Forest Volume Estimation using a Canopy Reflectance Model in Multiple-Forward-Mode, Kananaskis, Alberta

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ABSTRACT

Three dimensional canopy geometric optical reflectance models provide a physical-structural basis to the analysis of satellite imagery, representing a potentially more robust, objective and accurate approach for obtaining forest cover type and structural information for volume estimation compared to existing image analysis methods. In this study, the Geometric Optical Mutual Shadowing (GOMS) reflectance model was run in multiple-forward-mode (MFM) and used with digital multispectral IKONOS satellite imagery to estimate mean tree height by area and stand volume for a Rocky Mountain study site in Kananaskis, Alberta. Stand volume was estimated as a function of mean tree height and basal area over a series of $100m^2$ plots. Average tree height per plot was obtained from MFM model runs, with basal area per hectare calculated as a function of diameter at breast height (dbh). Stem counts were derived from the MFM density and horizontal crown radius model output, with MFM derived dbh estimated using a relationship between field measurements of dbh and height over specific species locations. Allometric relationships between these variables were used with MFM modeled tree heights to obtain dbh over larger areas. Results indicated that MFM modeled tree height was within 1.7m of field measured heights for conifers, and within 2.7m for deciduous species, with stem counts estimated to within 5 trees per $100m^2$ plot area. This result was combined with model derived basal area to estimate stand level volume to within 3.3 $m^3/100m^2$ for Trembling aspen, and 0.68 $m^3/100m^2$ for Lodgepole pine plots without the requirement for extensive ground based field measurements. This modeling approach can be used as a stand-alone capability or it may be integrated with existing air photo or satellite based forest inventories with distinct advantages over current methods.

INTRODUCTION

Forests are the most widely distributed ecosystem on Earth, producing 70 percent of the annual net global terrestrial carbon accumulation and resulting in the uptake of atmospheric carbon and the conversion of greenhouse CO_2 to O_2 (Wulder, 1998). Canada contains 10 percent of the global forest cover, with over 50 percent, or 2.4×10^{10} m^3 being commercially viable (Wulder, 1998, Hall *et al.,* 2001). Forest stand volume has been included in forest inventories and in estimates of carbon stocks along with a variety of ecological and environmental parameters. Forest stand volume refers to the total above ground volume of trees that is typically expressed in cubic metres per hectare (m^3/ha). This differs somewhat from merchantable timber volume, which is the net volume that may be processed to produce certain wood products based on utilization limits that define the proportion of the tree that may be harvested for a given product (Alberta Environmental Protection 1994). Individual tree volume is derived as a function of tree height and basal area. Basal area is the cross-sectional area at breast height defined at 1.3 m above ground. Stand volume expressed as m^3/ha is determined from the aggregation of individual tree volumes within a plot and typically expressed in m^3/ha units. Several previous remote sensing studies have estimated biomass and/or stand volume using conventional image analysis approaches, with mixed results (e.g. Trotter *et al.,* 1997; Anderson *et al.,* 1993; Guerra *et al.,* 1998; Franklin *et al.,* 2000; Friedl *et al.,* 1994; Soares *et al.,* 1995). However, these studies have relied on traditional empirical and/or statistical methods that require extensive field data collection, and further, they were conducted in areas of flat terrain. In this paper, we use a more direct and explicit approach to forest structure and biophysical parameter estimation using a canopy reflectance model, and we test this in a challenging area of mountainous terrain in western Canada.

Canopy geometric optical reflectance models can estimate a variety of forest structural and biophysical parameters over large regions. Recent advances in model utilization by Peddle *et al*. (1999-2003, described below) have resulted in new ways of using powerful 3-D forest models in which little or no *a priori* ground knowledge is required. Information such as land cover, tree height, density and stand volume can be provided over large areas where ground-based measurements are not readily available. As a result, these modeling capabilities are worthy of consideration for large area analyses such as assisting in updates to regional and national scale forest inventories and for monitoring carbon stocks for international policy compliance (e.g. Kyoto Protocol).

