ESTIMATING INDIVIDUAL TREE HEIGHTS OF THE BOREAL FOREST USING AIRBORNE LASER ALTIMETRY AND DIGITAL VIDEOGRAPHY

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ABSTRACT

Estimation of tree heights for large territories is either expensive if done in the field or imprecise when accomplished through automated stereophotogrammetry. While scanning laser altimetry provides a solution, estimating the height on an individual tree using such an approach requires that a laser spot fall near the point of maximum height, an event that cannot normally be verified unless ancillary data is available. Two distinct aerial surveys of an 8 km^2 area of the boreal forest in Québec, Canada, yielded respectively 50 cm resolution multispectral imagery and a laser altimetry coverage (the average distance between to hits being approximately 1.5 m). Subtracting the interpolated terrain altitudes from the interpolated canopy altitudes yielded a 50 cm resolution canopy height model (CHM). The multispectral imagery was overlaid onto the CHM after rectification to help locate trees and provide information on species. The height of individual trees read from the CHM at the center of the tree crowns visible on the overlaid multispectral imagery were compared with field observations consisting of the mean of two height measurements for each GPS-positioned tree. A linear regression model between actual and laser-predicted heights yielded a R^2 of 0.90 for 36 trees (hardwood and softwood). The mean difference between actual tree height and laser-predicted tree height is 1.4 m, while the mean difference between the two ground measurements for the same trees is 1.5 m, suggesting that the accuracy of height prediction based on laser altimetry is comparable to that of ground measures. The correlation between crown radius and laser-predicted height error is -0.76, confirming that smaller trees have a lower chance of being properly hit by the laser beam. Current research is directed toward the bettering of the predictions and the automation of the process.

RÉSUMÉ

L'estimation de la hauteur des arbres pour de vastes régions est coûteuse si elle se réalise par des mesures de terrain, ou imprécise dans le cas où une approche de stéréophotogrammétrie est utilisée. Si l'altimétrie laser constitue une solution, encore faut-il vérifier qu'un faisceau laser ait été réfléchi par un point situé près du centre du houppier, une vérification qui est irréalisable sans données additionnelles. Deux survols au-dessus d'un secteur de 8 km^2 la forêt boréale du Québec (Canada) ont produit des images multispectrales de 50 cm de résolution et une couverture laser d'une densité d'approximativement 1 point à tous les 1.5 m. En soustrayant en forme interpolée matricielle les altitudes du terrain de celles du couvert forestier on obtient un modèle de hauteur du couvert (MHC) de 50 cm de résolution. La superposition des images multispectrales au MHC permet de faciliter la localisation des arbres et l'identification des espèces. La hauteur des arbres lue dans le MHC au centre des houppiers visibles sur les images multispectrales superposées ont été comparées aux observations de terrain formées de deux mesures de hauteur pour chacun des arbres positionnés par GPS. Un modèle de régression linéaire reliant les hauteurs-terrain aux hauteurs-laser a produit un R^2 de 0.90 pour 36 arbres (feuillus et conifères). La différence moyenne entre les hauteurs-laser et les hauteurs-terrain est de 1.4 m cependant qu'elle s'élève à 1.5 m en moyenne entre les deux mesures de terrain, suggérant ainsi que les prédictions-laser sont d'une exactitude comparable à celles du terrain. La corrélation entre le rayon du houppier et l'erreur de prédiction basée sur le laser est de -0.76, ce qui confirme que les petits arbres se voient en général moins bien décrits par les faisceaux laser. Des recherche en cours portent sur l'amélioration et l'automatisation des prédictions.

