radiances. The constraints on their utilization are discussed in

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Section (8.3). Henceforth, these different techniques to infer information from radiance measurements will be commonly referred to as retrieval procedures. In spite of their conceptually different background, they share common features concerning the evaluation of their suitability and accuracy. A retrieval procedure is suitable for global and repetitive exploitation of remote sensing observation provided (1) the computational requirements are limited; (2) it provides meaningful reliable information and (3) the accuracy of the retrieved information can be estimated everywhere and all the time. This last requirement is particularly important for quantitative applications.

The evaluation of the performance of retrieval procedures to estimate relevant parameters has been investigated by many authors who rely on different validation methods. This may lead to different conclusions. Reasons for these divergences lie in differences in the investigated scales and developed strategies to assess these performances. The evaluation of retrieval procedures is essentially based on the following methods.

1. **Comparison with ground observations.** This represents the most widely used approach and relies on straightforward comparisons between the parameters derived from the retrieval procedures and simultaneous ground observations of the same parameters. *(e.g., Zhao-Lang and Becker 1990; Baret and Guyot 1991; Privette et al. 1994)*. Clearly, the method requires the acquisition of comprehensive reflectance data sets, coupled with exhaustive descriptions of the optical and structural properties of the surfaces. The use of the technique is limited, principally because of the difficulty of measuring the plant’s optical and structural properties routinely in the field. Consequently, the method can only be used with high spatial resolution remote sensing observations to ensure their consistency with ground observations. Furthermore, perturbing effects such as the atmospheric absorption and scattering or the soil brightness have to be taken into account since these parameters can strongly change over time. The accuracy of the retrieval procedure can be, at best, demonstrated for the specific conditions of the experiment.

2. **Intercomparison of remote observations at different scales.** The principle consists of comparing coarse and high resolution data assuming that the latter convey the “true” information *(e.g., Moran et al. 1992; D’Souza et al. 1995)*. The method assumes the linearity of the radiative processes over the relevant spatial scales. Such linear properties cannot be guaranteed especially if the directional effects are important. Specific algorithms need to be used to ensure the compatibility between the observations at different scales. Moreover, the geometry of observation often varies between the high and coarse scales because of the use of different sensors acquiring data at different dates. With respect to this problem, the combination of the VEGETATION instrument and the HRV sensor on the upcoming SPOT-4 platform will offer new opportunities since they will observe simultaneously the same scene at high and low spatial resolution.

3. **Comparison with simulated reflectances.** This technique is based on the same principle as the first method but the remote sensing observations of the reflectances are modeled *(Govaerts and Verstraete 1995; Leprieur et al. 1994; Goel and Qin 1994)*. The method permits exhaustive sensitivity studies where the effect of each parameter can be individually emphasized but it requires complex radiative transfer models where every
interacting media can be explicitly described. In this respect, Raytran can play a major contribution and extend the possibility of representing meaningful scenes as stated in Chapter (6).

Each of these approaches has its own advantages and drawbacks. Comparison of the results of different evaluation methods is however difficult due to the various underlying techniques and scales of investigation. In any case, it is necessary to ensure the spatial and temporal consistency between the ground (or reference) observations and the assessed values. In addition, all parameters which may affect both observations should be accounted for in the analysis. Consequently, we suggested a rational and unified strategy to evaluate retrieval procedures based on the following five steps which ensure the consistency of the approach.

1. **Ground observations of the variables of interest.** These observations are taken as the “truth” or what should be inferred from the remote sensing observations by the retrieval procedures. Their quality and accuracy are therefore of primary importance.

2. **Generation of realistic scenes on the basis of the ground observations.** The aim of this step is to control all the auxiliary parameters of the experiment such as the soil brightness or sky radiance. This represents a major advantage in regard to direct comparisons between retrieval procedure results and ground observations because it ensures the consistency of the investigated scales and accounts for the perturbing factors.

3. **Generation of synthetic reflectances.** The reflectances are computed with Raytran or equivalent models using the target described in the previous step for specific values of the perturbing factors. For all quantitative applications, it is important to account for the effects of the sensor electronics noise as well as the calibration and observation geometry inaccuracies in the simulated reflectances.

4. **Applying the retrieval scheme to the synthetic reflectances.** The retrieval procedures should be usable blindly if they are to be applied operationally.

5. **Comparison of the retrieved values and the original parameters.** Several statistical methods can be used to compare ground observations with retrieved values: absolute or relative differences, root mean square errors, variance analysis, etc. The main objective of this step is to establish the accuracy of the retrieval procedures with respect to the experimental conditions. Recently, Leprieur et al. (1994) suggested the application the concept of signal-to-noise ratio to evaluate SI. This ratio essentially indicates how a specific SI emphasizes the desired information (e.g., LAI, fractional cover, etc.) from spectral data with respect to the variance of the retrieved parameters for different values of the perturbing factors.

The evaluation of retrieval procedures should not be confused with the evaluation of their individual components. The canopy reflectance models can be validated with specific methods as suggested by Pinty and Verstraete (1992b). Renders and Flasse (1996) compared different inversion methods and suggested a very robust but slow inversion scheme. In the present study, we evaluate only the accuracy of the final output of the retrieval procedure. Moreover,
we underline the specific role of a model such as Raytran in regard to this evaluation strategy. The practical examples which are investigated here allow the assessment of the potentials and limitations of the approach. First, we explore the inversion of a physically-based canopy reflectance model (Section 8.3). Then, we investigate the evaluation of VI (Section 8.4).

8.3 Evaluation of the BRF model inversion

8.3.1 Principles of the BRF model inversion

The inversion of canopy reflectance models aims at inferring some or all of the model parameters from a set of measurements for a given wavelength and illumination zenith angle \( \theta_1 \) by minimizing a merit function defined as (Goel and Strebel 1983)

\[
\delta^2_{\lambda, \theta_1} = \sum_{j=1}^{n} (r_j - r_{jm})^2
\]

(8.1)

where \( r_j \) is the \( j^{th} \) measured value for a given viewing angle and \( r_{jm} \) is the corresponding estimation of the model. For more details on the inversion procedures, refer to Goel (1988). In brief, the approach essentially requires three ingredients: a BRF model, a merit function and a method which optimizes the convergence of the merit function when the model parameters are varied. Since the 1980s, tens of BRF models have been designed for that purpose (see for instance Nilson and Kuusk 1989; Pinty et al. 1990; Antyufeev and Marshak 1990a; Ahmad and Deering 1992; Myneni et al. 1992; Rahman et al. 1993; Liang and Strahler 1993; Iaquinta and Pinty 1994). According to Pinty and Verstraete (1991), inversion of BRF models imposes specific constraints on their design: limitation of the number of physical parameters used to describe the geometrical and structural properties of the medium and simplification of the radiation transfer formulation to limit the computer resource requirements. The maximum number of parameters which can be defined depends on the analytical form of the equation, on the efficiency of the inversion procedure, and on the variability present in the data.

Recently, Privette et al. (1994) and Flasse et al. (1993) have demonstrated the possibility of extracting quantitative data such as the LAI over grassland or the albedo by inverting bidirectional models against AVHRR data. To get sufficiently different geometries of observation, they both assume that the optical properties of the scene remain unchanged during the data acquisition time period. The two approaches differ on the type of model which has been inverted. In the first case, the authors inverted a physically-based model which permits the retrieval of structural parameters. The second authors inverted an empirical model. The inversion provided a statistical fit of the measured bidirectional reflectances and therefore permitted the retrieval of the surface albedo. The inversion of this model can, in principle, be applied to any kind of vegetated surfaces. However, physically-based models offer several advantages with respect to empirical ones. First, they provide physical parameters which characterize the medium’s properties. Another advantage of the approach lies in the fact that, since physically-based models solve the radiative transfer equations, their inversion should be better constrained in the case where some measurements are contaminated by perturbing factors such
as undetected clouds. Indeed, in this case, the inversion should normally fail if the mechanisms responsible for this noise have been explicitly described in the equations. However, due to the complexity of the description of radiative transfer in structured media, only one-dimensional physically-based models have been successfully inverted against measured data. The degree to which these models represent the real world and the range of conditions for which they are reasonably accurate has also to be documented.

<table>
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</thead>
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<td>Leaves</td>
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<td>0.500</td>
</tr>
<tr>
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<td>Soil</td>
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</tr>
<tr>
<td>o2</td>
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</tr>
<tr>
<td></td>
<td>Soil</td>
<td>0.150</td>
<td>0.350</td>
</tr>
</tbody>
</table>

Table 8.1: Spectral values for the various elements of the scene (\(\rho\) = reflectance; \(\tau\) = transmittance).

### 8.3.2 Presentation of a simple BRF model

The capability of Raytran to calculate reflectances for scenes of controlled complexity has been exploited to evaluate the potential of the inversion of a simple one-dimensional BRF model called IAPI (Iaquinta and Pinty 1994) to retrieve structural information of the target. The IAPI model is based on the canopy reflectance model developed by Verstraete et al. (1990) but includes a representation of the underlying soil. This model is very attractive for inversion purposes since it addresses some of the constraints enumerated above. It has 7 independent parameters: the LAI, the leaf reflectance and transmittance, the soil reflectance, a hot spot parameter and two coefficients to describe the leaf angular distribution. This model assumes that radiation is asymptotically absorbed by the canopy and that the hot spot effect is important as far as the single scattering is concerned. In addition, to save computer time, the multiple scattering contribution is approximated on the basis of a discrete ordinates method reduced to a one-angle problem, assuming isotropic scattering. Raytran does not have these limitations and represents explicitly these features. Confidence in the IAPI model can therefore be gained if any differences between IAPI and Raytran solutions are consistent with the fundamental hypotheses on which IAPI is built. For that purpose, we have generated a one-dimensional turbid medium canopy composed of fixed radius discs, uniformly distributed in space and with a specified distribution of their normals. Since Raytran is able to simulate explicitly the radiation transfer in that discrete quasi-homogeneous canopy, direct comparisons between the two approaches provide a straightforward way to quantify the effects of the three main hypotheses of the hybrid model. Systematic comparisons have been carried out with planophile and erectophile LND for LAI running from 1 to 8 and the optical properties of Table (8.1). With regard to the assumption of isotropic distribution of the multiple scattering in the IAPI model, it is expected that the largest differences between the two models should occur at the nadir since the multiple scattering is generally U-shaped. Figure (8.1) shows the
reflectance factors at the nadir calculated with Raytran and the IAPI model. In the visible spectral region, the models agree to within ±5%. In the NIR region, where multiple scattering is important, the IAPI model systematically overestimates the Raytran solution with a mean relative error of 6% and a maximum of 14%.