The Multiple-Forward-Mode (MFM) approach (Peddle, 1999) to canopy reflectance modeling has been used successfully with different sensors, canopy reflectance models, and in different forest ecosystems in a variety of applications. These include structural change detection of partially harvested mixed forests in New Brunswick (Peddle *et al*., 2003a), several studies in the BOREAS project involving model-based cluster labeling in unsupervised land cover classification, and independent per-pixel modeling for mapping 25 detailed land cover classes and LAI for a mosaic of 7 Landsat TM scenes covering the entire BOREAS region in Saskatchewan and Manitoba (Peddle *et al*., 2003bc). This approach has also been used for biomass estimation in western Newfoundland (Pilger *et al.,* 2002; Peddle *et al*., 2003d), land cover and biophysical parameter estimation in mountainous terrain using airborne casi data (Johnson *et al*., 2000), and in topographic correction of IKONOS imagery in the Rockies (Soenen *et al*., 2003). The use of MFM modeling in the national and international landcover mapping forestry contexts was also reviewed by Cihlar *et al.,* (2003) and Gamon *et al*., (2003).

In this paper, the MFM approach is used with the Geometric Optical Mutual Shadowing (GOMS) canopy reflectance model (Li and Strahler, 1992) for estimating forest biophysical parameters and stand volume from high spatial resolution multispectral IKONOS satellite imagery within the Rocky Mountains of southwestern Alberta. These stand volume estimates are relevant to the Alberta Vegetation Inventory (AVI) and for inclusion in carbon budget and biomass estimation studies. This study involved fieldwork to provide extensive validation of model results, however, this modeling approach is intended to operate with little or no ground level data collection

REFLECTANCE MODELING AND MFM

Biophysical modeling in remote sensing entails relating digital image data to biophysical features and phenomena on the ground (Lillesand and Kiefer, 1999). Vegetation canopy reflectance models provide a suite of powerful tools for estimating biophysical information from digital imagery (Abuelgasim and Strahler, 1994). Reflectance models provide physical descriptions of forest biophysical structure based on the geometry, structure and spectral characteristics of forest stands. These models characterize forest structure and vegetation spectral response with respect to sun-sensor-surface geometry to model the spectral information that would be obtained from a sensor viewing a forest canopy from above. When viewed from above, forest stands comprise several components or endmembers: the canopy, the shadows cast by the canopy, and the background understorey vegetation (Peddle *et al.,* 2000). Physical descriptors of forest stands are used as model inputs in terms of characteristic shapes of objects (individual trees), their spatial arrangement and density, and the spectral properties of the forest stand component endmembers of canopy, shadow and background (Li and Strahler, 1985, 1992). Traditionally, canopy reflectance models have been run in two distinct modes - forward and inverse. Forward mode utilizes physical descriptions of forest stands to compute waveband specific pixel reflectance values as output. Conversely, inverse mode requires the image reflectance values as input from which the model attempts to solve for the physical descriptors of canopy structure. However, model inversion can be complex, computationally demanding, with a “no-solution” result not uncommon. Furthermore, many of the more sophisticated canopy models are not invertible and can only be run in forward-mode, yet this level of model complexity is often required to meet forest information needs. These problems were addressed and solved with the development of the Multiple-Forward-Mode (MFM) approach to canopy reflectance modeling (Peddle, 1999). MFM was introduced as a different way of running canopy reflectance models in which model inversion output was achieved using only forward mode model runs, thus taking full advantage of model sophistication, forward-mode speed, with a more robust solution-set that is accessible to any type of canopy model regardless of its level of complexity. The principle implementation goal was to bring canopy models into the domain of regional and national scale image processing. MFM works using an algorithm that controls multiple runs of the model in forward mode where the input parameters are systematically varied according to user defined or automatically generated ranges, with all inputs and outputs from each model run stored in a look-up table (LUT) (Peddle *et al.,* 2000, 2003a). The reflectance values output by the model are matched with the remote sensing image reflectance values, with the physical structural model output obtained as the MFM structural parameters associated with a given match.