1 INTRODUCTION

Tree height is considered one of the most useful variables, along with stocking and diameter at breast height, in estimating forest stand wood volumes and productivity. It also determines the light penetration in the forest canopy and is of importance for certain habitat studies. It is however one of the most difficult variable to measure when forest covers are dense. Ground measurements can take a few minutes per tree and are error prone. Alternatives include automated photogrammetric approaches that consist in finding the difference between tree altitude and nearby ground altitude using stereo comparison. Because seeing the ground is of critical importance, good results can only be obtained in open forest covers, a situation seldom encountered in mature commercial stands of the boreal forest. One-dimensional radar or lidar resolve this problem by being able to penetrate the forest covers to a good extent and getting a clear echo from the ground. Lidar-based techniques were successfully used to estimate basal area, volume and biomass (Nelson *et al*., 1997, Lefsky *et al*., 1999) as well as accurate mean stand height estimations (Naesset, 1997) and percent canopy cover (Ritchie *et al*., 1993; Weltz *et al*., 1994). Estimating tree height from small footprint one-dimensional data can however only be accomplished by building statistical relationships between spot height data and average tree height in a stand since it is very difficult to establish if a particular impulse was echoed by the top of a tree or by its side. Moreover, mapping the forest cover by creating continuous coverage is impossible. Recent technological developments in laser remote sensing will most likely improve remote sensing measurements of trees. Indeed, scanning laser altimetry can now provide sub-meter resolution DTMs, i.e. continuous coverages, of both canopy top and underlying terrain, with high horizontal and vertical accuracy (Flood and Gutelius, 1997). High point densities even enable the recognition of the shape of individual tree crowns. While scanning laser altimetry provides a solution, estimating the height on an individual tree using such an approach requires that a laser spot fall near the point of maximum height, an event that cannot normally be verified unless ancillary data is available. The advent of high resolution satellites, such as IKONOS, a 1-m resolution launched on September 24th 1999, will help in obtaining imagery putting laser data in context. Meanwhile, aerial imagery can be used for that purpose.

Our general objective is to evaluate the usefulness of combining high density scanning laser altimetry to high resolution multispectral data to measure the accuracy of the estimation of individual tree height (this paper), wood volume per hectare, productivity, for dense and mature stands of the boreal tree forest. The combination of tree height data and variables such as drainage derived from the laser DTM are also used to study the relationships between ecological factors and productivity. The general approach we follow consists in overlaying multispectral imagery over interpolated laser data to help locate trees and verify if a given tree was hit near the center of its crown, i.e., at the most probable location of the highest point in the tree. This paper is specifically concerned with the accuracy assessment of laser prediction of individual tree heights. We show how the laser data was obtained and geometrically matched with 50 cm resolution multispectral imagery. We then show how ground measurements were correlated with laser measurements for trees that have a good hit coverage. Factors determining height prediction errors are then discussed.

2 STUDY REGION

Data and methods have been developed and tested for the *Training and Research Forest of Lake Duparquet* (TRFLD), a 80 square km of the boreal forest in the Abitibi region, Quebec (79.3 W, 48.5 N), which is part of the *Forest Ecosystem Research Network of Sites*. The boreal forest is the largest forest biome, covering 17% of the terrestrial land. Its floristic composition is rather simple, indeed, only nine species are commonly found. The forest landscape at the TRFLD is essentially composed of hardwood, softwood and mixed stands aged from 50 to more than 230 years growing on a part of the Canadian shield culminating at 382 m. Common species include: Trembling aspen (*populus tremuloides*), White spruce (*picea glauca*), White birch (*betula paperifera*), Balsam fir (*abies balsamea*), severely attacked by spruce budworm, Jack pine (*pinus banksiana*), Eastern cedar (*thuya occidentalis*), and Black spruce (*picea mariana*). The study site was commercially exploited until 1992 and bears regeneration areas. This test area was chosen for its landscape and habitat diversity, representative of the mixed boreal forest, the wide availability of data, and the important collaborative effort between universities, forest companies and the socio-economic environment.

3 DATA ACQUISITION

Airborne scanning laser altimetry data

Scanning laser altimetry data was acquired on June 28th 1998 using Optech's ALTM 1020 instrument on a Piper Navajo plane flying at 700 m. Separate passes were needed for vegetation (two passes) and terrain description (single pass) respectively. Vegetation/terrain separation was carried out by the data provider using Optech's ALTM software. Flight, laser and GPS characteristics are presented in Table 1 and a sample of the derived imagery is presented in Figure 1. The impulse frequency combined with the lowest sustainable flight speed and altitude did not allow to achieve the desired laser hit density of one hit every 50 cm. To alleviate this problem, each flight line was flown twice in an effort to double point density for the first return (vegetation). However, since some first pass hits fall very near the second pass hits, the effective hit density was increased but not usefully doubled. This does not constitute a severe operational limitation because of the existence of higher frequency instruments and the possibility of using a helicopter. However, it does have consequences on this study's results. Still it provides a very good database to carry out a crossover study to assess laser accuracy (not presented in this paper).