![Figure 8.1: Comparison of BRF calculated by Raytran and IAPI at the nadir.](image)

8.3.3 Inversion scheme

We discuss now the inversion of the model. With 7 parameters, it is likely that different sets of them may produce almost identical reflectance surfaces. This is principally due to the fact that a change in the optical thickness of the medium (LAI) has a somewhat similar effect as a change in soil reflectance. Privette et al. (1994) have shown with an equivalent model that bidirectional reflectances are very sensitive to these two parameters, especially for sparse canopies. When the LAI is greater than 3, the sensitivity to LAI and soil reflectance tends to be smaller. These models should correctly retrieve LAI for a sparse canopy provided LAI and soil reflectance effects can be separated. Conversely, leaf reflectance and transmittance seem to be easier to infer with acceptable accuracy for dense canopies and to a lesser extent for sparse ones. For that reason, we will mainly focus the discussion on inferring LAI. Classical inversion techniques cannot easily solve the optical thickness problem when inversion is performed individually on a single spectral band. To address this question, several solutions have been suggested. The first one consists of freezing the soil reflectance value to a fixed value (Liang and Strahler 1993). This solution can be useful when some or all optical and structural properties of the ground are available. However, in the framework of space-borne remote
8.3. EVALUATION OF THE BRF MODEL INVERSION

sensing of large areas, this solution is not applicable. A second approach consists of retrieving one or more parameter’s data at a given wavelength and imposing their values when inverting the model in another wavelength for which the model sensitivity to that parameter is weak (Pinty et al. 1990). Unfortunately, this technique cannot be applied blindly in operational schemes. Finally, Privette et al. (1994) averaged the retrieved LAI values for all the different wavelengths and sun zenith angles. However, even if this method can provide good results for a given area, its general applicability is not guaranteed.

We have developed an original method to separate the combined effects of the LAI and soil reflectance. Different optimization techniques can be used to minimize equation 8.1. Rather than inverting a model separately against the different reflectance data sets corresponding to the same scene, we invert them simultaneously, forcing, at regular intervals during the iterative process, each of the structural parameter $s_{1...p,i}$ to converge on a mean value $\langle S_{1...p,i} \rangle_i$ to get corrected values $s^*_1...p,i$. Specifically, the mean value of a structural parameter at iteration $i$ is calculated as

$$\langle S \rangle_i = \sum_{l=1}^{L} \sum_{t=1}^{T} s_{l,t,i} w_{l,t,i}$$

with

$$w_{l,t,i} = \frac{1 - \text{MIN}(1, \delta^2_{l,t,i})}{\sum_{l=1}^{L} \sum_{t=1}^{T} [1 - \text{MIN}(1, \delta^2_{l,t,i})]}$$

where $\sum_{l=1}^{L}$ is the sum on the different wavelengths and $\sum_{t=1}^{T}$ the sum over the illumination zenith angles. $\delta^2_{l,t,i}$ is the merit function calculated with equation 8.1. The parameter $s_i$ is then corrected with

$$s_i^* = s_i + (\langle S \rangle_i - s_i) \alpha$$

where $\alpha$ is in the interval $[0, 1]$. The choice of the value of the coefficient $\alpha$, as well as the iterations for which the convergence tests are performed, are to be adjusted depending on the variability of the data. The same technique is used for the optical parameters except that the sum is computed only for the different illumination zenith angles. The minimization of the merit function $\delta^2_{l,t}$ is implemented with a quasi-Newton algorithm (subroutine EO4JAF of the Numerical Algorithms Group) which has been modified to control the number of iterations (Renders et al. 1992). We inversed IAPI against its own synthetic data to test this inversion procedure. For LAI lower than 4, we succeeded in retrieving all of the optical and structural parameters of the model.

The retrieval procedure is therefore fully defined by the IAPI model and our inversion scheme. Direct comparisons between the Raytran and IAPI solutions showed that the latter model exhibits some differences to the solution of the former model because it relies on some additional assumptions to speed up the computation of the radiative transfer equation solution. We presented a new inversion scheme which has been designed to minimize the effects of the indeterminate nature of the medium’s optical thickness resulting from the combined effect of the LAD and soil brightness. Henceforth, we consider both the model and the inversion scheme as a single “black box” system, designed to retrieve the optical and structural parameters. In the next section, we illustrate the evaluation of this system.
8.3.4 Results of the evaluation

We investigated the accuracy of this retrieval scheme with two different scenes. The geometry of the first one is defined by an homogeneous cloud of disks, i.e., what the IAPI structural parameters aim at representing statistically. This scene thus constitutes an “ideal” case for our retrieval procedure. The height of the canopy was fixed at 1.5 m and the radius of the disks to 0.04 m. Different scenes were generated to represent planophile and erectophile LND for LAI running from 1 to 5. The scene is lit by direct illumination with a zenith angle of 30° and 60° in the red and near-infrared (NIR) spectral regions, using the optical properties of Table (8.1). All surfaces are assumed Lambertian. Results are presented in Table 8.2 for LAIs of 1 and 3.

**OPTICAL DATA SET o1 (DARK SOIL)**

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<tr>
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<td>(\tau_l)</td>
<td>(\rho_s)</td>
<td>LAI</td>
<td>(\rho_l)</td>
<td>(\tau_l)</td>
<td>(\rho_s)</td>
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<td>LAI</td>
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<td>(\tau_l)</td>
<td>(\rho_s)</td>
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<td>(\rho_l)</td>
<td>(\tau_l)</td>
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</tr>
<tr>
<td></td>
<td>LAI</td>
<td>(\rho_l)</td>
<td>(\tau_l)</td>
<td>(\rho_s)</td>
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<td>(\rho_l)</td>
<td>(\tau_l)</td>
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<td>band</td>
<td>IZA</td>
<td>LAI</td>
<td>(\rho_l)</td>
<td>(\tau_l)</td>
<td>(\rho_s)</td>
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<td>(\rho_l)</td>
<td>(\tau_l)</td>
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<td>3.614</td>
<td>0.496</td>
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Table 8.2: Model parameter values retrieved by inversion of IAPI against Raytran-generated reflectances for a discrete homogeneous canopy for two illumination zenith angles (IZA) in the red and NIR. \(\rho_l=\)leaf reflectance, \(\tau_l=\)leaf transmittance, \(\rho_s=\)soil reflectance.

As expected, leaf reflectance and transmittance, which mainly determine the mean level
of the reflectance surface, are correctly inferred, especially in the case of erectophile canopies. On the contrary, the soil reflectance is very poorly inferred. For LAI = 1, the retrieved LAI values are systematically overestimated by approximately 40%. This overestimation occurs principally for bright soil. In the case of dark soil, the LAI is estimated with an accuracy of 20%. Conversely, for LAI = 3, the estimated values are underestimated (-20%), except in the case of the erectophile LND over bright soil where the LAI values are overestimated (27%).

The geometrical properties of these scenes are highly idealized. However, natural media exhibit much more complex structure. So, we want to evaluate the performance of IAPI for more realistic scenes. To address this question, we used our artificial grassland composed of “generic” gramineous plants described in Chapter (6). This scene presents clear leaf clumping effects and the LND depends on the elevation in the canopy since polygons close to the soil are more vertical than the polygons of the upper part of the canopy. The grassland LAI is fixed to 2.8. The different parameters are retrieved with the same accuracy as for ideal discrete homogeneous canopies. In particular, the inferred LAI value is underestimated by about 20%. In spite of the vertical heterogeneity of the polygon angular distribution, IAPI retrieved the values of the beta distribution coefficients within about ±5%. Additional results are provided in Table 8.3.

Next, we tried the retrieval procedure in the case of the artificial forests generated with the L-system trees described in Chapter (6). However, the spatial heterogeneities for these scenes are too large and the retrieved LAI values were unrealistic. The potential of other retrieval methods such as VI should be investigated in this case.