Another benefit of MFM over forward or inverse mode reflectance modeling is that exact model inputs are not required. Instead, only a model range and increment are used. These are easily obtained or estimated for small or large areas, even if no prior knowledge exists. This approach also enables the spatial variability of forest stands to be more accurately characterized (instead of using one sample mean for a given forward mode input such as crown width, a full range is applied and the best match determined). Accordingly, per-pixel analyses are more accurate and representative.

MFM-LUTs also provide a digital library of rich forestry information and serve as a valuable resource of information relating forest spectral response to their corresponding physical attributes. This can be used for direct land cover classification and/or biophysical-structural estimation, or for a variety of follow-on studies in which selected portions of an MFM-GOMS LUT would be analyzed statistically and/or output in graphical form for further analysis.

EXPERIMENTAL DESIGN

STUDY AREA AND DATA SET

The study area was centered at 51° 1'13"N, 115 ° 4'20"W in the Kananaskis region of the Rocky Mountains of southwestern Alberta, Canada. Elevation ranged from 1400m at Barrier Lake to 2010m (above mean sea level.) at the summit of the 'Prairie View' ridge. In the Kananaskis region, the microclimate ranges from warm and dry (xeric) conditions where Trembling Aspen (*Populus tremuloides* Michx.) and Lodgepole Pine (*Pinus contorta* Dougl.) flourish, to cool and moist (mesic) less variable conditions where White Spruce (*Picea glauca* (Moench) Voss) prevails. Balsam Poplar (*Populus balsamifera* L.) also occurs intermittently within stands dominated by aspen (Achuff, 1992; Kirby, 1973).

Digital multispectral IKONOS satellite data were acquired for the study area on August 27, 2001 with a solar zenith angle of 50.68° and solar azimuth of 154.37°. The image was radiometrically corrected to reflectance using spectroradiometer surface reflectance measurements of pseudo-invariant targets at established radiometric calibration sites in the area with reference to calibration coefficients supplied by the satellite image vendor (SpaceImaging, Boulder Colorado). The image was geometrically rectified using differentially corrected Trimble Pro-XRS GPS data collected in the field. Non-vegetated and mixed-wood areas were masked and excluded from analysis using maximum likelihood classification and validated against AVI data prior to height and stand volume estimation.

Forest stand structural data were collected in the field during July and August of 2001 and 2002 throughout eight distinct zones, each representing a different species/slope/aspect regime. A total of 41, 10m x 10m field plots located in softwood (n=19), hardwood (n=19) and mixed wood (n=3) stands were established throughout the study area. Plots were separated based on dominant species for model input and subsequent validation. Sample sizes were established with 130 trembling aspen trees selected for model estimation and validated against 247 trees from separate, independent plots, with 62 lodgepole pine trees analysed by MFM and validated against 189 pine trees from separate plots.

MFM input parameters for the GOMS model included stand density, horizontal crown radius, vertical crown radius, height to crown center, and height distribution. These physical descriptors were coupled with spectral reflectance values (endmember spectra) of the forest components (e.g. sunlit canopy, background, shadow) for the spectral bands being used. In this study, image based spectral endmembers (Table 1) were derived using a multi-dimensional scatterplot of the red and near-infrared (NIR) IKONOS bands and a pixel location/value interface from known homogeneous species areas, and incorporated with the physical structural input ranges and model step increments for MFM-GOMS runs for aspen and pine forest stands (Tables 2 and 3, respectively). In Tables 2 and 3, the number of different values run for each parameter is shown (n), with the resulting total number of model runs computed as the product of the number of runs for each parameter, which constitutes the MFM Look-up Table (LUT) size. These ranges were established with reference to available field data – however we emphasize that such field information is not required to specify these ranges for running MFM. The process can be entirely independent of field information, and, as discussed in Peddle et al. (2003c,d), Cihlar *et al*., (2003) and Gamon *et al*., (2003), the fact that MFM does not need field inputs is one of the fundamental tenets for its design and use for more regional and national scale studies.

