Synergy of Airborne Laser Altimetry and Digital Videography for Individual Tree Crown Delineation*

François A. Gougeon[1], Benoît A. St-Onge[2], Mike Wulder[1], and Donald G. Leckie[1]

[1] Natural Resources Canada, Canadian Forest Service, Pacific Forestry Centre, 506 West Burnside Rd., Victoria, British Columbia, Canada, V8Z 1M5. Email: fgougeon@pfc.forestry.ca
[2] Department of Geography, Université du Québec à Montréal (UQAM), Montréal, Québec, Canada.

Abstract

For forest inventory, laser altimetry can provide an alternative to conventional stereoscopic methods or field measurements to obtain forest stand heights, an important factor in the inference of numerous other forestry parameters. When the density of LIDAR data becomes high enough, one can think in terms of individual tree heights. New systems could incorporate individual tree crown (ITC) delineation and species recognition from multispectral imagery with ITC-based height measurements from LIDAR data to produce precise, accurate and timely ITC-based forest inventories. Volume and biomass inferences could then be done on an ITC-basis.

This study examines three aspects of the synergy between airborne laser altimeter data and multispectral video imagery: (a) the elimination of non-forested or poorly forested areas from the analysis of mature forests, (b) the potential improvements in ITC delineation, and (c), the possibility of a separate ITC analysis of young regenerating areas. A combination of masks generated from multispectral rules and by selecting a minimum LIDAR height led to a very good separation of the forested areas, and even of individual trees in open fields. The ITC delineation process was then applied to the unmasked forested areas, first on a smoothed version of the near infrared image and then, on a smoothed version of the LIDAR height image. Both cases produced numerous tree clusters rather than individual tree crowns, but for different reasons. A post-processing combination of both results led to superior crown delineation, with few tree clusters.

Résumé

Pour l'inventaire forestier, les altimètres au laser peuvent être une alternative aux méthodes stéréoscopiques conventionnelles ou aux mesures sur le terrain pour obtenir la hauteur des peuplements forestiers, un paramètre important dans l'inférence de nombreux autres paramètres forestiers. Quand la densité des données LIDAR devient assez élevée, on peut penser en termes de hauteurs individuelles d'arbres. De nouveaux systèmes pourraient incorporer une délinéation et une identification «à l'arbre près» à partir d'images multispectrales avec des mesures de hauteurs individuelles provenant de données LIDAR pour produire des inventaires forestiers «à l'arbre près» qui seront précis, valides, et opportuns. Les inférences de volume et de biomasse pourraient alors se faire à l'arbre près.

Cette étude examine trois aspects de la synergie entre les données d'altimètre au laser et l'imagerie vidéo multispectrale : (a) l'élimination des zones non-boisées ou pauvrement boisées de l'analyse des forêts matures, (b) les améliorations potentielles de la délinéation «à l'arbre près», et (c), la possibilité de faire une analyse séparée des zones de jeune régénération. La combinaison d'un masque généré à partir de règles multispectrales avec celui généré en choisissant une hauteur LIDAR minimum mena à une très bonne séparation des zones boisées, et même, d'arbres individuels dans les clairières. Le procédé de délinéation «à l'arbre près» fut appliqué aux zones boisées non masquées, premièrement sur une version lissée de la bande du proche infrarouge et puis aussi, sur une version lissée de l'image des hauteurs LIDAR. Les deux cas produisirent de nombreux regroupements d'arbres plutôt que des cimes individuelles, mais pour des raisons différentes. Une combinaison «a posteriori» des deux types de résultats produisit une délinéation supérieure avec peu de regroupements d'arbres.

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[*] Presented at the 23rd Canadian Symposium on Remote Sensing / 10e Congrès de l'Association québécoise de télédétection, Sainte-Foy, Québec, Canada, August 21-24, 2001.

Introduction

The obvious attraction of LIDAR data acquisition for forestry is its potential to infer forest stand heights using mean heights or dominant tree heights by separating returns from the forest canopy from returns coming from the ground. Stand heights are an essential component of existing forest inventories as they lead to estimations of merchantable wood volumes and biomass. For forest stands, laser altimetry could replace conventional stereo methods or the costly field acquisition of tree heights.

