The Use of Airborne LiDAR and Aerial Photography in the Estimation of Individual Tree Heights in Forestry

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SUMMARY

This document describes the use of aerial photography and airborne LiDAR to estimate individual tree heights in forest stands. The advantages and disadvantages in the use of LiDAR systems are revised and a data fusion analysis with digital aerial photography is proposed. The work shows an example of these techniques in a forested area in Scotland. An algorithm has been devised to extract a high resolution digital terrain model of the bare ground. This information was used to obtain a tree canopy model as a difference between the laser first pulse and the model of the underlying terrain. The information at a tree level was obtained by image segmentation and classification. The analysis showed a good estimation of individual tree canopies and heights.

KEYWORDS: *Remote Sensing, Forestry, Lidar, Aerial photography, eCognition, data fusion.*

1. INTRODUCTION

The penetration of GIS into the British forest industry has made possible the optimisation of current working methods and, as result, GIS is becoming one of the most essential tools for forest management. In this context, there is a business need for a continuous up-to-date inventory of existing forest resources. There is a requirement for gathering information about the location, condition and sustainability of the actual forest resources. This is compelling foresters to look for more cost-effective alternatives to field-estimated surveys. Internationally, there have been important scientific advances in the use of remote sensing over the last 30 years that have produced mature techniques ready for implementation in the management of forest resources. Along with the traditional reliance on aerial photography, there are abundant examples of the use of other systems such as Radar, Lidar, thermography and optical sensors that may equally offer tools for spatial data collection (Suárez, 2002).

However, the uptake of remote sensing methods in operational forestry has been precluded traditionally by a mixture of mistrust and lack of understanding by forest practitioners. This has been reinforced by the costs of the imagery, the limited ground resolution of some satellite images, the endemic cloud cover problem in the British Isles, the over-reliance on optical methods and the lack of staff with remote sensing expertise. One factor that has led to the disillusionment with the technology, especially in the analysis of the optical wavelengths, has been the lack of direct relationships between remotely sensed reflectance values and those forest parameters of direct interest to foresters (e.g. tree density, timber volume, tree heights or mean diameter). Therefore, nowadays it is rare to find applications directed at the information requirements necessary to supporting tactical decisions at the forest stand or sub-stand levels.

This paper shows an application for automatic data capture for forest inventory using data fusion techniques between airborne LiDAR and digital aerial photography. The system is intended for capturing forest, stand and individual tree parameters in an easier and more intuitive manner.

2. USE OF AIRBORNE LiDAR IN FORESTRY

2.1 LiDAR Characteristics

LiDAR (Light Detection and Ranging) is an active sensor that emits laser pulses and measures the return time for each beam to travel between the sensor and a target using ultra-accurate clocks. The location of every return to a known coordinate system is achieved by precise kinematic positioning using differential GPS and orientation parameters obtained by an Inertial Measurement Unit (IMU). The IMU captures orientation parameters of the scanner such as roll, pitch and heading angles. Thus, the GPS provides the coordinates of the laser source and the IMU the direction of the pulse. With the ranging data accurately measured and time-tagged by the clock, the position in the horizontal and vertical planes of the return points can be calculated. A good description of system components is found in Renslow (2000).

Data capture is obtained as the aircraft moves forward. A scanning mirror directs laser pulses back and forth across the flightline. As a result, the datasets present a typical sawtooth arrangement of points. The majority of the commercial systems can collect between 20,000 to 75,000 records per second and the Lidar data sets are large point files in an ASCII XYZ format. Data point density depends on the number of pulses transmitted per unit time, the scan angle of the instrument, the elevation of the aircraft above ground level, and the forward speed of the aircraft. The system is capable of achieving high vertical and horizontal accuracies. They may vary from 15-20 cm RMS vertically, while horizontal accuracies are about 20-30cm.

