MFM CR Modeling of Forest Stand Height

Neal Pilger[1,2], Derek R. Peddle[2], Ronald J. Hall[2,3]

[1] Dept. of Geography, Brock University, St. Catharines, ON., L2M 5M5. npilger@brocku.ca
[2] Department of Geography, University of Lethbridge, Lethbridge, AB., T1K 3M4 Canada
[3] Natural Resources Canada, Northern Forestry Centre, Edmonton, AB., T6H 3S5

A geometric optical canopy reflectance (CR) model was run in multiple-forward-mode (MFM) to estimate tree heights at 34 conifer and deciduous forest plots in the Canadian Rocky Mountains. MFM provides a pseudo-inversion modeling capability that requires no ground data inputs and is instead based on structural look-up tables (LUTs) produced from forward model runs. IKONOS satellite image red and NIR reflectance values were searched in the MFM-LUTs, with the associated modeled structure used to derive forest stand height estimates. Overall MFM height accuracies were ±0.9m for pine and ±1.4m for aspen against field measured heights. MFM provides a capability for height estimation from passive optical satellite imagery over larger areas that are neither feasible nor cost-effective using current LiDAR data, aerial photography, or field-based surveys alone. The MFM approach is suitable for independent use, or for integration with existing forest inventories or other applications.

Keywords: Canopy reflectance model, remote sensing, forestry

1. INTRODUCTION

Spatial, spectral, and temporal resolution of remotely sensed imagery has improved significantly over the past 15 years. Finer spatial resolution image data have led to particular improvements in environmental mapping, such as the shift from forest stand, and plot area analysis to the identification and classification of individual trees (Nelson, *et al.,* 2005). Lowered costs associated with both image acquisition and processing has in turn increased the temporal resolution by making the frequent collection of remotely sensed data more attractive for industrial, government and academic forest managers and researchers. The quantification of forest resources, whether from an ecological or industry based perspective have traditionally been performed through small area fieldwork and/or aerial survey, of which both have been criticized for inaccuracies and high costs, especially when multiple observations are required (Maltamo *et al*., 2006) as in growth and yield and/or change detection analysis. Tree height information over large areas is important in forest inventories and for estimating parameters such as stem diameter, basal area, biomass, stand volume and carbon stocks (Brown, 2002; Cihlar *et al.,* 2002; Fournier *et al*., 2003; Rosenqvist *et al.,* 2003; Hese *et al.,* 2005; Hall *et al*., 2006). Active sensors such as radar have been problematic for deriving tree heights (Lefsky *et al.,* 2002) and current LiDAR systems, while well suited for tree and stand height measurement (St-Onge *et al.,* 2003; McCombs *et al.* 2003; Coops *et al.* 2004; Hopkinson *et al.* 2006; Thomas *et al.* 2006), are nonetheless expensive and limited in spatial coverage compared to passive optical satellite imagery (Wulder and Seemann, 2003). As a result, deriving tree height information from passive optical spaceborne sensors is of high interest to the forest and natural resource community. Results from conventional image analysis approaches for height estimation, however, have generally been poor (Franklin, 2001). Errors inherent in photogrammetric height estimates, including inconsistencies among photo-interpreters, have led to considerable variation in height-based structural parameter estimation. Yet, forest growth and yield are monitored using species-specific allometric relationships between tree height and stem diameter measurements, as these variables can be used to provide physical descriptions of forest structure and volume (Todd *et al*., 2003). While LiDAR may act to reduce the requirements in user photogrammetric analysis for both individual tree and canopy height by decreasing this subjectivity (Lockhart, 2005), it is still prohibitively expensive for many small area localized assessments. Three-dimensional canopy reflectance (CR) models provide a physical-structural basis to satellite image analysis and have distinct advantages over conventional, empirical and vegetation index based approaches (Spanner *et al.,* 1991; Hall *et al*., 1995, 1997; Strahler, 1997; Peddle *et al.,* 1999; Chen *et al.,* 2000; Kimes *et al.,* 2000; Asner *et al.,* 2003). Some of these models include vertical structural dimensions in their specification and thus represent a potentially more robust, objective and accurate approach for estimating forest height. Fundamental constraints associated with CR model use in forward and inverse modes, however, have prevented or limited their use for extracting height and other structural attributes (Peddle *et al*., 1999). MFM solves these problems and enables height estimation without field or other inputs. The objective of this study was to implement and evaluate MFM for forest stand height estimation in mountainous terrain, with validation against field measurements for two common montane forest species.