The performance and acquisition speed of LIDAR systems is continually increasing, leading to a higher density of returns. The possibility of acquiring “individual” tree heights arises with spacings of the order of one or two hits per square metre. Simulating such circumstances, an earlier paper (St-Onge *et al*., 2000) reported good R^2 (0.90) between laser-predicted heights and heights measured in the field for 36 test trees. Image interpretation and GPS acquired coordinates were used to identify corresponding trees in the Canopy Height Model (CHM) and on the ground. The potential of this higher density data will be more fully realised within the context of the semi-automatic production of Individual Tree Crown (ITC) based forest inventories (Leckie, 1990; Leckie, 1994).

The generation of ITC-based forest inventories from high spatial resolution (10-100 cm/pixel) multispectral imagery, although still a research subject, is coming of age (Gougeon, 2000). At present, the tree crowns are first delineated using one of the spectral bands or a derived illumination image and then, their species are assessed using a maximum likelihood classifier relying on crown-based multispectral, textural, and structural signatures. This ITC-based information can be kept in its entirety when warranted or, can easily be summarised by existing, newly-interpreted, or automatically-derived forest stands.

This automatic ITC delineation process relies on the presence of shaded material between tree crowns, making it effective in high to medium density coniferous forest areas. However, in more open low density areas, it has to rely on pre-processing techniques to mask out the non-forested areas. Such pre-processing can take the form of rules in the spectral domain, separating vegetated from non-vegetated covers. This works well when the openness is due to man made-features, rock outcrops, sand or gravel, logging debris, dry lichens or other senescing vegetation. Alternatively, this masking can be based on a textural analysis of the image, separating the denser forested areas from others. Using LIDAR data provides an additional way to deal with lower density forests by creating masks based on vegetation heights.

A second potential contribution of LIDAR data to the production of ITC-based inventories is with the crown delineation process. Using the existing valley following software, crown delineation can be performed directly on a LIDAR based Canopy Height Model (CHM), rather than on the multispectral imagery. Given an appropriately high spatial resolution, this could lead to precise crown delineations. The multispectral data would then be used only for species recognition, bypassing crown separation problems in the direction normal to the sun illumination. However, given the real spatial resolution of our LIDAR data set (sampled at a 1.5m interval), one can not expect great crown delineation from the CHM alone. Fortunately, a combination of crown delineations from the multispectral data with that of the CHM is possible and should lead to better delineation results than with the LIDAR or multispectral imagery alone.

This paper examines the synergy of LIDAR data and multispectral imagery towards the production of individual tree crown based forest inventories at two levels: the generation of masks of open or low density areas and the delineation of tree crowns. The obvious benefits of knowing height, species and crown area on an individual tree basis, coupled with estimations of local tree densities, to the production of detailed forest inventories and to the subsequent inferences of volume and biomass have been assumed and will be the subject of more in-depth studies.

Dataset and Study Area

A dataset over the Lake Duparquet Research and Teaching Forest, Québec (79.3 W, 48.5 N) is being used in this study. It essentially consists of a multispectral video image and a LIDAR canopy model coregistered at 50 cm/pixel, although the laser altimeter mean distance between two hits is about 1.5 metre. The laser data was obtained with three passes over each area, one for ground returns and two for returns from the vegetation. The laser footprint diameter on the ground was 19 cm. Details of the data acquisition can be found in (St-Onge *et al*., 2000), which reported a good relationship (R^2=0.90) between the canopy model heights and heights from field measurements of 36 trees. The study area is representative of the mixed boreal forest and contains: trembling aspen and white birch; white spruce, balsam fir, jack pine, eastern cedar and black spruce; regenerating areas covered by shrubs and some residual trees; and severely defoliated trees (Figure 1).

Techniques and Methods

Preprocessing: Filters and Masks

The valley following technique (Gougeon, 1995), which typically relies on the presence of shaded material between tree crowns to separate them, has to depend on preprocessing techniques in more open, lower density areas, to eliminate (mask-out) non-shaded background material. With multispectral imagery, a simple rule such as, detect pixels with lower radiances in the near infrared band than the mean of the visible bands (with various normalisation schemes), was used to create an effective non-vegetation mask. Within the vegetative areas, one can use a texture measure to separate the forested from non-forested areas (not used here). With LIDAR data, after substracting the interpolated terrain heights from the interpolated canopy heights and thus, generating a Canopy Height Model (CHM) as a grey level image, simple thresholds can be used to separate areas of interest. Here, masks were generated to separate ground features (<0.1m) from shrubby vegetation (0.1 – 2 metres) and from mature trees (> 2 m in height), allowing us for the first time to analyse these two important components of the forest separately. In addition, the images used for crown delineation (i.e., the near infrared and the CHM images), were smoothed with a 3x3 window averaging filter. Masks for water areas and the sub-area common to both data sets were also generated.

