ASSESSMENT OF FOREST PARAMETERS BY MEANS OF LASER SCANNING

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ABSTRACT:

This paper deals with forest inventory methods based on laser scanning and satellite remote sensing. It will be demonstrated to what extent forest inventories can benefit from the synergistic use of both sensor types. The forest inventory parameters to be assessed are: tree height, timber volume, tree species, tree age, stand boundary, and basal area. The results presented are derived from the "HIGHSCAN" project (Assessing forest stand attributes by integrated use of high-resolution satellite imagery and laser scanner) which is coordinated by the Helsinki University of Technology and financed by the EU, DG XII. Developments have been carried out in close co-operation with forest management authorities, in particular with private forest owners. In this paper the results derived from the Austrian test sites will be presented.

1. BACKGROUND

In the Austrian Federal Forests and those belonging to large forest owners, forest inventories are performed every ten years on a stand-wise basis using cost-intensive field surveys in combination with yield tables. Inventory data for small forest owners are collected on the basis of questionnaires (Wood Felling Reports). Inventories of a similar intensity to those taken for the national forests and large forestry companies are carried out only for those small forest owners which have combined into agricultural associations. The proportion of small forest owners participating in agricultural associations is very small, therefore field inventories are only carried out to a limited extent. It may therefore be concluded that small forest owners, which actually own 65 % of the total area of Austrian forests, lack optimal planning data.

The investigation concentrates on private forest owners since the lack of reliable forest inventory data is far more critical in this sector than is the case for federal forests or large forest owners. In order to overcome these shortcomings inventory methods are required which are capable of gathering inventory data in an effective manner.

2. APPROACH

Laser scanner data have the potential to assess forest parameters. The most important parameters required by forest owners is timber volume and tree height, which can be indirectly derived at stand or tree level. To classify these parameters the following approaches were tested in this study.

Statistical stand-wise approach

One approach to be used in this investigation is to determine the mean tree height of stands using merely statistical techniques (Naesset et al., 1997). This method demands the availability of digitized stand boundaries stored in a GIS system. Using this method, noise reduction with different mean value calculation is first applied to the tree surface model. In a second step the tree height is determined by calculating the differences of the surface model derived from the last pulse data and the crown model derived from the first pulse data. Since laser scanner data systematically underestimate tree height, empirically derived correction offsets must be introduced to correct the data. Naesset et al. (1997) found out that the accuracy of a stand-wise estimation of tree height outperformed traditional estimates for their test areas. In a next step timber volume can be derived from the average tree height using yield tables available for most of the forest regions in Austria. One restriction of the statistical stand wise approach is that this method can only be used in pure stands.

Tree-wise approach

Although the statistical methods are very simple, the full potential of the high resolution laser scanner data cannot be utilized. In addition to the statistical stand-wise approach, this investigation was therefore also aimed at classifying the inventory parameters on the basis of single trees. The tree-wise approach assesses the following basic parameters directly from laser scanner:

- Tops of trees
- Segmented tree crowns or groups of crowns
- Forest floor model

In a second step timber volume can be derived on the basis of increment models using the above listed basic parameters:

- Breast height diameter derived from tree height and crown diameter
- Timber volume of single trees:
  - derived from the basic parameters tree species, tree height and crown diameter
- Timber volume on a stand basis:
  - derived from the basic parameters tree species, tree height, crown diameter and number of trees in a stand

Forest floor model

Because of difficult terrain conditions at the test sites (steep slopes and small structured relief) considerable attention was placed on the question of generating accurate forest floor DEMs. Raw last pulse data were processed in a regular 1 x 1m grid using a multi-resolution method in combination with an improvement by the integration of gradients.