2. EXPERIMENT

The 75 km^2 study area was located in Kananaskis, Alberta, Canada centered at 51˚ 1' 13"N - 115˚ 4' 20"W in a montane ecological subregion on the eastern slopes of the Canadian Rocky Mountains (Kirby, 1973; Achuff, 1992). IKONOS 4m multispectral satellite data were acquired August 27, 2001 with solar azimuth and zenith angles of 157.21° and 42.57°, respectively. This study utilized the red and near-infrared IKONOS image bands, radiometrically corrected to reflectance using pseudo-invariant field calibration targets and geometrically registered to the UTM projection using differentially corrected GPS (DGPS) field data. A total of thirty-four 100m^2 field plots were located in predominant stands of trembling aspen (*Populus tremuloides*) (n=20) and lodgepole pine (*Pinus contorta*) (n=14). Using DGPS, the location of the four corners and center of each 10×10m plot was measured for accurate plot placement within the digital image.

The Li and Strahler (1992) Geometric Optical Mutual Shadowing (GOMS) canopy reflectance model was run in MFM to produce reflectance values for use with the satellite imagery. The structural parameters utilized in GOMS were horizontal crown radius (r), vertical crown radius (b), height to crown center (h), and height distribution (dh), with stand density indicated as percent crown closure and based on a Poisson distribution. GOMS model parameters were measured at each plot for the purpose of MFM model validation (i.e. these values were not required for MFM processing). Tree height, and height to live crown was measured throughout each plot using a clinometer to derive values for vertical crown radius and height to crown center. Horizontal crown radius was measured using a tape-rule and densitometer.

Image endmember values for sunlit canopy (Pc), background (Pb) and shadow (Ps) were obtained by analysing red and near-infrared image scatterplots with Pc derived from the area of brightest canopy response in spectral space, Pb from pixels located in areas of open background, and Ps from the darkest image areas as a surrogate for shadow. This approach was consistent with earlier work involving endmember determination in forest stands by Peddle and Johnson (2000) in this study area, as well as by Hall *et al.* (1995) and Peddle *et al.* (1999).

A full range of structural input possibilities was considered in MFM for this study area with increment step sizes selected based on the desired precision of the structural output and with reference to LUT size considerations. The image and MFM analysis was conducted at the scale of forest stands, as represented by the series of plots. The nearest neighbour satellite image pixel reflectance value corresponding to each plot DGPS location was used for MFM matching. MFM height was derived as the sum of vertical crown radius and height to crown center (h+b) from the MFM matches obtained. Validation of MFM height at each plot was achieved against individual tree heights measured in the field aggregated to the plot.

3. RESULTS AND DISCUSSION

A higher level of agreement between modeled and measured height was evident for *Pinus contorta* than for *Populus tremuloides*, with mean differences of ±0.9m and ±1.4m, respectively. The variability associated with these results was consistent for both conifer and deciduous (standard deviation of 1.3m for *Pinus contorta*, 1.7m for *Populus tremuloides*). For *Pinus contorta*, 6 of the 14 plots had height differences <1m, and 12 of the 14 plots had differences <2.5m. Two plots (23, 31) had differences exceeding 4m. For *Populus tremuloides*, 5 of the 20 plots were within a 1m difference in height, whereas 5 other plots had height differences that were up to 5m. This greater level of error occurred with taller deciduous trees (above 17.5m in all cases). The results by plot indicate that MFM errors generally involved underestimation of tree height. The greater correspondence of MFM results for *Pinus contorta* compared to *Populus tremuloides* was likely due to the GOMS model being better suited for conifer stands in terms of crown shape, distribution, and model function (Li and Strahler, 1992).

Table 1. MFM vs. Field Height Estimates

Species	Field Height			MFM Height			Absolute Difference		
	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean
Pinus contorta	9.9	18.8	15.3	13.4	15.0	14.6	0.7	5.1	**1.8**
Populus tremuloides	10.5	18.8	15.1	12.5	13.8	13.2	0.0	5.4	**2.7**

These results compared favorably to other studies in height estimation from passive optical (St-Onge *et al*., 2008; Magnusson and Fransson, 2005; Oza *et al*., 1989), SAR (Rowland *et al*., 2008), and LiDAR (Suárez *et al.,* 2005; Takahashi *et al*., 2005; Holmgren *et al*., 2003; Næsset, 1997), while removing the requirement for in-depth field level pre-assessment of forest stand characteristics. It is felt that the height estimation methods presented in this research are suitable for general provincial and national inventory purposes in areas of difficult terrain.