2.2 The use of LiDAR in Forestry.

There are numerous examples worldwide of the use of Lidar instruments to characterise forest structure and underlying terrain. Consult the following proceedings for a complete compilation of applications of LiDAR in forestry:

- Scandlaser workshop: http://www-earsel-sig-forestry.slu.se/scandlaser
- Canadian workshop: http://larsees.geog.queensu.ca/lidar/LiDAR_Workshop/lidar_workshop.html

LiDAR instruments can generate canopy height models that subsequently provide accurate estimations of important forest parameters such as canopy heights, stand volume, and the vertical structure of the forest canopy. The estimation of tree heights is performed by the subtraction of bare ground values from the canopy layer. In commercial airborne systems, the canopy layer is estimated from the first laser return, which measures the intensity of the signal as it first encounters an object on the ground. In semi-opaque objects like vegetation, the signal will penetrate through them till it runs into a definite barrier. The last return will provide information about the location and height of the mid-point of the last strong waveform that is normally associated with the ground (see Figure 1).

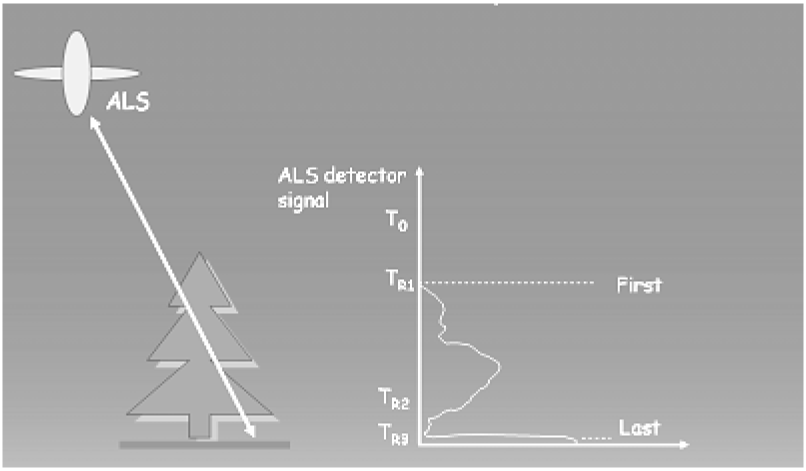

Figure 1. Interactions between the commercial Airborne Laser Systems (ALS) and the vegetation. Canopy height is estimated as the difference between the first and the last laser returns.

Several authors have highlighted the commercial advantages in the use of Airborne Laser Systems (ALS) in forestry (Nelson et al., 1988; Renslow et al., 2000 or Wulder, 2003). However, they also identify limiting factors for the operational use of this technology, for example, the cost of the data, the lack of common standards or the low number of processing algorithms available. Technically, Baltsavias (1999) and Ackermann (1999) describe the importance of ALS systems compared to standard photogrammetric methods. They conclude that ALS has a higher degree of automation in the delivery of raw X, Y, and Z data than conventional photogrammetry. One of the main advantages being the generation of sample points with polar geometry versus the perspective geometry obtained by aerial photography. Lidar data does not require aerial triangulation and orthorectification, because all the measurements are individually georeferenced by means of a differential GPS. This differential correction allows a vertical and horizontal accuracy of a few centimetres.

Lefsky et al. (2001) found that ALS performed better than other remote sensing systems in its predictions of forest structural attributes (mean tree height). Unlike other optical systems, Lidar sensors introduce the possibility of three-dimensional analysis. In ALS with a high sampling density of returns, individual tree crowns can be detected (Persson, et al., 2002; Brandtberg, et al., 2003). This makes possible the detection of the height and crown dimensions of individual trees. Hyyppä et al. (2001) estimated stem diameters using a correlation with crown diameters. Hirata, et al. (2003) retrieved the vertical structure of the forest canopy and the understory vegetation in a temperate forest in Japan. Previously, Magnussen and Boudewyn (1998) and Naesset (1997) estimated mean tree heights at stand level from canopy-based quantiles. This technique basically assumes a rate of interception of the laser returns at different canopy heights per unit area that is later related to stand parameters like mean height, canopy depth or Leaf Area Index (LAI).