The method searches the raw data for the minimum values within the respective resolution and increases the minimum by an appointed amount as a function of the gradient in the neighborhood. Smoothing and thresholding algorithms are performed in each resolution step, thus resulting in corresponding pixel values. The method starts with a coarse resolution (e.g. 10 m) and compares the results with better resolutions (e.g. 7, 5, 3, 1 m) step by step. Hence, the method allows forest floor information to be obtained even in dense stands, as it is assumed that within 10 x 10 m at least one laser signal comes from the ground. The multi-resolution method - decisions whether to take the coarse or better resolution are made by thresholding - assures that ground results are taken from better resolutions whenever there is a ground signal, in other cases (dense stands) the value from the coarse resolution is taken. The accuracy obtained varies between 18 and 45 cm. More detailed information on the filter method is given in Ruppert et al., 2000.

3. TEST SITES AND DATA USED

Test sites

Investigations were carried out at two Austrian test sites:

- Hohentauern test site:
  mountainous (Alpine) test site characterized by high relief energy and steep slopes (ranging from 1200 - 1700 m); tree species mainly consist of spruce (94 %)
- Eastern Styria test site (Burgau and Ilz):
  small structured hilly test site located at the south-eastern border of the Alps, which is characterized by moderate height differences (ranging from 250 - 400 m) and small troughs and hillocks; the main tree species are beech (30 %), spruce (30 %) and pine (15 %).

Laser scanner data

The described approaches are only feasible if the following parameters are fulfilled:

- high measurement density in order to achieve a good separation between individual trees
- steep viewing angle in order to have a sufficient number of ground points (Hyyppä et al., 1999, Samberg et al., 1999)
- two different modes - first pulse and last pulse - to obtain ground information (last pulse) on the one hand and information of the crown surface on the other hand.

The laser scanner campaigns were therefore carried out using the TopoSys I scanner because of its high measurement density, steep viewing angle and capability of providing both first and last pulse modes.

The following laser scanner data were acquired for the two test sites:

- Hohentauern test site:
  First pulse: 22.8.1999; flight height 800m; 4-5 points per m^2
- Eastern Styria test site:
  First pulse: 23.8.1999; flight height 800m; 4-5 points per m^2
  Last pulse: 26.3.1999; flight height 800m; 4-5 points per m^2

4. METHODS AND RESULTS

This chapter describes the methods and algorithms used for the different processing steps necessary to implement the approaches outlined in Chapter 2.

4.1 Method and Results of the Stand-wise approach

The stand-wise approach was carried out for the Hohentauern and Ilz test sites. Data processing is based on first pulse data (crown DEM) which are resampled to a regular 1 x 1 m grid using a simple algorithm, which searches for maximum values within the grid and the forest floor model roughly described in Chapter 2.

4.1.1 Assessment of top heights

The aim of the study was to assess the top height on a stand-wise basis. The top height is an important inventory parameter and can be defined as the average height of 20% of the strongest trees of a stand. The processing steps and the statistical analyses are described in the following sections.

In a first processing step a maximum filter (window size 3 x 3) is applied to the first pulse data (tree height image) in order to eliminate pulses which are reflected on the lower parts of the trees. Based on the filtered laser data (max laser) the following parameters were extracted at stand level.

- arithmetic mean of the laser derived tree heights (h), stand-wise
- crown closure, assuming heights larger than 6 m to be crown hits (c),

For this purpose the digital stand boundaries obtained from the forest owners were superimposed on the laser scanner data.

The arithmetic means (h) derived stand-wise from the filtered tree height image were compared with the top heights provided by the forest owners. Table 1depicts the statistics of this comparison for each test site separately and for both test sites together.

	Number of stands	Mean difference top heights – h	Standard deviation of differences
Hohetauern	139	-0.3256	5.1259
Ilz	49	-0.9099	5.2412
both test sites	188	-0.4949	5.0520

Table 1. Differences of tree heights derived from laser scanning data and top heights from the forest inventory

Further investigations have shown that the mean differences in Table 1 significantly depend on the crown closure of the stands. The identified correlation is shown in Figure 1 for both test sites. In cases where the crown closure is below 65 % the laser-derived tree heights (h) are significantly lower than the top heights from the forest inventory.