Multispectral imagery

The area covered by laser data had been surveyed the year before (September 27th, 1997) using a Super VHS video camera, functioning in zoom mode, mounted onboard an airplane. The videotape was later converted to a series of multispectral digital images having a 50 cm resolution. The characteristics of the multispectral digital video survey are presented in table 2. A sample of the digital images is presented in figure 2. Tree growth between the end of September 1998 (multispectral data) and the end of the following month of June (laser data) is minimal at these latitudes (48.48 degrees north), allowing for direct comparison of the geometry of trees (size, shape) between the two dates.

Ground measures

The height of individual trees was measured on the ground using a standard clinometer and distance tape method. Two measures were taken from different vantage points separated by at least 90 degrees to insure independence between the two measures. Trees for which the two height measures differed by more than 3 meters or by more than 15% were discarded so that errors in comparing laser heights to actual heights can mostly be attributed to the laser methodology. These two heights for all well measured trees were later used to assess the accuracy of ground measurements. The study focused on two species: Trembling Aspen (*Populus tremuloides*) and White Spruce (*Picea glauca*) but some other species mentioned in section 2 were measured. Of the approximately 200 trees measured, only 40 had been positioned on the laser and multispectral imagery at the time of paper submittal. After ground error filtering, 36 trees remained. Other ground measures include: diameter at breast height, crown radius measured in the four cardinal directions, species, and GPS positioning. A Corvallis Alto GPS was used as a base station continuously downloading differential data on a computer while a Corvallis MC-GPS served as the mobile unit to position trees. Three hundred epochs were obtained for each GPS point allowing for a maximum error after differential correction that does not exceed three meters for most trees.

4 METHODOLOGY

Creation of the Canopy Height model

The Canopy Height Model (CHM) was obtained by subtracting the interpolated terrain altitudes from the interpolated canopy altitudes. Triangulated irregular network (TIN) interpolation of the X,Y,Z points was converted into a 50 cm resolution grid using Surfer 6.04.

A TIN interpolation assumes that altitudes vary linearly between points, a fact that is not necessarily observed in reality. However, the choice of a different interpolation model would have to rely on appropriate knowledge of the three-dimensional geometry of the canopy in the case of the vegetation, which can vary with species and was not available. An outlook of future research presented at the end of this paper discusses this matter further. Subsequent work will compare interpolation alternatives for the terrain hits in their ability to better tree height predictions by providing a more accurate description of terrain altitudes. The three stages of the creation of the CHM are presented in Figure 1.

Multispectral image registration

The multispectral imagery was rectified to allow for accurate overlay on the CHM. A minimum of five control points were acquired for each 740 x 540 pixel multispectral images (approx. 370 m x 270 m) covering areas corresponding to ground tree measures sites. These control points were obtained by visually matching the center of small tree crowns that could be recognized on the CHM and the corresponding crowns found in the multispectral imagery. On both types of imagery, the control points were positioned at the center of the crown. The multispectral images were rectified by cubic convolution resampling guided by a first order polynomial. The resulting RMS residues of the polynomial are typically between one and two meters. The fact that the raw multispectral images were acquired in zoom mode (narrow view angle), yielding quasi-orthographic images, helped in achieving low RMS. After rectification, the multispectral images were overlaid on the CHM allowing for 2D and 3D rendering (figure 2). A total of 40 images were rectified. All image processing operations were carried out using ER-Mapper 5.5 software.

Establishing ground position to image position correspondence

Tree location on the imagery was established either by marking the tree on a printout of the multispectral imagery based on observations made during the ground survey, or by plotting a differentially corrected GPS point on the imagery. The first method is unpractical in that it asks for extreme care in visually matching trees observed in the field to trees appearing on the printouts. Trees near a lakefront can be identified after careful examination, but trees a few dozen meters from the lakefront and further can only be identified by progressing from one outstanding tree to another, thus rendering walking in the forest a very slow and tiring process. The other method of locating trees used GPS technology. The X, Y coordinates of each tree was plotted on the laser and rectified multispectral imagery. The color of the tree (that relates to species) and the crown diameters in the four cardinal directions (describing crown shape and size) Were used as collateral data to insure that the correct tree was identified by the GPS approach. In some instances, a tree having the correct color and shape could not be identified with certainty within a 5 meter radius of the GPS point because two or more candidate trees with similar characteristics were present in the vicinity of the plotted GPS point. These trees were discarded from the study to avoid error.