	Trembling Aspen		Lodgepole Pine	
	Band 3 (red)	Band 4 (NIR)	Band 3 (red)	Band 4 (NIR)
Sunlit Canopy	4.2	48.7	4.5	37.4
Sunlit Background	11.2	38.2	10.5	33.3
Shadow	1.9	3.9	1.1	1.7

Table 1. Image based spectral endmember data.

Structural Ranges: Trembling Aspen				
Parameter	**Min**	**Max**	**Step**	***n***
Horizontal crown radius (r)	0.5	4	0.5	8
Vertical crown radius (b)	1.5	6.5	0.5	11
Height to center of crown (h)	3.5	18.5	1	13
Height distribution (dh)	16	16	1	1
Density (D)	5	95	10	10
		LUT size (returns)		**11440**

Table 2. Physical MFM-GOMS inputs - Aspen.

Structural Ranges: Lodgepole Pine				
Parameter	**Min**	**Max**	**Step**	***n***
Horizontal crown radius (r)	0.5	4	0.5	8
Vertical crown radius (b)	1.5	9.5	0.5	19
Height to center of crown (h)	5	11	1	9
Height distribution (dh)	16	16	1	1
Density (D)	5	95	10	10
		LUT size (returns)		**13680**

Table 3. Physical MFM-GOMS inputs - Pine.

MFM ANALYSIS OF FOREST STRUCTURE AND STAND VOLUME

MFM-GOMS outputs provided the necessary information to derive forest stand volume (Figure 1). The results were validated against volume estimates derived from field measurements. The same analysis sequence (Figure 1) and set of equations (discussed below) were used for both the field and MFM-based forest stand volume estimates. The only difference with MFM analysis was that the inputs to these equations were derived using the canopy reflectance model and remote sensing imagery, instead of field measurements. The field data are used primarily for comparison and validation of MFM results.