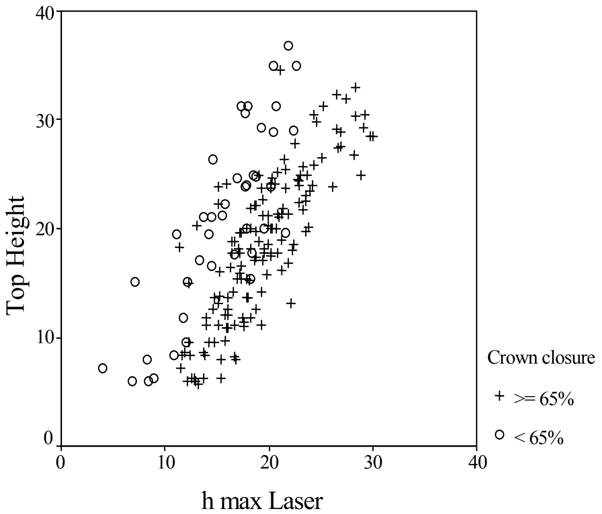

Figure 1: Top heights vs. laser-derived tree heights in two crown closure classes.

Hence, the assessment of top heights can be improved by using both laser-derived tree heights (h) and crown closure (c). The relationship of the predicted top height (h_f), average height (h) and crown closure (c) can be depicted from the following formulas.

predicted top height = 16.16 + 1.35 * h – 29.3 * c ,
(1) Hohentauern test site

predicted top height = 12.366 + 1.619 * h – 31.889 * c,
(2) Ilz test site

predicted top height = 15 + 1.43 * h – 29.5 * c
(3) both test sites together

Table 2 shows the statistics for the fitted top height models and figure 2 shows the predicted top heights for both test sites using equation (3).

	R Square	Std. error of estimation
Hohentauern	0.633	3.9833
Ilz	0.823	3.0045
both test sites	0.715	3.8018

Table 2: Statistics for the fitted top height models

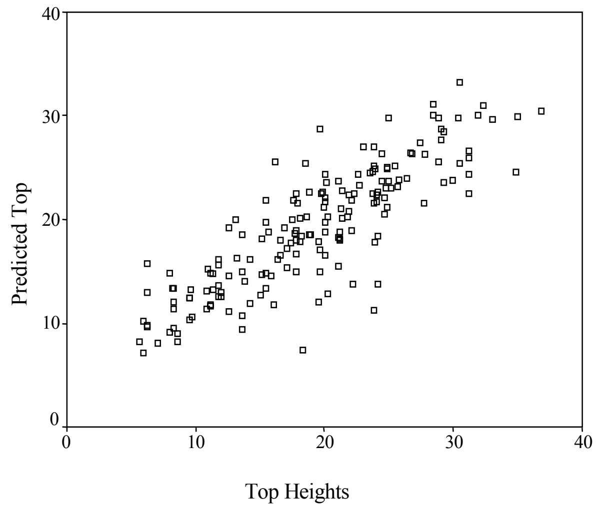

Figure 2: Predicted top heights vs. top heights for both test sites using equation (3)

The statistics show that 72 % (R square 0.715) of forest inventory top heights can be predicted by laser-derived mean tree heights and crown closure using the same model for different test site conditions concerning tree species mixture and terrain.

4.1.2 Assessment of timber volume using a statistical approach

The assessment of timber volume was only carried out at the Ilz test site. The predicted timber volume was calculated as a function of the predicted top heights derived from equation (2) (h_f) as statistical analyses have shown that this parameter is the best predictor for timber volume. The regression model based on this predictor was formed and the obtained model, coefficient of determination (R square) and standard error (SE) of the model are shown in Figure 3.