<table>
<thead>
<tr>
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<th>Retrieved values</th>
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</thead>
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</tr>
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<td></td>
<td>RED</td>
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<td></td>
<td>NIR</td>
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<table>
<thead>
<tr>
<th>Data</th>
<th>Retrieved values</th>
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<tr>
<td>LAI</td>
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</table>

Table 8.3: Inversion of the IAPI model against Raytran reflectance for an artificial grassland at IZA in the red and NIR. $\rho_l$=leaf reflectance, $\tau_l$=leaf transmittance, $\rho_s$=soil reflectance.
8.4 Evaluation of spectral indices

8.4.1 Principles of spectral indices

Spectral indices are dimensionless quantities resulting from the combination of measured radiances in different spectral bands. They are designed to exploit specific spectral features which may be linked to a property of the observed medium. Typically, all vegetation indices take advantage of the high difference of reflectance between the visible and NIR spectral region which typically characterize plant leaves. However, VIs are also sensitive to other features referred to as perturbing factors. In particular, the ‘Normalized Difference Vegetation Index’ (NDVI) is also sensitive to the soil brightness, the atmospheric absorption and the geometry of observation. Consequently, the detailed quantitative interpretation of VI is particularly difficult because of the spectral signature of the parameter of interest (the signal) being tightly coupled with the signature of the perturbing factors (the noise). Pinty and Verstraete (1992a) showed the feasibility of optimizing the design of indices to make them more sensitive to a desired feature and less sensitive to unwanted perturbing effects. They proposed the ‘Global Environment Monitoring Index’ (GEMI), designed to globally satisfy the following constraints: (1) to be sensitive to the presence of vegetation, (2) to be unresponsive to atmospheric contaminations, (3) to be insensitive to dark and medium soil brightness changes under the vegetation, (4) to be sensitive to bright soils and (5) very sensitive to clouds. Generally, the more a VI takes these perturbing effects into account, the simpler is its interpretation. Other improved indices have also been derived by different authors such as, the ‘Soil Adjusted Vegetation Index’ (SAVI) (Huete 1988), and the ‘Atmospherically Resistent Vegetation Index’ (ARVI) (Kaufman and Tanré 1992).

A VI may be formally written as a function of reflectances at the TOA: $R_{TOA}$ which depends on the geometry of observation ($\Theta$) and the sets of parameters that describe the surface $s(x, t, \lambda)$ and the atmosphere $a(z, t, \lambda)$ such that

$$VI = VI(\Theta; s(x, t, \lambda); a(z, t, \lambda))$$ (8.5)

where $x$ (or $z$), $t$ and $\lambda$ indicate their spatial, temporal and spectral variability respectively. Typically, $s_{0,\ldots,n}$ represent parameters such as the LAI, the fractional cover, etc. VI can be conceptualized as a “device” which optimizes the spectral sensitivity of a parameter of interest (for instance $s_0$) and minimizes the effects of all other parameters. In regard to this definition, Leprieur et al. (1994) suggested the utilization of the signal-to-noise concept, traditionally used to describe the efficiency of electronic measurement devices, to evaluate the suitability of a vegetation index to emphasize the desired information. In this context, it is necessary to establish criteria to define the VI signal and noise. An index designed to infer the parameter $s_0$ should provide a monotonous response to the variations of top-of-canopy reflectances $R_{TOC}(s_0(x, t, \lambda))$ and be insensitive to changes of $\Theta$, $s_{1,\ldots,n}(x, t, \lambda)$ and $a(x, t, \lambda)$. In the simplest case of a linear estimator

$$\bar{s}_0 = a_0VI(\Theta; s(x, t, \lambda); a(x, t, \lambda)) + b_0.$$ (8.6)

This expression is analogous to the equation used to calibrate radiometers where $a_0$ can be assimilated to the gain of the electronics device. The slope of the line $a_0$ can be normalized
with $G_{VI} = \cos (\arctan a_0)$ in order to vary between 0 and 1. Two extreme cases should be discussed. When $G_{VI} \rightarrow 0$, whatever the values of $R_{TOA} (s_0 (x, t, \lambda))$, $VI (\Theta; s (x, t, \lambda) ; a (x, t, \lambda))$ always delivers the same value of $\bar{s}_0$. Clearly, the VI is insensitive to the parameter $s_0$ and cannot be used to estimate it. Conversely, when $G_{VI} \rightarrow 1$, the index is extremely sensitive to small variations of $s_0$ and becomes too dependent on inaccuracies in the measurements of $R_{TOA} (s_0 (x, t, \lambda))$. Optimal values for the gain of the VI should lie between these two extreme values. In the present case, we will assume that this value corresponds to $G_{VI} = 0.5$. We define therefore the signal of a VI $S_{VI}$ as

$$S_{VI} = 1 - 2 | 0.5 - G_{VI} | . \tag{8.7}$$

such that when $G_{VI} = 0.5$, $S_{VI}$ gets its maximum value of 1. When $G_{VI} \rightarrow 0$, $S_{VI} \rightarrow 0$ and the signal delivered by the index is irrelevant because it is insensitive to variation of $s_0$. When $G_{VI} \rightarrow 1$, $S_{VI} \rightarrow 0$ and the signal delivered by the index is also assumed to be irrelevant because every measurement inaccuracy and perturbing factor effect is over-amplified.

The noise $N_{VI}$ of $VI (\Theta; s (x, t, \lambda) ; a (x, t, \lambda))$ is the dispersion of $\bar{s}_0$ when $\Theta$, $s_1, ..., n (x, t, \lambda)$ or $a (x, t, \lambda)$ vary. $N_{VI}$ may be estimated as a function of the linear correlation between $VI (\Theta; s (x, t, \lambda) ; a (x, t, \lambda))$ and $\bar{s}_0$ with

$$N_{VI} = 1 - r_{VI} \tag{8.8}$$

where $r_{VI}$ is the coefficient of linear correlation. The signal-to-noise ratio of the index $SNR_{VI}$ is given by the following expression

$$SNR_{VI} = \frac{S_{VI}}{N_{VI}} \tag{8.9}$$

Equations (8.7) and (8.8) are certainly not the only way to express the signal-to-noise ratio of an index. However, they allow the main properties which are expected from a VI to be accounted for. They are designed to linearly amplify the spectral sensitivity to a specific parameter irrespective of changes in the other parameters. The linearity of the response is a stronger condition since, formally, only a monotonous amplification is necessary. However, a linear response of the index simplifies its interpretation. Because the effects on the reflectance of the different parameters are tightly coupled, such a perfect index is almost impossible to design and the effects of the variations of other parameters are also amplified. Consequently, the actual equation of an index results in a trade-off: the more the spectral signature of the parameter of interest is emphasized, the more the effects of the perturbing factors are emphasized. The actual gain of an index should be tuned to optimize this trade-off. We used equation (8.9) to evaluate the performance of the GEMI and NDVI. The $SNR_{VI}$ of an index should be ultimately used to define the accuracy with which the parameter $\bar{s}_0$ can be globally inferred.

### 8.4.2 Example of spectral indice evaluation

In Chapter (7), we generated different artificial forests with fractional covers ranging from 0.45 to 0.9 (refer to Table 7.2). In Section (8.3.4), we saw that the inversion of a one-dimensional physically-based BRF model against the reflectances of these canopies failed because of the
complexity of their spatial organization. Hence, only an approach based on the VI can be used in this case to infer the properties of the scenes. We used these simulated forests to evaluate the performance of the GEMI and NDVI in assessing the LAI, the fractional cover and the fraction of absorbed photosynthetically active radiation (FAPAR). These evaluations have been carried out using hemispherical reflectance values, in the absence of atmospheric effects, in order to limit the number of possible combinations of the perturbing factors. The different scenes are lit with direct illumination at zenith angles running from 0 to 70°. Results are shown in Figure (8.2).

Figure 8.2: Sensitivity of the NDVI (+) and GEMI (△) to variation of LAI, fractional cover and FAPAR over forests of various densities.

The range of VI over the scenes runs from 0.82 to 0.91 for the NDVI and from 0.80 to 0.96 for the GEMI. Clearly, GEMI exhibits a better dynamics in this specific case. The diagrams of Figure (8.2) should be interpreted in the following way: when GEMI=0.9 for instance, the estimated LAI values can range from 2.15 to 3.6, i.e., the minimum and maximum possible values. This index thus conveys no useful information on the LAI of the observed scenes. However, for the same GEMI index value, the FAPAR varies only from 0.72 to 0.82 within the possible range of variation from 0.45 to 0.95. This index thus delivers suitable information on the FAPAR. To quantify the efficiency of these VI in retrieving the LAI, fractional cover and FAPAR, we calculated the corresponding $\text{SNR}_{VI}$ (Table 8.4). For the LAI, $\text{SNR}_{VI}$ is lower than 1 which means that neither index contains any significant information on the LAI. GEMI provides a weak signal on the fractional cover and a 4.33 $\text{SNR}_{VI}$ for the FAPAR. The NDVI is clearly unrelated to the variations of these parameters in these particular forest scenes.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Signal to noise ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>NDVI</td>
</tr>
<tr>
<td>LAI</td>
<td>0.76</td>
</tr>
<tr>
<td>$\sigma_f$</td>
<td>0.01</td>
</tr>
<tr>
<td>FAPAR</td>
<td>1.07</td>
</tr>
</tbody>
</table>

Table 8.4: Signal-to-noise ratio of the NDVI and GEMI calculated for the LAI, the fractional cover ($\sigma_f$) and the FAPAR over various artificial forests.
8.5 Concluding remarks

The evaluation of retrieval procedures is of prime importance to assess the accuracy of the delivered geophysical parameters and to detect the possible presence of systematic biases in these retrieved values. Classical approaches which consist of comparing directly ground measurements with remote sensing observations are often unsuitable because of (1) the inconsistency between the different spatial scales investigated (unless they are explicitly modeled) and (2) the large number of parameters which affect the observed radiances. To address this problem, we suggested the generation of an artificial plant canopy on the basis of the ground observations and the calculation of the corresponding reflectances with our Monte Carlo ray tracing model. This approach offers the clear advantage of allowing explicit control of the perturbing factors and ensuring the consistency between the spatial scales of the ground and remote sensing observations. However, the method can provide reliable evaluations only if the ground observations are integrated in a realistic environment where all the scattering processes are correctly represented. In these sensitivity studies, we assumed Lambertian surfaces and we did not simulate either the atmospheric scattering and absorption effects, or the actual characteristics of the radiometers. The atmosphere can be simulated in the Raytran model provided the appropriated scattering phase functions are defined. Further developments are required to improve the simulation of the directional properties of the phyto-elements and to account for the measurement inaccuracies.