Individual Tree Crown Delineation

After masking non-forested areas, selecting the appropriate image and smoothing it, the individual tree crown delineation process is done in two stages. In the first stage, valleys of shade are followed in an attempt to separate well lit tree crowns from the shaded (or masked) background material and from each other. In the second stage, potential tree crown or cluster boundaries are followed pixel by pixel in a clockwise fashion in order to fully delineate a tree crown or, make decisions about further crown separations or segment regroupings. A rule-based system is used to make such decisions at each contour pixel and later, for a fully enclosed entity. Each stage generates a bitmap known respectively as, the VFOL bitmap and the ITC (or ISOL) bitmap.

From the multispectral data, the near infrared channel was selected as illumination image for the valley following process. Typically, the near infrared band has a good dynamic range when it comes to vegetation and reacts poorly to the non-vegetated material (that preprocessing steps may have missed masking out). First, a radiance (or grey level) threshold is selected, either automatically or manually, below which pixels are considered part of the initial shaded material of the image. It is called the *lower* threshold. From this initial shaded material, crown-separating valleys are grown in all directions. Pixels are considered valley material if they have a lower radiance than their immediate neighbours on each sides. A *high* radiance threshold may also be used to prevent valleys from growing too aggressively into crowns. Finally, a third threshold, valley *roughness*, exists to compensate for a certain level of radiometric variation (or noise) within the valleys of shade. It essentially allows the valley following process to look further aside for valley walls by disregarding some spurious rises in radiance within valley floors. This leads to stronger valley growing (i.e., longer valleys), but with the side-effect of creating wider valleys.

The subsequent rule-based program, although making many complex decisions, has only one parameter available to the user: a *jump factor*. While the boundary of a potential tree crown, or more to-the-point of a cluster of trees, is being followed pixel by pixel in order to enclose it as a distinct entity (an isol), the process may encounter what could be described as inlets into that entity. These inlets, which correspond to the growth of valleys of shade into that entity, are considered strong indicators that the entity may consist of more than one tree crown. For example, an inlet could be a valley of shade separating two tree crowns that got interrupted in its growth by a branch extending from one crown into the other. When these inlets are encountered, the process is allowed to check at the foremost pixel of each inlet whether it could reach the other side of the entity by just bridging a small gap. The jump factor simply dictates the maximum distance that can be bridged. It can be set manually by the user in terms of the number of pixels to bridge or with the predefined values of *mature* or *regeneration* (corresponding to 1 and 0.5 metre, respectively).

The individual tree crown delineation process was also run on the Canopy Height Model image. As lower heights correspond to darker pixels and taller heights to brighter ones, a simple *lower* threshold can be established to define non-forested areas from which valleys will grow. Theoretically, given a CHM image with an appropriate spatial resolution, the valley following process should have an easier task of separating tree crowns as sharper valleys should exist on the shaded sides of trees. Indeed, with images based on visible light, the separation between the shaded portion of a crown and the adjacent shaded background material is not as drastic as the height drop that may exist between two crowns. Unfortunately, the LIDAR data available for this study has a 1.5 spacing and is thus limited for crown delineation. On the other hand, the availability of height data allowed us for the first time to run separate delineation processes on the mature forest and, on residual trees and shrubs in regenerating areas.

Our main hypothesis is that synergistic effects should result from using the two media and lead to better tree crown delineation. Indeed, with the video data the crown delineation is hampered by the lack of shade between some tree crowns, while with the LIDAR data, crown delineation is limited by the lack of effective spatial resolution. Neither media is affected by the other media’s problem. Ideally, to benefit the most from a synergy, one should rely on a single sophisticated delineation process taking its cues from both datasets simultaneously while attempting to delineate each tree crown. However, for this preliminary study, we will resort to simple post-processing combinations of delineations from both media. Two such combinations were tested: a simple logical “and” combination of the ITC (or ISOL) bitmaps and, an “or” combination of the VFOL bitmaps followed by a run of the rule-based isolation process. All resulting ITC bitmaps were subjected to a filtering process removing crown delineations considered noise due to their small size.