2.3 Limitations of the Technique

It is worth noting that the majority of sensors commercially available have a small-footprint, which can be a limited solution for retrieving tactical forest parameters. These systems are characterised for having small diameter beams (c. 10 cm) that frequently miss the top of the trees. Therefore, they may be limited when reconstructing a fully three-dimensional tree canopy structure unless they increase the density of returns (Naesset 1997, Nelson 1997, Magnussen et al. 1999). Alternatively, an estimate of true canopy topography has been reconstructed statistically (Magnussen and Boudewyn 1998, Magnussen et al. 1999; Means 2000, Young et al. 2000).

Another important limitation is the fact that ALS provides pointwise sampling and not full area coverage like the optical systems. That means that laser data must be interpolated in order to convert the same coverage as an image. It is considered that the gridding process introduces error into the tree canopy model (TCM) via both the interpolation method and the grid spacing chosen. Moreover, the gridding method will ultimately affect the canopy dimensions of each individual tree. Especially the model of the breaklines that configure the crown dimensions of a tree in a 2-D plane and the heights that can be significantly altered by an excessive smoothing.

Finally, the accurate estimation of the TCM dimensions depends upon a good approximation of the ground cover underneath. In small foot-print systems, only the gaps in the canopy cover will allow individual laser shots to hit the ground. Accordingly, the terrain is modelled with the aid of spatial interpolation techniques like Inverse Distance to a Power (Young et al. 2000), Kriging or Spline functions (Magnussen and Bodewyn 1998). The choice of one or another will be determined by the number of hits reaching the ground and their distribution. For a fully automated system of DTM creation, the laser data has to be filtered in order to differentiate those returns reaching the ground from those being intercepted at different parts of the canopy (see Sithole and Vosselman, 2003 for a complete description of filters used for the construction of DTM,s).

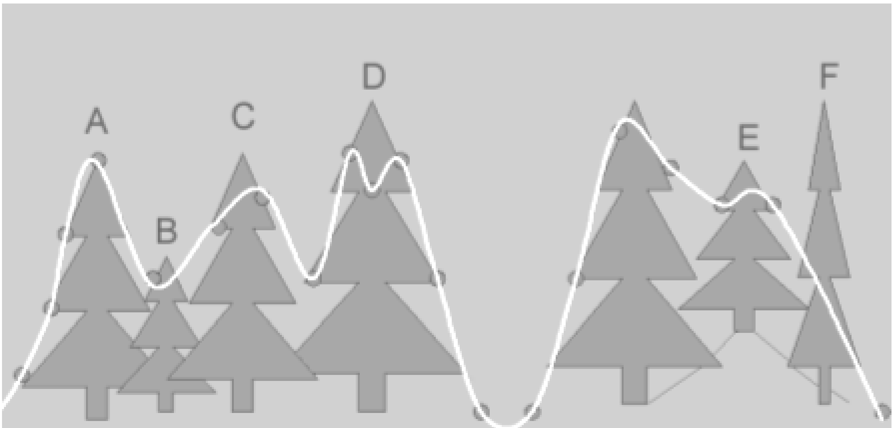

Figure 2. Likely scenario in the use of ALS in forest survey.

A. Laser hits the true top of the canopy,
B. Small trees close to bigger ones are ignored,
C. The most likely situation: laser returns do not hit the true top of the tree,
D. One of the hits is intercepted at a lower height and the model produces two tree tops,
E. Trees on a mound can be assigned a larger height in the absent of a good model for the ground cover underneath,
F. In a situation of sparse density of returns some trees can be ignored completely.

3. STUDY AREA IN ABERFOYLE FOREST DISTRICT

The study area in Aberfoyle Forest District (56^0 10’ North, 4^0 22’ West) was surveyed with high resolution digital aerial photography (less than 25 by 25 cm pixel size) and Lidar at a high density of returns per square metre (3-4) obtained by repeated pass. The work was carried out by contractors on the

16th of September 2002, at the end of the growing season, using an Optech ALTM2033 scanner. The total area covered by the two sensors was 20 km2 at a cost of £5 per ha (see Figure 3).