4. CONCLUSIONS

MFM CR modeling provides a pseudo-inversion modeling capability for estimating forest stand height information from passive optical satellite imagery. This was demonstrated for *Pinus contorta* and *Populus tremuloides* stands in a challenging, high relief mountainous environment. For larger areas and regional scales, the level of error suggested from this study is likely reasonable to tolerate compared with current LiDAR, aerial photographic or field based surveys that are prohibitively expensive, impractical, or both, over similar spatial extents. The advantages of MFM include: (i) an ability to extract structural information from non-invertible CR models; (ii) no ground data are required, only ranges of variables are needed which are simple to provide; (iii) the approach has been demonstrated in other published studies for a variety of biophysical-structural applications, so height information can be provided in a broader context; (iv) it is suitable for different types of imagery, models, and forest ecosystems; and, (v) it provides standard forest structural output that is appropriate both for independent usage, as well as to augment or update existing forest inventories (or for other forestry applications). A follow-up stage of this study is using the derived MFM height information together with other MFM outputs for estimating parameters such as biomass and stand volume.

ACKNOWLEDGEMENTS

This research was supported in part by grants to Dr. D.R. Peddle and/or collaboration from the Natural Sciences and Engineering Research Council of Canada (NSERC), Alberta Ingenuity Centre for Water Research (AICWR), Prairie Adaptation Research Collaborative (PARC), Water Institute for Semiarid Ecosystems (WISE), Natural Resources Canada and Canadian Forest Service-Edmonton, Alberta Research Excellence Program, Miistakis Institute of the Rockies (DEM), Center for Remote Sensing, Boston University (GOMS model) and the University of Lethbridge. Computing resources were provided through the Western Canada Research Grid (WestGrid NETERA c3.ca). We gratefully acknowledge Judy Buchanan-Mappin and staff at the Kananaskis Field Stations and University of Lethbridge research associate Scott Soenen and field assistants Jeff Jordan, Jennifer Pegg, and Susie Saunders.

REFERENCES

Achuff, P.L. 1992, Natural Regions, Subregions and Natural History Themes of Alberta: A classification for protected areas management. Parks Service, Alberta Environmental Protection, Edmonton, Alberta.

Asner, G.P., Hicke, J.A. and Lobell, D.B. 2003. Per-pixel analysis of forest structure: vegetation indices, spectral mixture analysis and canopy reflectance modeling. Chapter 8, In, "*Remote Sensing of Forest Environments: Concepts and Case Studies*" (Eds.: Wulder, M.A. and Franklin, S.E.) Kluwer Academic Press, London/Dordrecht/Boston (Norwell, Massachusetts, USA). pp.209-254.

Brown, S., 2002. Measuring carbon in forests: current status and future challenges, *Environmental Pollution*, 116:363-372.

Chen, J.M., Li, X., Nilson, T., and Strahler, A. 2000, Recent advances in geometrical optical modelling and its applications. *Remote Sensing Reviews*, 18, pp. 227–262.

Cihlar, J., Denning, S., Ahern, F., Anno, O., Belward, A., Bretherton, F., Cramer, W., Dedieu, G., Field, C., Francey, R., Gommes, R., Gosz, J., Hibbard, K., Igarashi, T., Kabat, P., Olsen, D., Plummer, S., Rasool, I., Raupach, M., Scholes, R., Townshend, J., Valentini, R., and Wickland, D. 2002. Initiative to quantify terrestrial carbon sources and sinks. *EOS Transactions*, American Geophysical Union. 83(1): 1,6-7.

Coops, N.C., Wulder, M.A., Culvenorm, D.C., and St-Onge, B. 2004. Comparison of forest attributes extracted from fine spatial resolution multi-spectral and lidar data. *Canadian Journal of Remote Sensing* 30(6): 855-866

Fournier, R.A., Luther, J.E., Guindon, L., Lambert, M-C., Piercey, D., Hall, R.J., and Wulder, M.A. 2003. Mapping above ground tree biomass at the stand level from inventory information: test cases in Newfoundland and Quebec, *Canadian Journal of Forest Research*, 33:1846-1863.