With this evaluation method, we explored the capability of a BRF model to retrieve structural information from three-dimensional targets whose reflectances are computed with Raytran. The inversion of this model provides direct estimates of the structural and optical properties of the scene. However, this method is limited to homogeneous canopies and requires multiple measurements from many different viewing geometries. On the contrary, vegetation indices can, in principle, be applied on any types of surface, but do not usually deliver geophysical parameters directly. We saw that their design can be optimized in order to be sensitive to a particular parameter such as the FAPAR or the fractional cover. Their performance can be estimated by a signal-to-noise ratio approach. Using reflectances computed with Raytran on artificial forests, we found that neither the NDVI nor the GEMI conveyed any significant information on the LAI within the range 2.15 and 3.6. However, GEMI can be exploited usefully to estimate FAPAR, and, to some extent, the vegetation fractional cover.
Chapter 9

General conclusion

This research has been motivated by the need to better understand space-borne observations of vegetated surfaces in the optical spectral region. These observations are driven for instance by the necessity to document and address Global Change issues, and in particular to characterize the global water, carbon and energy cycles. Since remote sensing observations from Earth-orbiting satellites do not provide direct measurements of the quantities of interest but only top-of-atmosphere radiances in a narrow field of view, the meaningful analysis of these radiometric measurements should take advantage of the reflectance variations, both in the spectral and directional domain. It is thus necessary to develop mathematical tools (or retrieval procedures) to extract the values of these parameters of interest from radiometric observations. However, the interpretation of space-borne remote sensing data in terms of vegetation physiological or morphological properties is rendered difficult by:

1. the unknown spatial organization of plant canopies;
2. the large number of different interacting media (atmospheric gases and aerosols, various vegetation types and underlying soil);
3. the instrument noise and calibration errors;
4. the geometric inaccuracies of the observations.

All the perturbing factors which affect space-borne measurements of vegetated surfaces must be taken into account and quantified to properly establish the relationships between remote sensing data and plant properties. Only a clear understanding of these relationships can guarantee a successful design of efficient sensors and associated retrieval procedures. To address these issues, it is necessary to observe, understand and represent all individual mechanisms which affect the measured signal. In practice, they can be studied separately, but the investigation of their mutual interactions is almost impossible on the basis of their exclusive individual observations. For instance, the investigation of the factors which determine the BRF of the surface requires the simultaneous observations of the sky radiance, the position and orientation of each scattering element with their optical properties as well as the soil brightness. The
only rational approach to explore the radiative transfer problems underlying the interpretation of space-borne data of terrestrial surfaces lies in the design of models which can represent the effects and interactions of all these parameters. **This work has been focused on the development of such a radiation transfer model.**

The geophysical system which needs to be modeled is essentially composed of three main media: the atmosphere, the vegetation and the soil. However, our model has not been designed as a straightforward and exclusive representation of the radiative transfer in these three media. It is in fact a *virtual laboratory*, conceived to represent the radiation interaction with geometrical objects in general terms. Specifically, the **originality** of the Raytran model with respect to existing canopy reflectance models lies in the following properties:

- Each object in the scene may have different optical properties characterized by interaction models representing surface as well as volumetric (body) effects.
- The model can address radiative transfer problems in relation with remote sensing studies at a wide range of spatial scales.
- The estimation of the overall bidirectional reflectance and of the radiation regime in the scene using advanced filtering mechanisms are both possible.
- Natural as well as laboratory lighting sources can be explicitly represented.
- The optical properties of the sensor can be simulated.
- The latest techniques of computer graphics to describe complex natural or artificial three-dimensional scene have been included.
- The code is parallelized for computing efficiency and is based on the object oriented programming techniques.
- The software is designed to be maintained and improved at low cost.

The verification of the accuracy of the model has been achieved by comparison with laboratory reflectance measurements, simulating as faithfully as possible the actual experimental conditions. Preliminary results were encouraging, and justify future attempts at acquiring accurate measurements on this and other fully characterized targets. The comparison of Raytran with a simple Monte Carlo model has shown the advantage of our Monte Carlo scheme in terms of energy conservation.

The high level of complexity which can be accounted for does not rely so much on the diversity of physical processes which are represented, but on the high number of possible arrangements which can be achieved to represent spatially organized systems. These features have permitted to tackle new problems in relation with the current research efforts in remote sensing with an unprecedented level of realism. These studies concern mainly the effects of the spatial arrangement of the basic scattering components at various scales. Specifically:

1. **Effects of cell arrangement on the leaf optical properties**
• **Objective** To explore the optical and directional properties of a single plant leaf as a function of its cellular structure.

• **Method** We succeeded to represent, for the first time, the three-dimensional spatial distribution of the different component concentrations in the leaf tissues and to model the spectral and directional scattering properties of radiation in this structure. The size of the leaf cells, their spatial arrangement in the different tissues as well as the distribution of the various components in the cell membranes have been chosen exclusively on the basis of values found in the literature.

• **Results** The simulated spectrum and bidirectional reflectances of that artificial leaf section are very close to observations. This approach has permitted to verify and improve our understanding of the radiation transfer mechanisms in leaf cells and to investigate the effects of the leaf internal structure on its spectrum. The bidirectional reflectance properties of a leaf and, to a lesser extent, the amount of radiation which is absorbed in the case of direct illumination are both influenced by the roughness of the epidermis. On the other hand, the bi-hemispherical reflectance, measured to characterize the leaf spectrum, is only weakly affected by the epidermis roughness. We found that leaves with convex epidermis cells better focus the light of the palisade tissue, as has been already observed. Such leaves are mainly located in the lower part of the canopy where direct solar radiation does not easily penetrate. The absorbance of these leaves is larger than that of leaves with a smooth epidermis. This latter type of leaves better transmit the radiation.

2. **Measurement of the spatial organization of the canopy**

• **Objective** To investigate the potential of an advanced space-borne observation technique (laser altimetry) to retrieve the spatial organization of the canopy.

• **Method** We simulated with Raytran of the propagation of a pulse emitted by a laser, its scattering by forests of different densities (closures) and finally its reception by a telescope. We developed original L-system production rules to generate the artificial trees of the forests.

• **Results** For each scene, we were able to estimate the number of photons that would reach a laser altimeter flying on a space-borne platform. This analysis has permitted to assess the potential of the laser altimetry method to discriminate the different scenes, as well as to assess the vertical profile of the biomass as a function of its technical performance. Additionally, we showed that multiple scattering effects systematically bias the actual shape of the echo by increasing the travel time of the photons. We showed that laser altimeters are particularly well suited to observe forests provided reliable mathematical tools to extract accurate quantitative information are developed.

3. **Evaluate retrieval procedures**

• **Objective** To elaborate an objective strategy to evaluate the products delivered by remote sensing data analysis.
• **Method** The suitability of retrieval procedures to infer meaningful geophysical parameters is evaluated against Raytran generated reflectances for realistic scenes of controlled complexity, i.e., artificial canopies for which the structural and optical properties are precisely defined.

• **Results** We found that LAI can be retrieved by inverting a physically-based BRF model with a mean accuracy of 20% for an artificial grassland. For more complex scenes such as forests, we evaluated the potential of spectral indices using the concept of signal-to-noise ratio. We found that LAI can only be very poorly retrieved with vegetation indices, even on the basis of hemispherical reflectances, but the fraction of absorbed photosynthetically active radiation appears to be reasonably inferred.

Throughout the advanced design of Raytran and the applications we developed, we clearly showed the role and the contribution of an elaborated radiative transfer model with respect to the current remote sensing problems mentioned earlier. Specifically:

<table>
<thead>
<tr>
<th>Issue</th>
<th>Progress achieved</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) Identification of the spatial and temporal scales and resolutions at which information on vegetated surfaces are required.</td>
<td>Depend on the application, e.g., land use/cover change monitoring, crop yield forecasting, etc. See Chapters (1), (2) and (6).</td>
</tr>
<tr>
<td>(2) Characterization of the nature of relevant radiometric signatures.</td>
<td>We investigated various spatial scales, from a single leaf to a landscape. See Chapters (5) and (6).</td>
</tr>
<tr>
<td>(3) Implementation of an instrument designed to observe these signatures.</td>
<td>We explored the potential the LAER technique to infer the vertical profile of the vegetation biomass. See Chapter (7)</td>
</tr>
<tr>
<td>(4) Development of mathematical tools capable of interpreting the radiative measurements in terms of the environmental variables of interest.</td>
<td>The two main approaches are based on inversion of canopy reflectance models or spectral indices. See Chapters (7) and (8).</td>
</tr>
<tr>
<td>(5) Evaluation of the suitability and accuracy of the delivered products.</td>
<td>We simulated the reflectance of realistic artificial canopies to evaluate the performance of retrieval procedures. See Chapter (8).</td>
</tr>
</tbody>
</table>

Clearly, Raytran can be used in a wide range of applications with respect to remote sensing observations. However, despite its versatility, Raytran has some limitations:

- The nature of the physical processes which are described are limited. Rays are currently propagated without accounting for the phase or the polarization. These features could be implemented if the parameters which describe the changes of these values, when an interaction occurs, could be specified for all objects in the scene.

- The characterization of the reflectance and transmittance distribution functions of the scatterers also needs to be improved. Further research efforts are required to develop a simple physically-based leaf bidirectional reflectance model.
The Monte Carlo scheme we implemented is not very efficient in terms of variance reduction of the solutions but easily allows the extraction of any kind of statistics on the ray trajectories and guarantees the conservation of the energy. In fact, there are no unique methods (or variance reduction techniques) to improve the Monte Carlo procedures. The optimal technique depends on the kind of results or on the accuracy which are desired and on the conditions of the experiment. A forward ray tracer such as Raytran is more appropriate to represent complex illumination conditions and is quite efficient to compute the vertical radiation fluxes or the albedo in the vegetation. To calculate more efficiently the bidirectional reflectance on the whole hemisphere, a probability weighting mechanism, which is adjusted after each interaction, could be assigned to the ray paths. The hardest issue is the development of an efficient Monte Carlo scheme to simulate finite-size aperture sensors with determined field-of-view, accounting for the multiple scattering and diffuse illuminations.