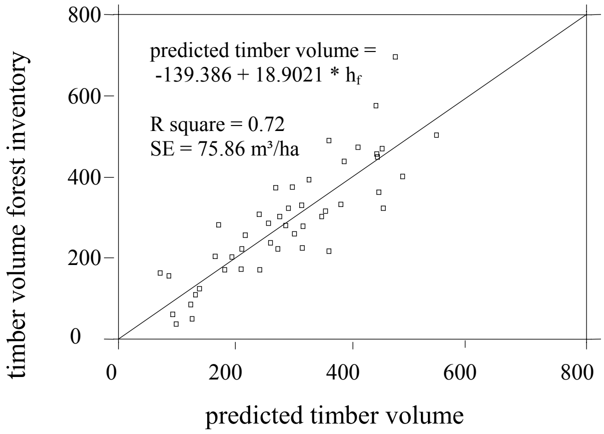

Figure 3: Timber volume from forest inventory vs. predicted timber volume – Ilz

Statistical analyses have shown that the laser-derived predicted top heights describe 72 % of the variability of timber volume in forest inventory data (R square = 0.72). The corresponding standard error obtained amounts to 76 m³ / ha. Typically, stand-wise inventories of the most important forest parameters are carried out with an error of about 15 % (in this case 55 m³ / ha for timber volume). This error affects the obtained R square and standard error and thus the outcome of the previous analysis. Assuming that these two errors (predicted timber volume and timber volume derived from forest inventories) are independent of each other, the corrected laser-based error can be estimated by taking the root of the difference of the squared errors, denoted by s,

$$s = \sqrt{76^2 - 55^2}$$

which is even slightly better than the error of the conventional forest inventory (s = 52.5 m³ / ha).

Conclusion

In summary this study demonstrates the feasibility of using laser scanner data for the stand-wise assessment of timber volume for forest inventories.

4.2 Method and Results of the Tree-wise approach

Different image processing steps are necessary in order to derive the tree wise parameters listed in Chapter 2. The methods described in the following section are suitable especially for conical-shaped coniferous trees, as it was developed for the Alpine Hohentauern test site.

4.2.1 Processing line for segmentation

In the following the whole processing chain is explained, starting with the tree height image and ending with a segmented image, where each homogenous region represents a single tree. Figure 4 depicts the working steps for segmentation (Ziegler et al. 2000). The basis for these processing steps are first pulse data which are resampled to a grid of 25 cm resolution and the forest floor model described in Chapter 2.

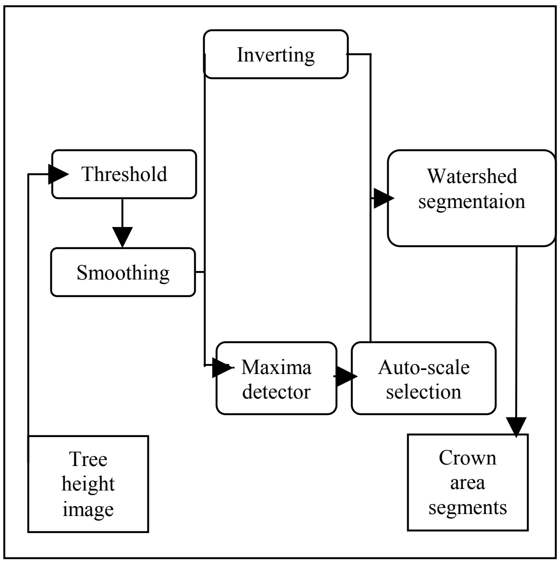

Figure 4: Working steps for single tree segmentation

Threshold filter

Most forests are a conglomerate of large trees, young trees, bushes, grasses and other undergrowth. But the main interest of forest economists is focused on large trees representing the major part of timber volume, while young trees and undergrowth are only of minor interest for timber volume assessment. Therefore, all pixel values representing heights less than a certain threshold (6 m in this case) were not taken into account for further processing. Another reason for neglecting these small trees was that they mostly stand close together and thus cannot easily be segmented. Although the spatial resolution of the TopoSys laser scanner is higher than provided by other systems, it is not high enough to capture every single crown.