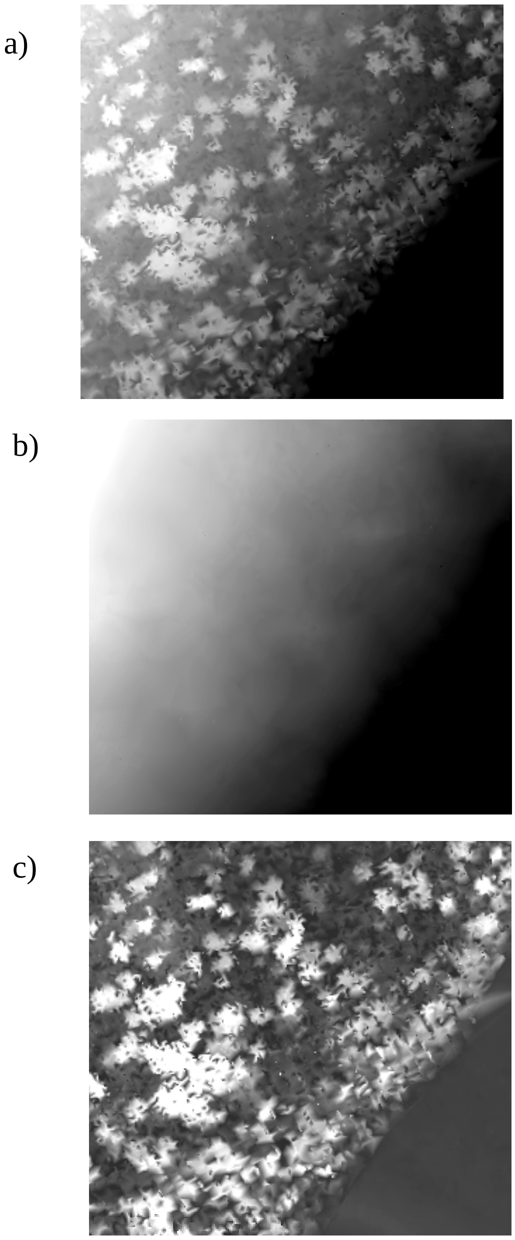

Figure 1 – 1.a) Example of the Canopy Altitude Model, 1.b) the Digital Terrain Model, 1.c) and the Canopy Height Model (c = a - b). Brightness is proportional to altitude or height.

Obtaining tree height from the Canopy Height Model

The CHM gives interpolated height of all points in the canopy in the form of a regularly spaced grid having a 50 cm resolution. The height of a tree was defined as the pixel having the highest value in a high-valued pixel cluster corresponding to a crown. This "top pixel" is normally situated near the center of the crown put can sometime be found a few pixels from the center in the case of large hardwood trees. We believe that a more accurate method would be to find the difference between the maximum laser spot altitude and the underlying interpolated DTM altitude in order to preserve the preciseness of raw laser data. However, due to time limitation, we chose the simpler method described above. Improvements in the near future will comprise preserving raw laser data for vegetation and using a better interpolation method for ground laser points.