Further developments could also be undertaken to include the radiation transfer in the microwave and thermal infrared spectral regions. In both cases, additional information would be needed to characterize the scattering properties of the elements at these wavelengths. In the microwave region, the propagation of the phase and polarization of the rays should be modeled to represent interferometric effects. In Chapter (7), we saw that it is possible to compute the exact length of the ray trajectories. Likewise, it should be possible to reconstruct the propagation of a wave and its interception by an antenna. However, with regard to the size of the wavelength, the role of the diffraction of radiation by plant leaves cannot be underestimated. The explicit representation of each individual scattering element size, position and orientation is probably not necessary and may be replaced by appropriate scattering phase functions. In the infrared region, it is necessary to represent the thermal emission of the elements. As we did for energy sources, an emission distribution function could be assigned to each object. Clearly, Raytran could be used to simulate the transfer of radiation (including the thermal domain) independently of the thermodynamic state of the system. However, in order to convert the fluxes of the absorbed or emitted radiation into heating and cooling rates and predict the thermal state of the system some small time interval later, new properties must be associated to all objects in the scene, such as their specific thermal capacities.

Raytran could also be used for applications not directly linked to remote sensing observations. For instance, the albedo of different biomes could be modeled for various illumination conditions. This information is useful to calculate the energy budget at the soil-vegetation-atmosphere interface in global circulation models. Raytran can estimate the light absorbed by a single leaf in a plant canopy. In turn, this information can be used in plant growth model. Our model could also be used for industrial applications to simulate the transmittance or reflectance of particular materials. In addition, since we succeeded in simulating the propagation of light throughout the various tissues of a plant leaf, this approach could be extended to the simulation of the radiation penetration and absorption in human tissues for medical research purposes.

The development of the Raytran model has been primarily motivated by the need to simulate the radiation transfer in a coupled system as complex as the soil, the vegetation and the atmosphere in order to work out advanced techniques for the interpretation of remote
sensing observations in the optical spectral region. With respect to this objective, our re-
search work constitutes principally an original contribution to a topical issue which uses the
latest techniques of computer graphics and parallel computing. However, beyond the practical
considerations which have been discussed above, it is worth underscoring the significant con-
tribution of this work with respect to the current effort undertaken to understand and predict
biospheric processes in the framework of the Global Change issue. Since most of these processes
cannot be reproduced in laboratories because of their temporal or spatial scales, mathematical
models provide the only practical solution to their studies. However, the complexity and the
diversity of the phenomena which have to be represented is a serious impediment to the un-
derstanding and prediction of global changes. Hence, the main issue is not only to model the
various individual subsystems by equations but to account for the hierarchical organization of
the subsystems across a range of space and time scales. The crux of the problem lies therefore
in the capability of representing multiscale interacting subsystems. Clearly, advanced tech-
niques able to represent these multiscale systems and to link ecological, chemical and physical
processes are highly desirable. The elaborate design methods we use to work out the concept
of virtual laboratory represent a relevant step in this direction. The design of the model
is not based on a hierarchical representation of the spatial scales but of the inter-
acting elements. As a result, it allows us to investigate which information must be retained
when one switches from one scale to another one such as, from the leaf to the plant, or, from
the plant to the canopy. We strongly encourage mathematical model designers in other geo-
physical branches to investigate the potential of this technique to represent arbitrarily complex
systems.
Bibliography


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Annex A

Fundamentals of Monte Carlo methods

Monte Carlo modeling is essentially a statistical method used to estimate certain average characteristics (e.g., mathematical expectations, variances and covariances) of complex processes. Raytran is based on a straightforward Monte Carlo technique in the sense that rays are generated in the forward direction without using any variance reduction techniques. In the case of a direct simulation processing, the Monte Carlo procedure itself involves three main steps: the generation of random numbers, the generation of more complex distributions on the basis of these numbers and finally the estimation of statistical properties of the simulated process (Ross and Marshak 1991).

A.1 Generation of random numbers

The generation of random numbers $U = u_1 \ldots u_N$ with a “random number generator” is required to build a uniform distribution. The algorithm which generates random numbers must be selected with care otherwise the resulting series may exhibit some periodicity. A pseudo-random generator is an algorithm which produces a sequence of numbers as uncorrelated as possible. We used the very long period pseudo-random generator developed by Marsaglia et al. (1990). Different seed values give rises to independent sequences of sufficient length for an entire calculation (James 1990). This property is needed when the code is implemented on a parallel machine where each node must be able to generate its own sequence. In the present case, the quasi-random generator suggested by Sobol (1992), which produces sequences with uniform rather than uncorrelated random numbers, is not appropriate. Indeed, this approach would require the definition in advance of the number of interactions per ray$^1$. Let us assume that $U = u_1 \ldots u_N$ are independent random values uniformly distributed between 0 and 1. The “probability distribution function” of a rectangular distribution $f_U(u)du$ to generate a

$^1$I. M. Sobol, personal communication
number in the interval \([u, u + du]\) is given by

\[
f_U(u)du = \begin{cases} 
  du & \text{for } 0 \leq u \leq 1 \\
  0 & \text{otherwise}
\end{cases}
\] (A.1)

The “probability density function” is

\[
f_U(u) = \begin{cases} 
  1 & \text{for } 0 \leq u \leq 1 \\
  0 & \text{otherwise}
\end{cases}
\] (A.2)

The associated “cumulative distribution function” is

\[
F_U(u) = \begin{cases} 
  0 & \text{for } u < 0 \\
  u & \text{for } 0 \leq u \leq 1 \\
  1 & \text{for } u > 1
\end{cases}
\] (A.3)

### A.2 Generation of random variates

The computation of random variables characterized by more complicated distribution functions of \(U\) is the core of Monte Carlo simulation techniques. Various methods exist to generate non-uniform random variates from probability distribution functions. These procedures are based on the following three methods: (1) inverse-transform method, (2) composition method and (3) acceptance-rejection method (Devroye 1986). The choice of one method or another depends on the form of distribution to be generated and on the affordable computer or resources available. In Raytran, we use either the inverse transform or acceptance-rejection methods according to the type of distribution. The inverse-transform method may be called a “direct” method in the sense that it deals directly with the probability distribution function to generate the random deviate. Let \(y_U(u)\) be a uniform distribution function on \([0,1]\) and \(X\) some arbitrary distribution of \(y\). The probability distribution of \(y\), denoted \(f_X(y)dy\), is determined by \(|f_X(y)dy| = |f_U(u)du|\). With \(f_U(u)\) given by equation (A.2), the solution of the differential equation

\[
\frac{du}{dy} = f_X(y)
\] (A.4)

is \(u = F_X(y)\), where \(F_X(y)\) is the definite integral of \(f_X(y)\)

\[
F_X(y) = \int_0^y f_X(y')dy'.
\] (A.5)

The inverse-transform method which turns a uniform deviate \(U\) into one distributed in \(X\) is thus

\[
y(u) = F_X^{-1}(u)
\] (A.6)

where \(F_X^{-1}\) is the inverse function to \(F_X\).

The acceptance-rejection method requires the specification of a function \(t\) which majorizes the probability distribution function \(f_X\), i.e., \(t(x) \geq f_X(x)\) for all \(x\). Let us define a majorizing function \(r(x)\)

\[
r(x) = \frac{t(x)}{\int_{-\infty}^{\infty} t(x)dx}
\] (A.7)
where \( r \) is a probability distribution function with which it must be possible to generate easily a random variate \( Y \) with the inverse transform method. The principle is thus to generate two random variates, \( Y \) and \( U \) and to test whether or not the inequality \( U \leq f(Y)/t(Y) \) holds. If the inequality holds, then \( Y \) is accepted as variate generated from \( f_X(x) \) otherwise the pair \( Y, U \) is rejected and another try is performed. The choice of the majorizing function depends on two principles: the computation of \( Y \) must be cheap and it must be close enough to \( f_X(x) \) not to reject too many tries.

### A.3 Estimation of statistical properties

A statistical property \( E \) of the simulated process is estimated by the realization of random variables \( \xi_i \), obtained in step 2. The quantities \( \xi_i = \xi_i(\alpha_i) \) which typically represent the probability of a random walk in the medium, are then independent realizations of \( \alpha_i \) with expectation

\[
E(\xi) = \int_0^1 \xi(\alpha) dP(\alpha)
\]

(A.8)

where \( P(\alpha) \) is the cumulative distribution function of \( \alpha \). If this function has a derivative \( p(\alpha) d\alpha \) where \( p(\alpha) \) is the probability density function of \( \alpha \), equation (A.8) becomes

\[
E(\xi) = \int_0^1 \xi(\alpha) p(\alpha) d\alpha.
\]

(A.9)

Therefore,

\[
\langle \xi \rangle = \frac{1}{N} \sum_{i=1}^N \xi_i
\]

(A.10)

is an unbiased estimator of \( E(\xi) \) when there is a finite but large number \( N \) of realizations. The variance of \( \langle \xi \rangle \) is

\[
\frac{\sigma^2}{N} = \frac{1}{N} \int_0^1 (\xi(\alpha) - E(\xi))^2 d\alpha.
\]

(A.11)

The standard error of \( \langle \xi \rangle \) is \( \sigma_{\langle \xi \rangle} = \sigma/\sqrt{N} \) and the confidence limits for estimating \( E(\xi) \) are given by \( E(\xi) \approx \langle \xi \rangle \pm z_c \sigma_{\langle \xi \rangle} \) where \( z_c \) is a constant which depends on the confidence level \( p \). For a given confidence level \( p \), the number of samples \( N \) must be chosen such that

\[
|E(\xi) - \langle \xi \rangle| \leq z_c \frac{\sigma}{\sqrt{N}}.
\]