Smoothing filter

In order to obtain optimal results for “tree top detection” (maxima detector) and “crown diameter” (watershed segmentation)” each single tree should be represented by a blob with one single intensity maximum at the position of the tree top. Optimally, the gray values should decrease with the distance from the top. Looking at geometrical models of some tree species derived by ground measurements, one can see that most trees, especially conical-shaped coniferous trees, come close to this ideal shape. Nevertheless, as laser scanning data represent the “real situation”, one single tree crown can be represented by two or more intensity maxima and, thus, single trees do not appear as compact blobs. This smoothing step was introduced to eliminate smaller peaks and to approximate the height image to the ideal model. Because of its unique properties a Gaussian Kernel was chosen for the smoothing task. One of the advantages of this filter, which was very important for this application, is that Gaussian smoothing does not produce new extrema when increasing the smoothing scale. In spite of the good performance of the filter applied, single branches sometimes cause local maxima even after smoothing. This circumstance must be taken into account in the subsequent processing steps. Further information about continuous discrete Gaussian smoothing kernels, their properties and the setting of kernel parameters can be found at Lindeberg (1993 and 1994).

Maxima detector and auto-scale selection

After smoothing, coniferous trees mostly show a characteristic tip at the top of the tree. This is true if the local gray value maxima within the data image can be interpreted as tree tops. Local maxima must be interpreted carefully (see auto-scale selection), since they are caused not only by tree tops but also by the single branches remaining after filtering.

Maxima are localized by means of a maxima detector in a first step. As tree crowns can present more than one local maximum and each maximum would produce one segment in the subsequent watershed segmentation process, the number of tree tops would be overestimated and large crowns would be split into several segments. Hence, each detected maximum must be reviewed. Assuming that single crowns appear as blobs with a gray value maximum in the center and decreasing gray values towards the edge, diameter and significance can be assessed for blobs by means of a scale-space approach (Lindeberg 1994, Roerdink & Meijster 1999). This algorithm searches within a predicted range of blob diameters of typically 1m to 10m for maximum responses. The resulting blob diameter (ideally presenting a single crown) is then determined by the maximum significance of all potential crowns.
The detection of blob diameters allows single crowns to be identified in most cases. Errors are caused, if crown density is very high (case 1), if larger crowns shadow smaller trees (case

2), or if one crown presents more than one significant local maximum (case 3). In the first two cases one blob covers more than one crown, in the third case one crown presents more than one blob. Using significance, the position of potential crowns and a-priori information on potential crown diameters, these situations can be interpreted by means of various rules within auto-scale selection. The result of auto-scale selection are labeled and all maxima belonging to one crown are labeled with a unique value.

Crown segmentation

Inverting the smoothed and thresholded tree height image

The tree height model was inverted in a next step in order to adapt the given information to the needs and properties of classical watershed algorithms. In short, watershed algorithms find local minima in a grayscale image and try to assign each pixel of the image to a local minimum. The problem to solve here was exactly vice versa. Each tree was represented by a single local maximum, and the pixels around the maxima should be assigned to the most probable maximum (treetop). A slightly adapted watershed algorithm could now be applied to the inverted data in order to delineate single trees.

Watershed segmentation

There are several formal definitions and implementations of the watershed problem, which basically follow the same idea. More detailed information on the algorithm and formal definition can be found at Soille (1999) and Roerdink & Meijster (1999).

Every grayscale image can be interpreted as a three-dimensional landscape, where each pixel's activation represents the altitude of the corresponding point in the landscape. Assuming a raindrop is falling down somewhere onto the landscape according to the law of gravitation, it will flow down along the steepest slope path until it reaches a minimum. The starting points of this procedure are the labels produced by auto-scale selection. The whole set of points whose steepest slope path ends in the same minimum, were assigned to this minimum. All pixels belonging to the same minimum were labeled with a unique value. In a next step each pixel in the image was assigned to a specific minimum. This decision could not be made for pixels with two or more steepest slope paths reaching different minima. These pixels were called watershed pixels and were labeled as such with a predefined value, different from all other labels. The watershed segmentation produced a partitioned image containing a set of watershed pixels and segments which were connected regions labeled with a unique id.