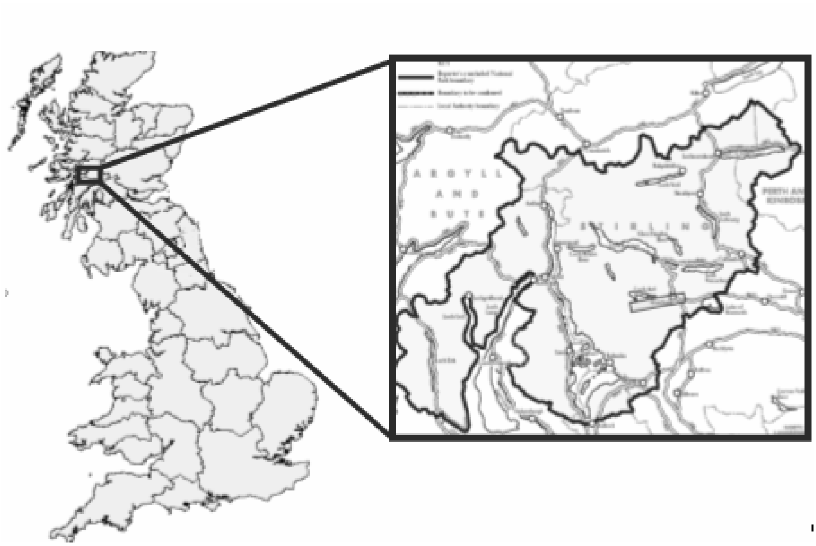

Figure 3. Location of the study area in Aberfoyle Forest District (Scotland). The red rectangle represents the area being surveyed with the Lidar and the aerial photography.

The field data for the validation of the model comprised ten 50x50 m plots covering thinned and unthinned mature Sitka spruce stands (see Figure 4). The plots were situated in relatively flat terrain with a mean slope gradient ranging from a 0% to 5%. The position of each plot was located with differential GPS and a laser relascope (Criterium laser, Laser Technology Inc. 1992-, Englewood, Colorado, US).

Each plot was surveyed for top height, tree diameters, tree position and dominance. The location of each tree within the plots was achieved by means of laser relascope and PocketGIS (Pocket Systems Ltd., 1996- Bedfordshire, UK). Additionally, three small plots of 10 by 10 metres were randomly located within each 50 by 50 metres plot in order to measure individual tree parameters such as tree height, canopy dimensions in a N-S and E-W axis and height to the first live whorl (see Figure 4).

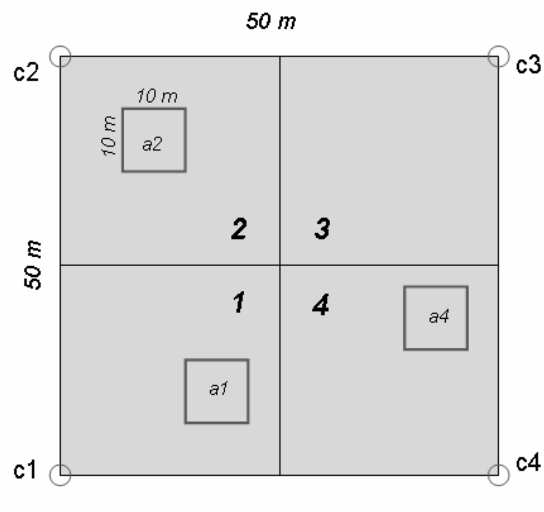

Figure 4. Configuration of the sample plots in the field. Plots are oriented to the magnetic north. Each corner is labelled with a 'c' and a number starting from the Southwest corner in sequence and finishing in the Southeast one. Each quadrant is labelled in the same sequence as the corresponding corners. Small plots of 10 x 10 metres are labelled with an 'a' and the number of the quadrant they lay in.

4. LIDAR ANALYSIS

4.1 Estimation of the Digital Terrain Model

One of the main problems when working with commercial ALS in forestry is the large number of returns that will be intercepted by the canopy cover. Normally, first and last returns will be intercepted by trees at some point in the vertical structure of the canopy. Only a relatively small proportion of them will go through and retrieve information at lower levels (Figure 5a and 5b).