(A.12)

Generally, the standard error \( \sigma_{\langle \xi \rangle} \) is unknown and must be estimated by its corresponding estimator

\[
s^2 = \frac{1}{N-1} \sum_{i=1}^N (\xi_i - \langle \xi \rangle)^2 = \frac{\sum_{i=1}^N \xi_i^2}{N} - \left( \frac{\sum_{i=1}^N \xi_i}{N} \right)^2.
\]

(A.13)

Since we use a straightforward Monte Carlo method without weighting mechanisms associated with the trajectory of each ray, the probability \( \xi_i \) of a ray path contributing to the realization of \( E \) is thus equal to 0 or 1. Equation A.13 may now be rewritten as

\[
s^2 = \frac{N_s}{N} \left( 1 - \frac{N_s}{N} \right)
\]

(A.14)
where $N_s$ is the number of ray paths which actually contribute to the realization of $E$ while $N$ is the total number of trials.
Annex B

Raytran code structure and parallel implementation

Raytran is written in C language using object oriented programming technique. The aim of this method is to organize the code around the data structure rather than on the procedures. Thus, instead of collecting the intersection routines into one module and the computation of the normal vector into another, the procedures for each geometrical primitive type (creation, intersection, normal, etc) are collected into a module of its own. This module (or object) provides therefore public “services” (or functions) to the code such as the computation of the intersection with a ray through controlled interface mechanisms. To deliver these services, the object uses its own “private” information which is not accessible by the other objects. However, an object may inherit the properties of a “ancestor” object. For instance, the object which describes the geometrical primitives inherit the properties of the object which describes the optical characteristics (interaction models). The main advantage of the method is a data abstraction which avoids large switch statement for each type of primitive or interaction model.

The first step of an object oriented code construction is to identify the various objects and to define their hierarchical organization (or inheritance), starting from the ancestor or bottom objects. The main objects of the Raytran model are summarized in Table (B.1). Figure (B.1) represents the hierarchical inheritance of these objects. At the lower level, the Distribution object delivers information on the scattering and emission distribution functions. The properties of this object are inherited by the Source and Interaction objects. In turns, the Interaction object is inherited by the Geom object and so on. This hierarchical organization shows clearly the main structure of the program. Rays are traced independently of any measurements. When a ray is completely traced, all the different measurements are applied.

The experiment to be performed is described in an ASCII file which contains the definition of the energy sources, the primitives and their interaction models and finally the measurements. This file is processed with the yacc parser. Each object has its own function to be instantiated (created) on the basis of these input data.

The parallel implementation of the Raytran model assumes a distributed memory parallel
### Table B.1: Main objects of the Raytran model.

<table>
<thead>
<tr>
<th>Name</th>
<th>Purpose</th>
<th>Main functions</th>
</tr>
</thead>
</table>
| Distribution  | Scattering distribution functions | object creation  
distribution function  
random variate  
probability density function |
| Interaction   | Ray-matter interaction model   | object creation  
interaction type  
outgoing direction |
| Geom†         | Geometrical primitives        | object creation  
intersection point  
normal to the intersection point  
bounding volume |
| Path          | Propagation of a ray          | object creation  
path initialization  
trace a path ray  
terminate a path |
| Source        | Energy sources                | object creation  
ray origin  
ray emission direction |
| Filter        | Filter a ray path             | object creation  
apply the filter |
| Measurement‡  | Extract information from the paths | object creation  
measurement initialization  
apply the measurement  
save the results to files |
| Scan‡         | Control the propagation model | object creation  
scan the energy sources  
control the propagation mode |

† indicates the object which is shared with the Rayshade code. ‡ indicates the objects which are concerned by the parallelization of Raytran.
processors (DMPP) architecture and is based on the message passing technique (Krishnamurthy 1989). The basic design therefore relies on the fact that each node (processor) contains a full description of the scene and the various experiments to be performed (statistics to extract on the ray paths). The optimization of the code is firstly based on the parallel processing requirements rather than on classical Monte Carlo optimization procedures. For instance, to minimize the need for synchronization between the nodes, one has to specify a priori the total number of rays to generate while traditional design would stop the process when a given result accuracy is reached. In addition, we designed Raytran to run in the same manner on any UNIX sequential machine, on a cluster of workstations or on an actual DMPP machine, such as the NEC Cenju-3 (Flükiger et al. 1994) at the Centro Svizzero di Calcolo Scientifico (CSCS) which has been extensively used to perform the various sensitivity studies described in this work. To achieve this objective, the code is divided into three main layers:

1. **The tracer layer.** This layer is responsible for I/O operations, creating the tables corresponding to the experiment description, tracing the rays and extracting the desired statistics. This layer contains the main part of the code.

2. **The job sharing and message buffering layer.** The routines of this layers distribute the jobs between the different nodes, synchronize them, broadcast the description of the experiments to each node and gather the final statistics. This layer affects only the **Scan** and **Measurement** objects.

3. **Communication layer.** This layer ensures the communication between the processors through the Message Passing Interface (MPI), an accepted industry standard for message passing (Message Passing Interface Forum 1994).
The first layer is common to all implementations while the last two apply only to the parallel version. The second layer differs slightly for the cluster of workstations or DMPP machine implementation. The former is based on a classical Master-Slave configuration and assumes a potentially heterogeneous network. The Master reads the input file and broadcasts it to the Slaves. Each node performs consistency checks and builds its own tables. When this operation is completed, each Slave sends a “request_of_job” message to the master. A job consists of a number of rays to be generated for a given light source. While waiting “request_of_job” messages, the Master traces rays. When all the rays have been traced, the Master sends a “stop_trace” message to the Slaves and gathers the requested statistics on the ray trajectories. Increasing the number of rays in a job will decrease the number of exchanged messages. However, too large jobs will penalize the slower nodes, especially at the end of the process when the Master has to wait for the last Slave node before collecting the results. To reduce waiting time, the Master monitors the efficiency of each node, comparing individual performances with the mean performance, such that slow nodes receive smaller jobs.

In the DMPP implementation, all nodes are essentially equivalent. Due to the lack of I/O management capabilities within MPI, we wrote specific routines for that purpose. On the Cenju-3 for instance, it is much more efficient to have one node read the input file and dispatch it to the other nodes, rather than to give each node access to the input file. An input file is typically a few Megabytes in size. Only one node is allowed to perform I/O operations, i.e., to read the input file and to write the results. Each node traces rays individually on the basis of the total number of rays to be generated and the number of cooperating nodes. The only messages which are exchanged concern the dispatching of the input file and the gathering of the results. As a result, the speed of execution is directly related to the number of processors, as can be seen on Figure (B.2). This test has been carried out using a standard scene made of 4000 Lambertian discs with an absorptance of 0.3 and lit with $50 \times 10^6$ rays. The BRF and the extinction profile have been computed.

The platform (sequential computer, cluster of workstations or DMPP machine) is chosen at compile-time, and is completely transparent to the user at the run-time. The parallel version is intrinsically scalable and offers the opportunity to consider complex problems and unprecedented numbers of incident rays. It takes full advantage of DMPP machines to solve Monte Carlo problems.

The computer time required to perform an experiment depends first on the number of rays which are generated. This number if dictated by the type of measurements. Typically, the calculation of the albedo or the extinction profile in the scene necessitates the generation of less ray than the computation of the BRF with a high angular resolution. Another factor which determines the computer time is the distribution function which are used to characterize the optical properties of the objects. The number of interactions per ray which depends on the absorption of the interacting objects also determines the computer time. Finally, the computer time depends on the type of geometrical primitives and the use of CSG objects. The number of geometrical primitives does not really affect the computer time. Table (B.2) gives the CPU time of different UNIX workstations and clusters of workstations for the same standard experiment as used for the Cenju-3 speedup test.
<table>
<thead>
<tr>
<th>Platform</th>
<th>Compiler</th>
<th>CPU time</th>
<th>Speedup</th>
</tr>
</thead>
<tbody>
<tr>
<td>IBM Risc 6000 220</td>
<td>cc -O2</td>
<td>79588.32</td>
<td>1.</td>
</tr>
<tr>
<td>SUN SPARC 10-40MHz</td>
<td>acc -O2</td>
<td>61977.43</td>
<td>1.282</td>
</tr>
<tr>
<td>SUN SPARC 10-40MHz</td>
<td>acc -O4</td>
<td>55441.56</td>
<td>1.433</td>
</tr>
<tr>
<td>IBM Risc 6000 320</td>
<td>cc -O2</td>
<td>55410.69</td>
<td>1.436</td>
</tr>
<tr>
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<td>acc -O2</td>
<td>31173.70</td>
<td>2.553</td>
</tr>
<tr>
<td>SUN SPARC 10-50MHz</td>
<td>acc -O4</td>
<td>28693.37</td>
<td>2.774</td>
</tr>
<tr>
<td>IBM Risc 6000 360</td>
<td>cc -O2</td>
<td>21963.20</td>
<td>3.624</td>
</tr>
<tr>
<td>IBM Risc 6000 360</td>
<td>cc -O3</td>
<td>21648.44</td>
<td>3.676</td>
</tr>
<tr>
<td>5 IBM Risc 6000 220 ‡</td>
<td>hcc</td>
<td>17299.51</td>
<td>4.601</td>
</tr>
<tr>
<td>IBM Risc 6000 580</td>
<td>cc -O2</td>
<td>16670.17</td>
<td>4.774</td>
</tr>
<tr>
<td>IBM Risc 6000 580</td>
<td>cc -O3</td>
<td>16450.92</td>
<td>4.838</td>
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<tr>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IBM Risc 6000 580 ‡</td>
<td>hcc</td>
<td>4836.93</td>
<td>16.394</td>
</tr>
</tbody>
</table>

Table B.2: Standard experiment CPU time in second for various workstations and clusters of workstations. The speedup coefficient is computed with respect to the slowest machine. ‡ indicates Master-Slave configuration.
Figure B.2: Speedup of the Raytran processes. The speedup is calculated as the ratio between the computer time with one processor and the one with the actual number of used processors for the tests. The scene is composed of 4000 discs lit with $50 \times 10^6$ rays. The mean number of interactions per ray is 2.6.
Annex C

Scattering distribution functions

This Annex contains the different scattering distributions which have been implemented in Raytran.