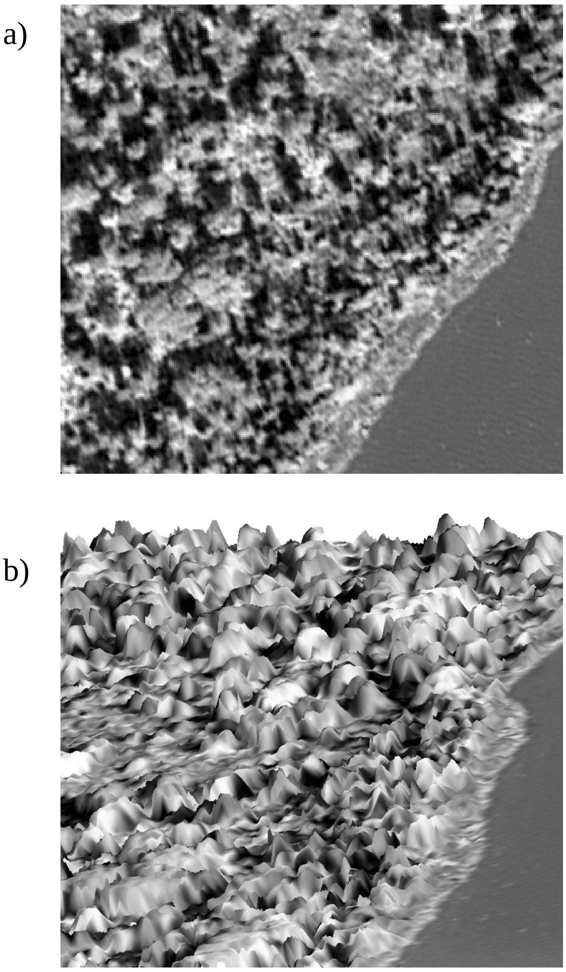

Figure 2 – 2.a) Digital multispectral videography (initially in color) rectified according to the laser altimetry images presented in Figure 1, and, 2.b) overlay on the Canopy Height Model of figure 1.c).

5 RESULTS

Linear Regression

Linear regression was performed between ground-measured height and laser predicted height on. The mean of the two height measures done in the field for these trees was regressed against the corresponding height read from the CHM for 36 trees (12 hardwood and 24 softwood). The linear model yielded a R^2 of 0.90 (significant at $\alpha=0.01$). The scatter of points in figure 3 does not bear any non-linear trends, an observation that was corroborated by the fact that the linear model fit gave the best results. The predictive model (true height from laser height) is given by:

$$\textit{Mean ground truth height} = 4.24 + 0.91 * \textit{laser height} \quad (1)$$

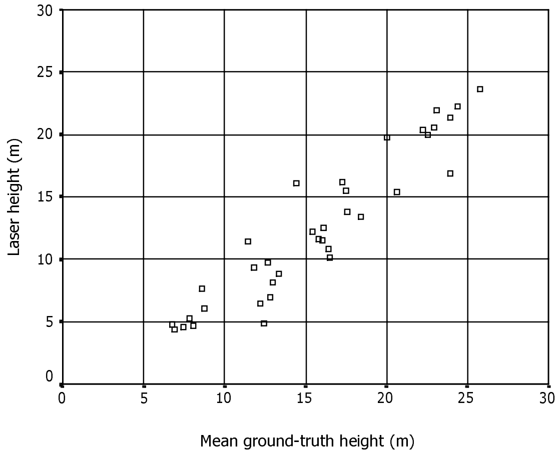

Figure 3 - Comparison of mean ground-truth heights with laser heights.

Error assessment

Tree heights predicted by the linear regression model in Figure 3 were compared to the mean of the two ground measurements, yielding an absolute difference of 1.42 m with a standard deviation of 1.15 m. The average relative error is 11 % with a standard deviation of 9 %. The average difference between the two ground measurements for each tree is 1.52 m (SD), and the relative error (the absolute difference between the two ground measurements divided by the average of the two measurements) is 10% (SD = 8%). The data thus suggests that after the laser absolute measurements of tree height are corrected by a linear model, the laser prediction have an accuracy comparable to that of ground measurements. Caution must be used in interpreting these results since the number of trees is relatively small. Also, “true” tree height, or tree height measured with, say, a centimetric accuracy is unknown. Rather, the accuracy of the laser predicted heights is evaluated from error–ridden ground-truth data. The R^2 of equation 1 would probably be higher if the error associated with ground measurements could be reduced. A manual photogrammetric approach will be tested in trying to alleviate this problem. Moreover, the comparison of the level of laser-predicted height errors relative to the level of ground errors is only indicative since the error source cannot be established with certainty. If most of the error was eventually attributed to ground measures, and R^2 proven to be higher, the use of laser predictions could then be considered as being of higher accuracy than ground measures.