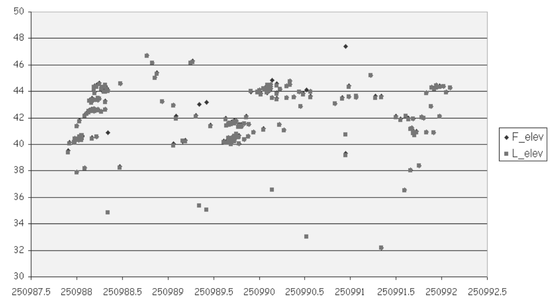

Figure 5$_a$. Proportion of last returns that show certain degree of penetration through the canopy cover.

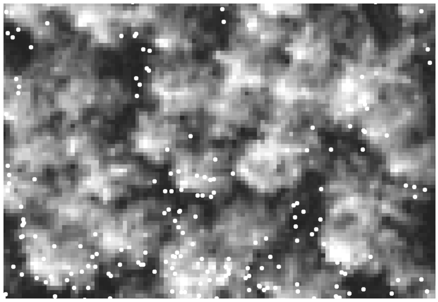

Figure 5$_b$. The location of the laser returns that go through the canopy structure is generally restricted to the flanks of the trees and canopy gaps.

In order to retrieve a good estimation of the ground surface, the ALS last returns have been filtered to eliminate those hits not reaching the underlying terrain. The method involved an iterative process of selection of points within kernels of variable size according to the local minima. The algorithm seeks the elimination of the noise created by spurious ground returns until their complete elimination. The process aims to create a high resolution DTM from the highest possible number of points (Figure 6). Once the points have been filtered, a DTM is interpolated into a regular grid of 0.5 x 0.5 m cells, using a kriging interpolator without anisotropy. The validation of these models against GPS measurements on the field provided RMS of less than 25 cm.

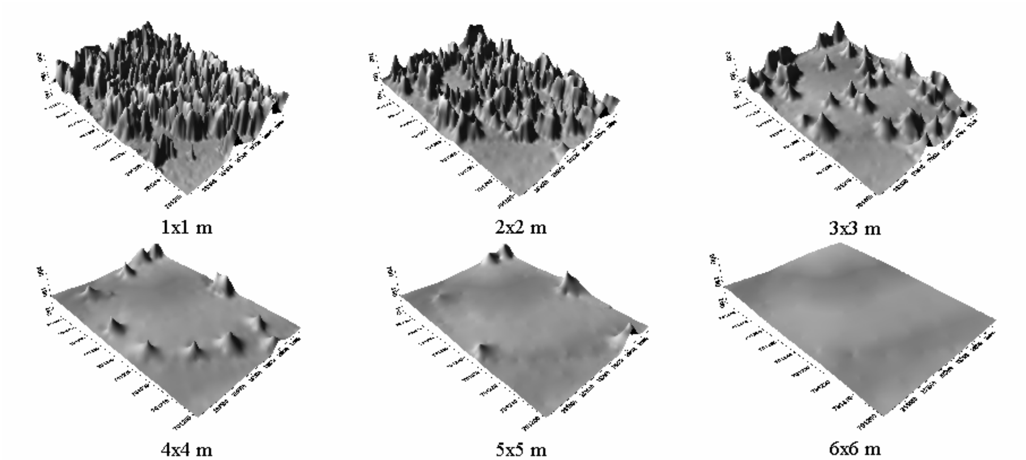

Figure 6. The filtering process of spurious ground hits is obtained by local minima in an iterative process using variable kernel sizes. Example obtained from plot 9 in Aberfoyle.

4.2 The Creation of a TCM and the Identification of Individual Tree Heights Using Data Fusion Methods and an Object Oriented Segmentation Method in Ecognition

The creation of a TCM is obtained by subtracting a gridded image created with the first laser return from the DTM (figure 7). Once the TCM has been created, it is necessary to segment this image in order to extract individual tree heights. The segmentation process aims to identify objects with correlated characteristics in terms of reflectance and height. This is performed by linking the TCM with the reflectance values in RGB from the aerial photography in each of the 10 plots of the study area.