C.1 Lambertian distribution function

In the case of a Lambertian surface, the reflectance distribution function is given by

\[ \rho(\theta_1, \phi_1; \theta_2, \phi_2) = \frac{D \cos \theta_2}{\pi} d\omega_2 \]  

(C.1)

such that the probability density function \( \rho_p = D \) and the normalized function is given by \( \cos \theta_2 d\omega_2/\pi \). The corresponding random variate is computed using the inverse transform method (Antyufeev and Marshak 1990b):

\[ \theta_2 = \arcsin(\sqrt{u_1}) \]  
\[ \phi_2 = 2\pi u_2 \]  

(C.2)  
\[ (C.3) \]

where \( u_1 \) and \( u_2 \) are uniformly distributed in \([0, 1]\). This distribution may be used to simulate the reflectance as well as the transmittance.

C.2 Gaussian distribution function

This function assumes that the scattering may be divided into two components: a diffuse Lambertian component as described above and a “specular” component. In the case of a phyto-element such as a leaf, several models (e.g., Vanderbilt et al. 1991; Nilson and Peterson 1991) assume the specular scattering contribution may be treated as a perfect mirror obeying the Fresnel formulae (3.2) multiplied by an attenuation factor \( K(\Omega_1, \Omega_L) \) to account for the effect of surface roughness such that

\[ \rho(\theta_1, \phi_1; \theta_2, \phi_2) = \left( D \frac{\cos \theta_2}{\pi} + F(\theta'_1, n_{12})K(\Omega_1, \Omega_L) \right) d\omega_2. \]  

(C.4)
ANNEX C. SCATTERING DISTRIBUTION FUNCTIONS

Figure C.1: Bidirectional reflectance calculated with the gaussian scattering distribution function at IZAs equal 0° (dashed-dotted line), 30° (dotted line) and 60° (solid line). $D = 0.3$, $n_{12} = 1.4$ and $\zeta = 0.2$.

These models assume the specular distribution $K(\Omega_1, \Omega_L)$ is a delta Dirac $\delta(\Omega - \Omega_2)$ function. However, if a surface roughness effect is included, the specular direction may not be a Dirac function anymore but is a peak whose spread depends on the surface roughness. As suggested by Ross and Marshak (1989), the specular contribution may be distributed according to a Gaussian distribution. For that purpose, the following function as been used

$$K(\Omega_1, \Omega_L) = M(\gamma) = \exp\left(-\frac{\tan^2 \gamma / \zeta^2}{\pi \zeta^2 \cos^3 \gamma}\right)$$  \hspace{1cm} (C.5)

Clearly, $\int_{2\pi} M(\gamma) d\omega = 1$ and the spread of the peak is a function of the surface roughness coefficient $\zeta$. $\gamma$ is the angle between the true specular direction $\Omega_2$ and the actual Gaussian dispersion direction. The maximum value allowed $\gamma_m$ for the angle $\gamma$ is a function of the directions $\Omega_1$ and $\Omega_L$ and is given by

$$\tan^2 \gamma_m = 1 / \left(1 - (\Omega_1 \cdot \Omega_L)^2\right).$$  \hspace{1cm} (C.6)

Figure (C.1) shows the shape of the function for various values of IZAs. To compute the outgoing direction, the diffuse or specular contribution is first selected at random according to the $D$ and $F(\theta'_1, n_{12})$ values such that the ray is diffusely reflected if $u \leq D/(D + F(\theta'_1, n_{12}))$. In the case of diffuse scattering, the direction is simulated with equation (C.3). Otherwise, the inverse transform of equation (C.5) is estimated with

$$\gamma = \arctan \left(\zeta \sqrt{-\ln u_1}\right)$$  \hspace{1cm} (C.7)

where $u_1$ varies between $\exp\left(-\tan^2 \gamma_m / \zeta^2\right)$ and 1. This distribution may be used to simulate reflectance only. Note that $D$ must be chosen in order that $D + F(\theta'_1, n_{12}) \leq 1$ for all $\theta'_1$ belonging to $[0, \pi/2]$. 
C.3 Torrance distribution function

In the previous distribution, the effects of surface roughness are very simply represented with the function $M(\gamma)$. However, these effects may be responsible for more complex phenomena than a simple Gaussian dispersion. Torrance et al. (1966) have observed that surface roughness may be responsible for off-specular reflection phenomena, as has been observed from a aluminium plate. Their model assumes that the surface consists of small, randomly distributed mirror-like micro-facets (Torrance and Sparrow 1967). The scattering function is expressed as

$$
\rho(\theta_1, \phi_1; \theta_2, \phi_2) = \frac{1}{\pi} \left[ D \cos \theta_2 + S F(\theta_p, n_{12}) T(\Omega_1, \Omega_L, \Omega_2) A(\Omega_1, \Omega_L, \Omega_2) \right] \, d\omega_2. \tag{C.8}
$$

where $S$ is a scaling factor and

- $F(\theta_p, n_{12})$ is the Fresnel reflection given by equation 3.2 where $\cos \theta_p = (\Omega_1 \cdot \Omega_H)$ with $\Omega_H = (\Omega_1 + \Omega_2)/2$.

- $T(\Omega_1, \Omega_L, \Omega_2)$ is the micro-facet distribution. This distribution function gives the number of micro-facets oriented in the direction $\Omega_2$ and is given by the Beckmann distribution (Cook and Torrance 1981)

$$
T(\Omega_1, \Omega_L, \Omega_2) = \exp\left(-\frac{\tan^2 \beta}{m^2}\right) \frac{4 m^2 \cos^4 \beta}{m^2} \tag{C.9}
$$

where $m \in [0, 1]$ is the root mean square slope of the facets. Small values ($< 0.2$) of $m$ characterize a smooth surface. Large values give a spread distribution. $\cos \beta$ is equal to $(\Omega_L \cdot \Omega_H)$.

- $A(\Omega_1, \Omega_L, \Omega_2)$ is a geometric attenuation term accounting for self-shadowing, i.e., the amount by which facets shadow and mask each other. This is an important effect whose formulae are given in (Blinn 1977).

The corresponding density function is numerically integrated with the Gaussian quadrature method and stored in a look-up table. The associated random variate is computed with an acceptance-rejection scheme. This model may be used to simulate reflectance only. While very attractive and widely used in computer graphics, this model suffers from intrinsic limitations such as the decomposition of the reflectance into a diffuse and a specular component. This assumption may be justified for a given illumination angle. However, inverting this model against the measured reflectances of a sanded aluminium plate, we found (Chapter 4) that the terms $D$ and $S$ strongly depend on the zenith illumination angles.

C.4 SOILSPEC distribution function

Granular surfaces with a particle size greater than the wavelength may generate opposition effects. Hapke has developed a very elegant formulation for this kind of surface which has been improved by many authors (Pinty et al. 1989; Jacquemoud et al. 1992). The SOILSPEC
model of the last authors has been implemented for non-transmitting surfaces. This model is perfectly suited to simulate bidirectional reflectances of bare soils. The corresponding density function is numerically integrated and the result stored in a look-up table. The associated random variate is computed with a acceptance-rejection scheme.
Annex D

Optical thickness of pseudo-turbid media

Dense uniform canopies may be represented as homogeneous scattering media (HSM) provided that the finite-size and orientation of the leaves are taken into account. The structural properties of such media can be described with the following parameters: the leaf area density (Λ), the coefficients of the scatterer normal distribution and finally the mean horizontal \( a_h \) and vertical \( a_v \) areas between the scatterers. The simulation of a collision in that medium is expressed as a function of its optical thickness. The optical thickness \( \tau(\Omega_1) \) in direction \( \Omega_1 \) of the incoming radiation is simply defined as (Verstraete 1987)

\[
\tau(\Omega_1) = \Lambda \sigma(\Omega_1) \quad (D.1)
\]

and has the dimension of the inverse of distance. \( \sigma(\Omega_1) \) is the total interaction cross section and is defined by the Ross function (Ross 1981):

\[
\sigma(\Omega_1) = G(\Omega_1) = \frac{1}{2\pi} \int_{4\pi} g_L(\Omega_L) |\Omega_1 \cdot \Omega_L| d\Omega_L \quad (D.2)
\]

where \( \int_{4\pi} \) indicates the integral over the sphere. The function \( g_L(\Omega_L)/2\pi \) is the leaf normal distribution function. If this function is uniform with regard to the azimuth direction \( \phi_L \), it may be rewritten as \( g_\theta(\theta_L)/2\pi \). The different functions which are commonly used to characterize this distribution have been presented in Section (6.3). To save computer time, the \( G(\Omega_1) \) function is numerically integrated once for all and stored in a look-up table. After the first scattering, equation (D.2) must be slightly modified to take into account the correlation between the incoming and the outgoing directions. In this case, the ray being scattered back exactly in the incoming direction must obviously be able to exit the medium without further interaction. To express this “hot spot” phenomenon, the geometrical-statistical approach developed by Verstraete et al. (1990) has been adopted. We present here only the adaptation of the method in the case of a non plane parallel medium. Let \( \Omega_L \) be the normal to the surface of the object which describes the medium at the intersection point \( P_1 \) with the incoming ray (Figure D.1). We will assume that the horizontal \( a_h \) and vertical \( a_v \) areas between the scatterers are circular and that the size of the medium’s spatial extension is much larger than \( a_h \).
and \( a_v \) such that the surface may be assumed locally plane in \( P_1 \). The projection \( a_1 \) of \( a_h \) and \( a_v \) in \( P_1 \) on a plane perpendicular to \( \Omega_L(\theta_L, \phi_L) \) is equal to

\[
a_1 = a_h \cos \theta_L + a_v \sin \theta_L. \quad \text{(D.3)}
\]