Franklin, S.E. 2001. Remote Sensing for Sustainable Forest Management. Boca Raton, FL, USA: CRC Press (407 pp.).

Hall, F.G., Shimabukuro, Y.E. and Huemmrich, K.F. 1995. Remote sensing of forest biophysical structure in boreal stands of *Picea mariana* using mixture decomposition and geometric reflectance models. *Ecological Applications*, 5, pp. 993-1013.

Hall, F.G., Knapp, D.E., and Huemmrich, K.F. 1997. Physically based classification and satellite mapping of biophysical characteristics in the southern boreal forest. *Journal of Geophysical Research*, BOREAS Special Issue, 102(D24), pp. 29567-29580.

Hall, R.J., Skakun, R.S., Arsenault, E.J., and Case, B.S. 2006. Modeling forest stand structure attributes using Landsat ETM+ data: application to mapping of aboveground biomass and stand volume. *Forest Ecology and Management* 225:378-390.

Hese, S., Lucht, W., Schmullius, C., Barnsley, M., Dubayah, R., Knorr, D., Neumann, K., Riedel, T., and Schröter, K. 2005. Global biomass mapping for an improved understanding of the CO_2 balance – the Earth observation mission Carbon-3D. *Remote Sensing of Environment.* Vol. 94, pp. 94-104.

Hopkinson, C., Chasmer, L., Lim, K., Treitz, P., and Creed, I. 2006. Towards a universal lidar canopy height indicator, *Canadian Journal of Remote Sensing*, 32(2):139-152.

Holmgren, J., Nilsson, M., and Olsson, H. 2003: Estimation of tree height and stem volume on plots using airborne laser scanning. *Forest Science.* 49, 419-428.

Kimes, D.S., Y.Knyazikhin, J.L. Privette, A.A. Abuelgasim and, F. Gao, 2000, Inversion methods for physically-based models. *Remote Sensing Reviews*, 18, pp. 381–439.

Kirby, C.L. 1973. The Kananaskis Forest Experiment Station, Alberta (History, Physical Features, and Forest Inventory). *Northern Forest Research Centre Information Report* NOR-X-51.

Lefsky, M.A., Cohen, W.B., Parker, G.G., and Harding, D.J. 2002. LiDAR Remote Sensing for Ecosystem Studies. *BioScience*. Vol. 52, No. 1, pp.19-30.

Li, X. and Strahler, A.H. 1992. Geometric-Optical Bi-directional Reflectance Modeling of the Discrete Crown Vegetation Canopy: Effect of Crown Shape and Mutual Shadowing. *IEEE Transactions on Geoscience and Remote Sensing*, Vol. 30: 276-296.

Lockhart, M.L. 2005. Applications of satellite remote sensing to develop forest inventory for strategic-level planning. *Masters Thesis*, Department of Forestry, Lakehead University, Canada. 105 pp.

Maltamo, M., Malinen, J., Packalen, P., Suvanto, A., and Kangas, J. 2006. Nonparametric estimation of stem volume using airborne laser scanning, aerial photography, and stand-register data. *Canadian Journal of Forest Research.* Vol. 36, No. 2, pp. 426-436.

Magnusson, M. and Fransson, J.E.S. 2005. Estimation of forest stem volume using multispectral optical satellite and tree height data in combination. *Scandinavian Journal of Forest Research*. Vol.20, No.5, pp. 431-440.

McCombs J.W., Roberts S.D., and Evans D.L. 2003. Influence of Fusing LiDAR and Multispectral Imagery on Remotely Sensed Estimates of Stand Density and Mean Tree Height in a Managed Loblolly Pine Plantation. *Forest Science.* Vol.49, no.3, pp. 457-466.

Næsset, E. 1997. Determination of mean tree height of forest stands using airborne laser scanner data. *ISPRS Journal of Photogrammetry and Remote Sensing*. Vol. 52 No.2, pp. 49-56.

Nelson, T., Boots, B., and Wulder, M.A. 2005. Techniques for accuracy assessment of tree locations extracted from remotely sensed imagery. *Journal of Environmental Management*. Vol. 74, pp. 265- 271.

Oza, M.P., Srivastava, V.K., Pariswad, B.S., and Setty, K.R.V. 1989. Relationship between Landsat MSS data and forest tree parameters. *International Journal of Remote Sensing*. Vol.10, No.11, pp. 1813-1819.