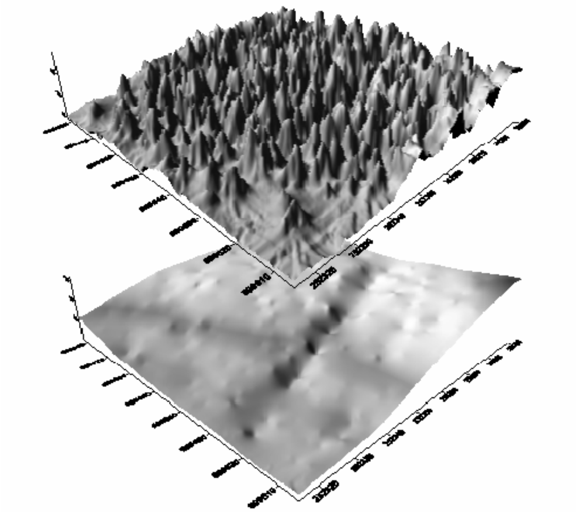

Figure 7. A Tree Canopy Model is created by the subtraction of the DTM from the original LiDAR first return. Example taken from plot 4 in Aberfoyle. The process of analysis will differentiate a tree canopy model and the underlying terrain.

The need for a data fusion between laser and optical data is sustained by several authors (Baltsavias, 1999; Wulder, 2003; Leckie et al, 2003). A strong argument claims that the laser measurements do not distribute homogenously and usually have gaps between them. Therefore, the three-dimensional structure of the objects might not be very well defined (Baltsavias, 1999). Therefore, it becomes fairly complex to obtain a good 3-D model of the canopy architecture of each tree with a low density of returns. In our example, we had 3-4 returns per square metre with a mean footprint of about 10 cm^2. This means that we have to model complex structures with only 3-4 % of the area covered. Therefore, optical systems are perceived as an ancillary piece of information for the segmentation of the height data layers.

Image segmentation methods have been applied to conventional aerial photography for the identification of individual tree crowns (Gougeon and Leckie, 2003; Suárez et al., 2003). In our example, the image segmentation method followed the Object Oriented classification method available in eCognition (Definiens Imaging GmbH, 2001; Trappenstreustrasse 1, 80339 Muenchen, Germany). This method identifies geographical features using scale and homogeneity parameters obtained from reflectance in RGB and elevation values.

After the segmentation, the geographical objects are classified according to an empirically defined rule-based system that aims to identify tree tops. The classification is based on a fuzzy logic classification system where membership functions set thresholds and weights for each one of the four data layers. Hence, elevation in the TCM is weighted 5 times more than each layer in the visible bands. In addition, elevation values follow a sigmoid function whereas reflectance saturates at a threshold in each band defined by a threshold at a DN of 102 or 40% of all the spectral range (Figure 8a and 8b). This classification process differentiated clearly tree crowns from the rest. The division of the fuzzy membership values in quartiles discriminated tree tops within each individual tree crown. In this case, the last quartile (0.75 to 1) was regarded to represent tree tops. However, the quartile division could not separate individual tree canopies automatically.

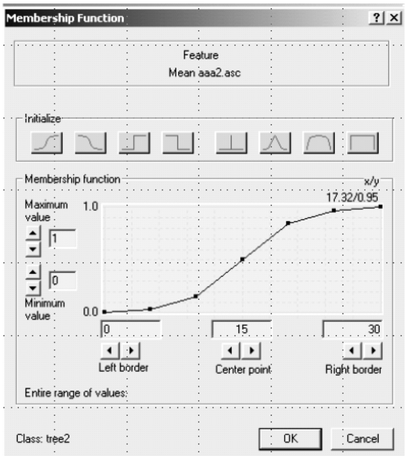

Figure 8_a. The membership of the segmented objects to the tree top class is defined by a sigmoid function.

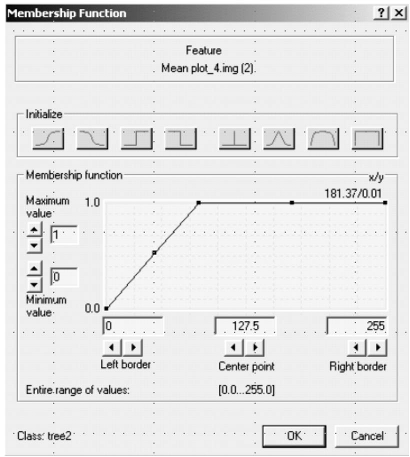

Figure 8_b. Membership in each visible bands is defined by a threshold at a DN of 102 or 40% of all the spectral range.