Instead of tracing a single ray, the trajectory of a beam in the medium will be considered. \( a_1 \)

![Figure D.1: Geometry of illumination of a scattering homogeneous medium. \( P_1 \) is the point where the ray of direction \( \Omega_1 \) intersect the medium envelope. \( \Omega_N \) is the normal to the surface in \( P_1 \). \( a_1 \) defines the surface of the corresponding beam projected in a plane perpendicular to \( \Omega_L \). \( P_2 \) is the simulated point of interaction in the medium and \( a_2 \) the section of the beam at that point. \( V_1 \) and \( V_2 \) are the cylinders which define the incoming and outgoing beams.](image)

represents therefore the section of this beam in \( P_1 \). This section decreases exponentially along the direction \( \Omega_1 \) until \( P_2 \) as

\[
a_2 = a_1 \exp(-\tau(\Omega_1)d_{a1}) \quad \text{(D.4)}
\]

where \( d_{a1} \) is the distance between \( P_1 \) and \( P_2 \) which is the point of interaction in the medium as given by equation (3.17). The area \( a_2 \) characterizes the section of the beam, projected on a plane perpendicular to \( \Omega_L \), along the trajectory \( P_1 \rightarrow P_2 \). This area and the direction \( \Omega_2 \) define therefore a cylinder \( V_2 \) which shares a common basis in \( P_3 \) with the cylinder \( V_1 \) in the direction \( \Omega_1 \). Consequently, as long as the rays scattered in \( P_2 \) remain in the volume common to the two cylinders, the optical thickness is zero. The effective interaction cross section in the direction \( \Omega_2 \) should be proportional to the ratio \( V/V_2 \) where \( V \) is the proportion of \( V_2 \) not common to \( V_1 \):

\[
\sigma(\Omega_2) = \frac{V}{V_2} G(\Omega_2) \quad \text{(D.5)}
\]
The expression of $V/V_2$ is given in Verstraete et al. (1990) with the difference that, in the present case, the plane parallel system which is used to derive the expression is perpendicular to the direction $\Omega_L$. After the second collision and for higher order, the relation (D.2) is used to compute the optical thickness.

The normal $\Omega_{L_2}$ at the simulated collision points $P_2$ is generated with the following distribution (Antyufeev and Marshak 1990b):

$$p(\Omega_{L_2}) = \frac{g_L(\Omega_{L_2}) |\Omega_1 \cdot \Omega_{L_2}|}{2\pi G(\Omega_1)}.$$  \hspace{1cm} (D.6)

The direction $\Omega_{L_2}$ is sampled with a rejection method.
ANNEX D. OPTICAL THICKNESS OF PSEUDO-TURBID MEDIA
Annex E

L-system principles

The principle of L-systems is based on the central concept of parallel rewriting, by successively replacing parts of simple objects which form an alphabet, using a set of production rules, starting from an initial condition or string of characters called the axiom. In the course of the algorithm, a long string of characters is generated. For example, the rule \( p_1 : a \rightarrow ab \) means that the letter \( a \) is to be replaced by the string \( ab \) and the production rule \( p_2 : b \rightarrow a \) means that the letter \( b \) is to be replaced by \( a \). If we assume that the axiom is the letter \( b \), in the first step of rewriting, \( b \) is replaced by \( a \) using rule \( p_2 \). In the second step, \( a \) is replaced by \( ab \) using production rule \( p_1 \). In the next rewriting step, both \( a \) and \( b \) are simultaneously and independently subjected to \( p_1 \) and \( p_2 \), and the resulting string is \( aba \). The next derivation generates the string \( abaab \) which in turn yields \( abaababa \) and so on (see Table E.1). The correspondence between the strings produced and the geometric interpretation is established via a ‘LOGO-like turtle’ (Papert 1980) which interprets the characters sequentially as basic commands such as “move forward”, “turn left”, and so on. In a tridimensional space, the state of the turtle is defined by its position and three vectors which define its current orientation (Prusinkiewicz and Lindenmayer 1990).

<table>
<thead>
<tr>
<th>Axiom</th>
<th>( \omega ) : b</th>
</tr>
</thead>
<tbody>
<tr>
<td>Production rules</td>
<td>( p_1 : a \rightarrow ab )</td>
</tr>
<tr>
<td></td>
<td>( p_2 : b \rightarrow a )</td>
</tr>
<tr>
<td>Derivation</td>
<td>( 0 ) ( b )</td>
</tr>
<tr>
<td></td>
<td>( 1 ) ( a )</td>
</tr>
<tr>
<td></td>
<td>( 2 ) ( ab )</td>
</tr>
<tr>
<td></td>
<td>( 3 ) ( aba )</td>
</tr>
<tr>
<td></td>
<td>( 4 ) ( abaab )</td>
</tr>
<tr>
<td></td>
<td>( 5 ) ( abaababa )</td>
</tr>
<tr>
<td></td>
<td>( \ldots ) ( \ldots )</td>
</tr>
</tbody>
</table>

Table E.1: Example of definition and derivation of an L-system.
There are many kinds of L-systems. The simplest one, the 0L-system may be formally defined as an ordered triplet \((V, \omega, P)\), where \(V\) is the alphabet, \(\omega\) is the axiom which is a non-empty word from the alphabet and \(P\) is a finite set of productions rules. A pair \((a, x)\) composed of a letter \(a\) and the word \(x\) is called the production, and is written as \(a \rightarrow x\). The letter \(a\) and the word \(x\) are called the predecessor and the successor of this production, respectively. A 0L-system is deterministic (D0L-system) if and only if for each letter \(a\) of the alphabet \(V\), there is exactly one word \(x\) such that \(a \rightarrow x\). Thus, in such L-systems, the number of productions cannot exceed the number of symbols in the alphabet of the L-system. A simple example of 0L-system is given in Figure (E.1) with the interpretation of the turtle movements.

| alphabet :  | `F`   | `-`  | `+`  |
| axiom :    | `F - F - F - F` |
| production: | `F \rightarrow F - F + F + FF - F - F + F` |

Turtle interpretation of strings:
- \(F\) : move forward a step of length \(d\)
- \(+\) : turn left by an angle \(\delta\) (90°)
- \(-\) : turn right by an angle \(\delta\) (90°)

Figure E.1: von Koch quadratic island. Top: definition of the corresponding D0L-system with the geometric interpretation rules. Bottom: the first 2 stages in the generation of the system.

Various extensions of the 0L-system have been proposed and studied to achieve flexibility and variety in the sequences of symbols that can be generated by the L-systems. We list here the main features we used in the present study. In a stochastic L-system, for one or more symbols, there is a set of rules such as \(a \overset{l}{\rightarrow} x\), \(a \overset{m}{\rightarrow} y\), which are applied with specific probabilities \(l\) and \(m\) with \(l + m = 1\). So far, L-systems are only able to represent discrete values and fail to capture properly continuous phenomena. To solve this problem, numerical parameters can be associated with production rules to give parametric L-systems, a formal definition of which is given in Prusinkiewicz and Lindenmayer (1990). A T0L-system (T is for table) is an ordered quadruplet \((V, \omega, P, T)\) where \(V, \omega, P\) have the same definition as for the 0L-system and \(T\) is a finite non-empty collection of subsets of \(P\), called tables. It is assumed that for each table \(t\) belonging to the collection \(T\), and for each letter \(a\), there is at least one production rule \(p\) in table \(t\) with the predecessor \(a\) (Goel et al. 1991). Such systems are used to describe two or more successive phases of growth by means of a change in the production rules. These changes in production rules can be used to alter the growth of the structure after a certain number of stages.T0L-systems can be combined with parametric ones as illustrated
in Table (E.2). Another useful implementation of the L-systems can be used to simulate branching mechanisms by saving the position and orientation of the turtle before generating a new axis and then restoring the original position of the turtle. Moreover, it is also possible to introduce a “tropism vector” to represent phenomena which influence physiological processes. This vector adjusts the orientation of the turtle in response to a stimulus, such as light or gravity.

Although the L-systems are very similar to fractals as is evident from Figure (E.1), they present the advantage of being more versatile and convenient for simultaneously manipulating different types of object. They also lend themselves rather easily to the mathematical description of simple physiological processes in the form of production rules. In the framework of canopy reflectance modeling, L-systems offer a unique opportunity to describe plant architecture with a very high level of complexity and realism, using a set of geometrical objects of given shape, size and position.

<table>
<thead>
<tr>
<th>Axiom</th>
<th>( \omega ) :</th>
<th>( A(4, 4), B(2) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Production rules</td>
<td>( p_1 ) :</td>
<td>( A(x, y) ) :</td>
</tr>
<tr>
<td></td>
<td>( p_2 ) :</td>
<td>( A(x, y) ) :</td>
</tr>
<tr>
<td></td>
<td>( p_3 ) :</td>
<td>( B(x) ) :</td>
</tr>
<tr>
<td></td>
<td>( p_4 ) :</td>
<td>( B(x) ) :</td>
</tr>
</tbody>
</table>

Table E.2: Example of production rules for a parametric T0L-system.