Results and Discussion

Preprocessing

Masks were generated, mostly to allow the individual tree delineation process to concentrate on the mature forested areas present in both images, but also to permit a separate analysis of the regeneration areas. The multispectral mask is particularly good at isolating non-vegetated areas like rock outcrops, bare ground, sand, and woody debris, but it has the undesirable effect of masking out non-healthy, senescing or dead trees, that one may have wanted to consider (i.e., insect damaged trees, snags). The multispectral rule itself exhibits some instabilities in deeply shadowed area, possibly related to a lack of radiometric resolution. Fortunately, such situations are usually eliminated when the *lower* threshold of the valley following process is applied.

The height masks suffer mostly from a lack of spatial resolution due to low spot density and the interpolation and gridding processes of this particular dataset. This is most evident in relatively dense forest areas. It is not a concern when the ITC delineation is done on the multispectral image but becomes significant when the ITC delineation is done on the CHM image alone. The main height mask (<2m) is particularly good at eliminating open areas covered with shrubby vegetation and low lying regeneration, while preserving, and even nicely isolating, the remaining standing trees.

Using both multispectral and height (<2m) based masks for the mature forest creates a synergistic effect which seems to capture the best of both situations and partially compensate for some of their respective weaknesses. For example, the low spatial resolution of the LIDAR data means that not all small forest openings will be detected. However, that same area may be represented by a definitively non-vegetated pixel. Conversely, one may need height information to separate forested areas, tree clusters and isolated trees from low lying shrubby vegetation areas or from surface vegetation such as grasses. The combination (logical “or”) of the two masks allowed us for the first time to easily analyse fairly open to widely open forested areas with an ITC delineation process premised on finding shadow between tree crowns. A second combination of the multispectral mask with a complemented height mask (0.1 to 2m) aimed at regenerating areas also performed reasonably well and made possible a separate ITC delineation of the regeneration.

Individual Tree Crown Delineation

The ITC delineation process was run on the multispectral image using the non-forest mask resulting from the synergy of both media. It led to relatively good delineation of tree crowns, with difficulties in separating some tree clusters, specially clusters aligned in a direction perpendicular to sun illumination azimuth. The ITC delineation process was then run on the height image using the same non-forest mask. It led to relatively good isolation of crown material. Some tree crowns, specially in densely forested areas, were not separated properly, generating tree clusters. However, for isolated trees, it produced very nice round crowns, as the shaded sides of tree crowns is not a confounding factor with a height image. Both delineations suffered from the weaknesses of the non-forest mask being used: the lack of spatial resolution of its LIDAR component and the masking out of damaged trees of its multispectral component. A separate analysis of the spruce budworm damaged trees is possible and is the subject of ongoing research.

The synergistic effects of the two media for the ITC delineation *per se* were tested two ways: (a) by combining the ISOL bitmaps and, (b) by combining the VFOL bitmaps and running the rule-based isolation process. The simple logical “and” combination of the ISOL bitmaps, which will keep as ITC material only pixels common to both delineations, seems to isolate a majority of relevant tree crowns. Indeed, tree clusters that were not separated in one media may get separated because of the other. However, it missed all of the tree crowns that were only delineated on one of the media and appears to underestimate the area of the delineated crowns. It also generates many noise pixels where crowns generously delineated on one media intersect with other neighbouring crowns generously delineated on the other media.

A logical “or” combination of the VFOL bitmaps from both media on which the isolation process is run appears to lead to slightly better results (Figure 2). The synergistic effects leading to better breakdown of tree clusters are generally the same but without the generation of the so-called “noisy” pixels. On the other hand, some smaller trees are being missed when location imprecisions from both media generate VFOL holes smaller than the absolute minimum crown size that the ITC suite will consider (2x2 pixels). Again, tree crowns that could have been delineated with only one of the media are missed and, the area of the delineated tree crowns is typically underestimated. In both cases (a and b), it is the very nature of such simple combinations, compounded by image registration imprecisions, that lead to an underestimation of crown areas. However, because of its improved separation of tree clusters, the synergy appears to lead to better overall results than using any of the two media separately.

The negation of the 0.1-2.0m height mask, combined with the multispectral-based non-vegetation mask, allowed the ITC delineation process to concentrate on the isolation of small trees and shrubs in the regenerating areas. The near infrared image was used because of its sensitivity to vegetative material and its higher spatial resolution relative to the LIDAR image. The delineated young trees are shown as a separate colour in Figure 2. The benefits of using height data are more obvious here, as this constitutes one of the first applications of the valley following ITC delineation process to an area that so blatantly violates its basic assumption (i.e., an area without shade). Here, surrogate shade is essentially created by the height threshold masking ground level vegetation and woody debris.