The selected polygons were exported to ArcView (Environmental Systems Research Institute Inc., 1992- Redlands, California, USA) for the extraction of the LiDAR local maxima. This information retrieved automatically the position and the height of each individual tree in all the 10 plots.

5. RESULTS AND DISCUSSION.

The comparison between the predictions of LiDAR and the observations in the field (354 trees) confirmed that the ALS underpredicted individual tree heights by 7 to 8%. The analysis of the residuals did not show any bias in the data and the relationship proved to be fairly consistent for all the tree diameter ranges. The tree height recovery model created from the linear relationship was able to predict 73% of all the heights within 1 m; 91% within 1.5 m and 96% within 2 m.

The analysis of the results proved consistent in all the diameter distributions (Table 1). The largest variations were obtained in diameters between 20 and 30 cm due to the low number of trees in this diameter range and the existence of a few outliers. In the smallest diameters, the relationship between predictions and observations seem to suggest that LiDAR can predict tree tops more efficiently that in the case of the larger trees. A possible explanation could be the small number of observations in this range. Another explanation related to the fact that these trees are generally sub-dominants. That means they have canopy heights below the mean height of the surrounding trees. As they tend to grow near the bigger trees our method of classification seems to misinterpret the information retrieve for these trees.

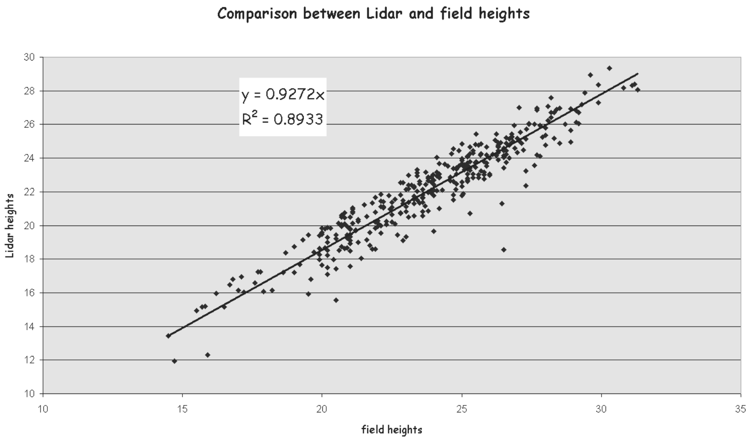

Figure 9. Tree height recovery model.

Finally, our method of classification did not seem to map canopy dimensions at individual tree level. The segmentation method created a group of polygons that represented each individual tree. Nevertheless, the subsequent classification was not able to discriminate individual each canopy dimensions in a 2-D plane. Therefore, more work should be done in order to estimate diameter distributions and volume from current models that link canopy architecture with diameter classes.

DBH (cm)	Model	R^2	number
>40	y = 0.9257x	0.825	105
30-40	y = 0.9273x	0.861	163
20-30	y = 0.9253x	0.694	65
<20	y = 0.9494x	0.861	21

Table 1. Tree heights recovery model by tree diameter distribution.

The method was able to locate automatically all the tree tops in eastings and northings within a metre distance. This information was contrasted with the field data obtained with the laser relascope. This is an important achievement because it allows us to estimate the number of trees in a forest stand too.

FUTURE WORK

The preliminary results obtained from the analysis of LiDAR and Aerial Photography are encouraging. The method allows an accurate estimation of the number of trees in a forest stand and their individual heights. This is relevant information that can be used to link remote sensing data to existing mensuration models for the estimation of volume. The method also can be adapted to show the extent of stand variability in terms of dominance. The presence and location of the largest trees within the forest can provide important information about the quality of the forest stands.

Future work in this area will include a refinement of the process of image segmentation and classification in order to map the crown dimensions of every tree. This process will allows us to obtain a better estimation of standing volume and its geographical variability across the forest that ultimately led to an improvement in forest management.

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