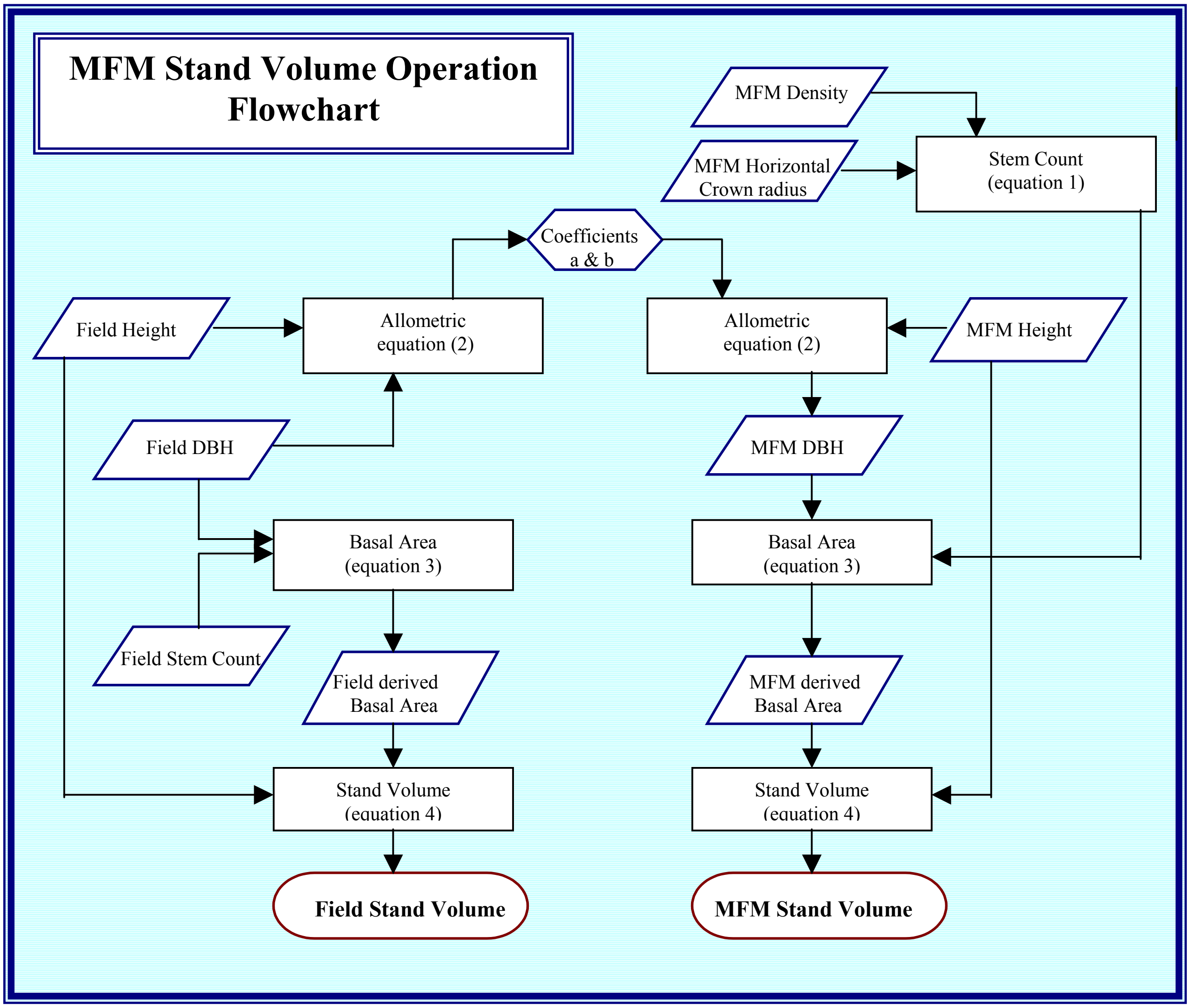

Figure 1. Flowchart of model operations for Stand Volume estimation.
(a & b = slope and intercept coefficients derived from scatterplots for Equation 2).

MFM-LUTs generated from model runs were exported to Microsoft Access and Excel for database searching and for generating follow-on statistical summaries, respectively. Database searches encompassed mean reflectance values +/- one standard deviation for known stand areas, with MFM-GOMS output (e.g. height, density, crown diameter) obtained from modeled reflectance values matching the red and NIR IKONOS image reflectance values.

Stand volume is a function of height and basal area. MFM mean tree height values per plot were calculated by summing all height to center of crown (h) and vertical crown radius (b) model results. These MFM tree heights were validated against field-based tree-height measurements to assess the level of agreement for use in stand volume calculations.

Model-based basal area was derived over forest stand plots as a function of diameter at breast height (dbh) and stem counts derived from MFM-GOMS. Stem count (T) was computed using the area of the forest plot in m^2 (A), MFM-LUT density (D) and MFM horizontal crown radius (r) using equation 1 (Peddle et al., 2003a):

$$\mathbf{T = (A * D) / (100\pi r^2)} \qquad \text{(Equation 1)}$$

Diameter at breast height (dbh, in cm) was derived from MFM using a field-based relationship established between tree height and dbh, with a logarithmic function used to obtain slope and intercept coefficients (a & b) as:

$$\mathbf{\log(dbh) = \log(a)+b*\log(H)} \qquad \text{(Equation 2)}$$

By substituting field height values with MFM derived height values, dbh estimates were obtained from the MFM model. These dbh values were then multiplied by T from equation 1 and utilized in the MFM stand basal area equation. Stand basal area (BA, in m^2/ha) for each plot area was calculated using the following equation adapted from Brack (1997) in which c is area (hectares) and the constant (π/40000) corrects for the difference in units (cm and m) and converts diameter to radius. Field basal area was computed for comparison by substituting the sum of all plot measured dbh values for T * dbh^2 below

$$\mathbf{BA = (\pi / 40000) * (T * dbh^2 / c)} \qquad \text{(Equation 3)}$$

Stand volume (SV) was computed by multiplying MFM derived height (H) and basal area results (BA) at individual plot (100m^2) and zone areas. The modelled SV results were converted to the more commonly used units of cubic metres per hectare for reporting.