The main factors determining accuracy of raw laser measurements, and thus of the prediction of tree height are believed to be laser spot density relative to crown surface and laser penetration in vegetation. Indeed, the correlation between crown surface (obtained by modeling the crown as a circle and by using the average of the four crown radii measured on the ground) and relative laser tree height prediction error is –0.76. This indicates that the probability of a laser hit falling directly on the tree top (maximum height) is directly proportional to the crown projected surface. However, even trees that were well covered by laser hits, such as large hardwoods, gave a raw laser height estimate that was systematically lower than ground measured height, i.e. often two to three meters less than true height. Light penetration in the first layers of leaves or needles is the most probable explanation for the fact that laser raw heights are systematically lower than ground heights. For example, when the height of a conifer is measured, the top of the tree is defined as the tip of the highest branch. The volume of needles and branches in the tip of the tree is very low and does not constitute a very good interceptor of light, even in the case of a very small footprint falling exactly on the center of the tree. This also applies to the somewhat ragged tree top surface of hardwoods. The first return from the top of the tree probably comes from a level lower than the height that is measured on the ground. Moreover, our study area is located in an old forest. The forest floor is often covered by dense regeneration growing across numerous debris such as fallen branches or trees, boulders and rotten tree trunks. Even in the field, the ground level is in some cases difficult to see. Therefore, it is safe to assume that the last return could come from objects above true ground level.

The shape of the crown, determined by species, can theoretically influence the probability that the laser beam hits at a level close to the maximum tree height simply because the hardwoods have a much more rounded crown top. However, when absolute and relative error are compared by hardwood versus softwood categories using ANOVA, no statistically significant differences are revealed. This conclusion must be interpreted with caution since only 8 hardwood trees and 14 softwood trees were used in this analysis. Finally, the TIN interpolation and the conversion from a TIN to a grid could also induce some errors. Indeed, the height of a grid cell normally corresponds to that of the center point of the grid cell projected on the TIN rather than the maximum TIN height observed inside the grid cell. Since the apex of trees defines a convex shape, the center point of any grid cell covering the apex of the tree will most probably be projected at a lower level than the maximum height observed in that cell.

6 CONCLUSION

By comparing tree height measured on the ground with tree height measured by a small foot print high density airborne lidar, we observe that the accuracy of laser measurements show an accuracy comparable to that of ground measurements. The errors can be mostly attributed to the size of the crown since larger crown have a higher probability of being hit at a level close to that of maximum tree height. Many improvements are considered: increasing the number of tree in the sample, using a better algorithm for interpolating ground points and preserving the raw first return altitude instead of using the gridded version. Also, we are looking at fitting three dimensional models of tree crowns (ellipsoid, cones and bullet shaped solids) to laser first returns to try to better capture maximum tree height and to automate the process of identifying individual tree position, species and height for forest ecology studies.

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Laser survey characteristics
Survey carried out by Lasermap Image Plus,
Boisbriand, Canada
Contact name : Pierre Bélanger
WWW site : www.lasermap.com

Flight characteristics
Date of survey: June 28th 1998
Plane: Piper Navajo
Flight altitude for vegetation and ground: 700 m
Flight speed for vegetation and ground: 65 m/s
Area covered by the survey : approx : 8 km^2
Flight line width : 0.25 km
Number of flight lines for vegetation and ground: 10
Number of passes for vegetation: 2
Number of passes for ground : 1
Flight time for each pass: 80 minutes

Laser characteristics
Laser sensor: Optec's ALTM1020 built in 1995
Impulse frequency: 4000 Hz, scan frequency: 16 Hz
Power: 140 microjoules
Laser wavelength: 1047 nm
Ground spot size: 0.19 m
Scan mode: zig-zag
Maximum scan angle from nadir : 10 degrees
Approximate X,Y,Z accuracy: +/- 15 cm
Average hit density for vegetation: 1 hit/m^2
Average hit density for ground: 1 hit/2.5 m^2
Vegetation/ground separation : Optec's ALTM

Positioning system characteristics
Plane Trimble 4000 SSI kinematic GPS frequency: 1 Hz
GPS base: Trimble 4000 SSE on a geodetic point
Inertial system: Litton

Table 1 – Scanning laser altimetry survey characteristics

Flight date: September 27, 1997
Flight time: 11h00 - 13h00
Sun elevation: 37 - 39 degrees
Flight altitude: 1890 m
Spatial resolution: 50 cm

Spectral bands (3 x 8 bits):
- green = 520 nm - 600 nm
- red = 630 nm - 690 nm
- infrared = 760 nm - 900 nm

Table 2 - Multispectral digital video survey characteristics