Peddle, D.R. and Johnson, R.L. 2000. Spectral Mixture Analysis of Airborne Remote Sensing Imagery for Improved Prediction of Leaf Area Index in Mountainous Terrain, Kananaskis Alberta. *Canadian Journal of Remote Sensing*. 26(3): 176-187.

Peddle, D.R., Hall, F.G., and LeDrew, E.F. 1999. Spectral Mixture Analysis and Geometric Optical Reflectance Modeling of Boreal Forest Biophysical Structure. *Remote Sensing of Environment.* 67(3): 288-297.

Rosenqvist, A., Milne, A., Lucas, R., Imhoff, M., and Dobson, C. 2003. A review of remote sensing technology in support of the Kyoto Protocol, *Environmental Science and Policy*, 6:441-455.

Rowland, C.S., Balzter, H., Dawson, T.P., Luckman, A., Patenaude, G., and Skinner, L. 2008. Airborne SAR monitoring of tree growth in a coniferous plantation. *International Journal of Remote Sensing*. Vol.29, No.13, pp. 3873-3889.

Spanner, M.A., Pierce, L.L., Peterson, D.L., and Running, S.W. 1990. Remote sensing of temperate coniferous forest leaf area index: the influence of canopy closure, understory vegetation and background reflectance, *International Journal of Remote Sensing*, 11:95-111.

St-Onge, B., Hu, Y., and Vega, C. 2008. Mapping the height and aboveground biomass of a mixed forest using lidar and stereo Ikonos images. *International Journal of Remote Sensing*. Vol.29, No.5, pp. 1277-1294

St-Onge, B., Treitz, P., and Wulder, M. 2003. Tree and canopy height estimation with scanning lidar, In Remote Sensing of Forest Environments: Concepts and Case Studies, Eds. S. Franklin and M. Wulder, Kluwar Academic Publishers, pp. 489-509.

Strahler, A.H., 1997. Vegetation canopy reflectance modeling – recent developments and remote sensing perspectives, *Remote Sensing Reviews*, 15:179-194.

Suárez, J.C., Ontiveros, C., Smith, S., and Snape, S. 2005. Use of airborne LiDAR and aerial photography in the estimation of individual tree heights in forestry. *Computers and Geosciences.* 31, 253-262.

Takahashi, T., Yamamoto, K., Senda, Y., and Tsuzuku, M. 2005: Estimating individual tree heights of sugi (Cryptomeria japonica D. Don) plantations in mountainous areas using small-footprint airborne LiDAR. *Journal of Forest Research.* 10, 135-142.

Thomas, V., Treitz, P., McCaughey, J.H. and Morrison, I. 2006. Mapping stand-level forest biophysical variables for a mixedwood boreal forest using LiDAR: an examination of scanning density, *Canadian Journal of Forest Research*, (36):34-47.

Todd, K.W., Csillag, F., and Atkinson, P.M. 2003. Three-dimensional mapping of light transmittance and foliage distribution using lidar. *Canadian Journal of Remote Sensing*. Vol. 29, No. 5, pp. 544-555.

Wulder, M.A. and Seemann, D. 2003. Forest inventory height update through the integration of LiDAR data with segmented Landsat imagery. *Canadian Journal of Remote Sensing.* Vol. 29, No. 5, pp. 536-543.

Proceedings
Actes

The Prairie Summit
Le sommet des Prairies

CAG/AGC

CGGCRG

The Canadian Geomorphology Research Group
Le Groupe Canadien de Recherche en Géomorphologie

Joint Conference of
Canadian Association of Geographers
Canadian Cartographic Association
Canadian Geomorphology Research Group
Canadian Remote Sensing Society

CANADIAN REMOTE SENSING SOCIETY
SOCIÉTÉ CANADIENNE DE TÉLÉDÉTECTION

Conférence conjointe de
l'Association canadienne des géographes
l'Association canadienne de cartographie
le Groupe canadien de recherche en géomorphologie
la Société canadienne de télédétection

Proceedings
The Prairie Summit

Actes
Le sommet des Prairies

June 1–5 juin 2010
Regina Saskatchewan Canada

Compiled by / *sous la direction de*

Joseph M. Piwowar

Department of Geography
University of Regina
3737 Wascana Parkway
Regina, Saskatchewan
S4S 0A2
Canada