$$\mathbf{SV = H * BA} \qquad \text{(Equation 4)}$$

RESULTS AND DISCUSSION

	Trembling Aspen		Lodgepole Pine	
	Field	**MFM**	**Field**	**MFM**
Height (m)	15.2	13.2	15.0	14.5
Stem Count (Trees/100m^2)	20	19	23	20
Dbh (cm)	19.6	16.6	18.6	18.5
Basal Area (m^2/ha)	63.3	48.4	66.0	63.8
Stand Volume (m^3/ha)	962.2	634.9	990.0	922.4

Table 4: Mean field and MFM-GOMS derived stand volume parameters.

Field and MFM model results were similar for conifer height, basal area and volume, and for deciduous height and stem counts, with an overall trend that MFM model outputs underestimated forest parameters when compared to field data (Table 4). Differences between field estimated and MFM modeled stand volume were more pronounced in trembling aspen than with lodgepole pine. The under-estimation was attributed, in part, to the first-order method used to estimate stem counts (equation 1), for which non-overlapping crowns were assumed. There may also be some error introduced by the method used to derive dbh, particularly for the deciduous stands since it is at this stage in the analysis that the correspondence between field and modeled results was reduced for trembling aspen plots. These errors were then propagated through to the stand volume estimates. Although the stem counts had a higher level of agreement in the deciduous species, the conifer modeled results had a higher level of agreement in both height and dbh values, which are key variables in the estimation of basal area, and subsequently stand volume. Current work has focused on an improved field validation data set with stand volume derived from taper functions that more closely incorporates tree form into volume computation (Hall *et al.,* 2001) for which we have found improvements in the correspondence of these new field values with the MFM-GOMS stand volume output presented here (e.g. an improved mean difference for Aspen from 3.27 $m^3/100m^2$ reported here, to 2.29 $m^3/100m^2$ when compared to the new field method).

As stand volume is dependent upon accurate height estimation for which more variability is expected on a per-pixel basis, it is recommended that the scale of the analysis correspond to that of forest stands or plots. By running MFM-GOMS using a larger sample of pixel reflectance values, rather than simply using the mean and standard deviation from a limited number of samples, localized variance is reduced in favour of more reliable height estimates. Therefore, for an operational study, several model access queries utilizing a range of red and near-infrared reflectance means and standard deviations should be employed at the stand level. This scale is appropriate for forestry studies and also for large-area regional and national scale forest inventory and reporting requirements. As the results generated from such access queries stem from a single look-up table generated per-species, MFM-GOMS physical values should maintain a high level of agreement (e.g. with field validation data), and although variation will exist in actual field measurements, mean un-weighted averages appear to be consistent between actual and modeled output at the scale of forest stands and plots.

CONCLUSION

The Multiple-Forward-Mode Geometric Optical Mutual Shadowing modeling approach has provided a capability for estimating forest stand volume at the plot level from satellite image data in a complex area of mountainous terrain in western Canada. To achieve this, a variety of forest structural parameters such as tree height, stem counts, dbh and basal area were derived using MFM canopy reflectance modeling. Stand level height estimates were similar to field height measurements, providing a key basis from which stand volume was derived. This model based approach provides a different means of forest information extraction without the requirements for expensive fieldwork.

Practical benefits of model driven forest volume assessment queries include:

- Potential for consistent monitoring of Canada's natural forests
- Carbon and biomass estimations
- Vegetative cover distribution for wildlife species monitoring
- Vegetative spectral response analysis for disease and pest monitoring
- Re-growth monitoring and volume estimation of forest cut-blocks
- Use of powerful canopy models with minimal field data inputs required
- Consistent with other MFM modeling applications

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