In general, these simple pre- and post-processsing combination techniques have allowed us to get a glimpse at the potential synergy of multispectral and height data for non-forested area filtering and individual tree crown delineation. A much better separation of mature forest from regenerating areas was achieved and a separate ITC analysis of the regenerating areas was made possible. Within the mature areas, the synergy between the two media often led to a good breakup of tree clusters into individual tree crowns. However, this improvement comes at the expense of loosing some trees with small crowns and, all of the crowns delineated in only one media. Higher resolution LIDAR data (0.5m/pixel) may alleviate some of these drawbacks and will be the subject of future investigations. This work also illustrates the possible need for a more sophisticated ITC delineation process capable of fully building on the synergy of multispectral and LIDAR data.

Conclusion

As they represent two different renditions of the same scene, a useful synergy between airborne laser altimeter and digital multispectral video data was expected. In this study, some aspects of this synergy for individual tree crown delineation were examined. Preliminary results are encouraging. As expected, multispectral delineation was better in denser areas because the LIDAR data did not have the required sampling density. The height-based delineation was better in open areas because the optical delineation is based on the presence of shade between tree crowns. Delineations based on both media were able to capitalise on these two strengths and exhibited substantial improvements in the separation of tree clusters into individual tree crowns, especially as the delineation in the optical part of the spectrum is usually hampered in a direction perpendicular to the illumination angle. The synergy between multispectral and height data was also used to separate forested from non-forested, or sparsely forested yet vegetated areas. In addition, a low height mask (0.1 - 2 m) was used to make a completely separate analysis of the regenerating areas.

It was already known that within dense to medium dense coniferous forest, good quality multispectral imagery at an appropriate spatial resolution (~50 cm/pixel) typically leads to good individual tree crown delineation, species recognition and regrouping into forest stands (Gougeon, 2000). With the addition of LIDAR data of equal or slightly poorer resolution, one should be able to get good ITC-based heights (St-Onge *et al*., 2000), improved tree cluster separations, an easier assessment of standing trees in open areas, and a separate analysis of young regeneration. Alternatively, if the LIDAR spatial resolution is high enough (around 50 cm/pixel), one could get good crown delineation and height measurement from that data set, and rely on coarser multispectral data for species recognition (Gougeon, 2001). An ideal system would incorporate individual tree crown delineation, species recognition, and LIDAR-based height measurements to produce precise, accurate and timely ITC-based forest inventories. Such information may also permit forest productivity inferences such as volume, biomass and growth estimates to be done on an ITC-basis.

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Figure 1 – Digital multispectral video (original in colour) image at 50 cm/pixel.

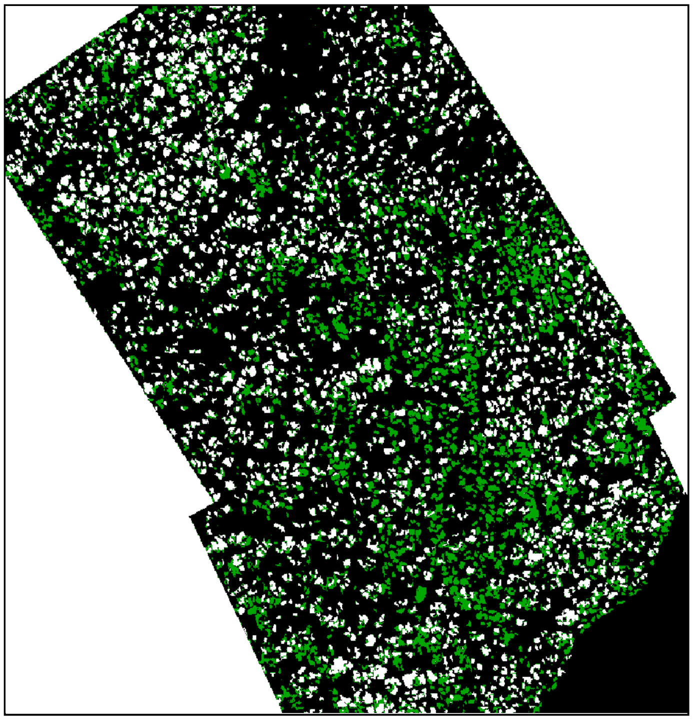

Figure 2 – Delineated tree crowns (in white) and regeneration (green or darker)