The presented watershed algorithm will run into trouble if the input image contains non-minimum gray-level plateaus. The difficulties occur when the steepest slope path reaches such a plateau. In this situation it is not clear in which direction the steepest slope path should be continued. Therefore the input image had to be turned into an image which does not contain non-minimum plateaus, without changing the steepest slope direction of non-plateau pixels. This was achieved by applying a lower completion algorithm, as is presented in Roerdink & Meijster (1999). This algorithm transforms non minimum plateaus into steep hills by iteratively increasing the plateau values from the borderlines to the center of the plateaus. This method ensures that after the transformation each pixel – with the exception of minimum pixels - has a lower neighbor. Images fulfilling this precondition can then be deterministically segmented by the watershed algorithm presented.

Verification

Hohentauern test site

Figures 5a and 5b represent segmentation results from the Hohentauern test site. For verification purposes 197 single trees scattered across the test site (8 reference areas with 15 – 30 trees measured within the area) were surveyed by ground measurements. The exact positions of the single trees were determined using a differential GPS system and accurate ground measurements (within 10 cm accuracy in x, y). The crowns of the reference trees were delineated in the field; Bhd (breast height diameter), tree height and tree species were recorded. All the reference areas are homogeneous with regard to crown closure.

The verification of the segmentation result was performed by comparing the segmented crowns with the crowns measured in the field. Table 3 depicts the overall accuracy of the segmentation method within the Alpine test site.

number of verification trees	197
number of correctly segmented crowns	98
number of crowns merged [1]	89
number of crowns split	9
number of crowns not found	1

[1] 64 of these crowns due to missing maxima, 20 due to wrong blob assessment, 5 due to smoothing effects

Table 3: Overall accuracy of segmentation method within the Alpine test site

Two main errors occurred for crowns which had not been segmented correctly can be summarized as follows:

- Within one tree crown two or more local maxima were detected in the tree height image (9 out of 197 cases).
- Two or more crowns merge. This is mainly caused by missing local maxima in the tree height image, e.g. small trees in dense stands (68 out of 197 cases).

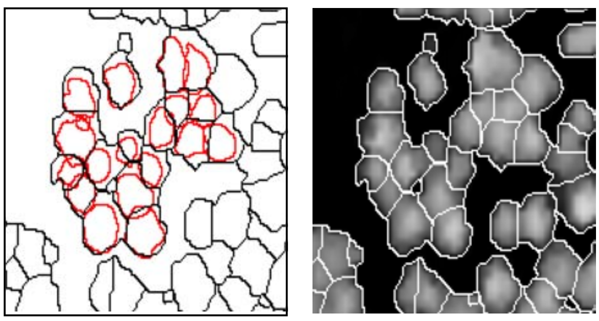

Figure 5a: Area 3, crown closure 62 %, section of 50x50 m: left – segmentation result (outer circles) and reference trees (inner circles), right – tree height image and segmentation result

Burgau test site

At the Burgau test site 85 trees (spruce, pine and oak) were measured in the field. 62 % of these trees were segmented correctly. The reasons for segmentation errors are described above.

In summary, the results show that the segmentation algorithm tends to merge single tree crowns, which leads to an underestimation of the number of trees.

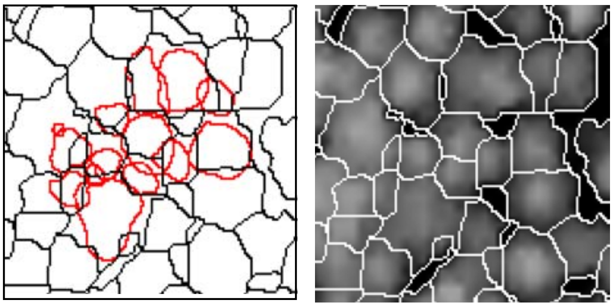

Figure 5b: Area 7, crown closure 89 %, section of 40x40 m: left – segmentation result and reference trees, right – tree height image and segmentation result (white)

4.2.2 Derivation of inventory parameters

The following inventory parameters can be derived from the results obtained in Chapter 4.2.1:

- Crown area
- Number of trees
- Tree height
- Breast height diameter
- Timber volume

Derivation of crown area

The crown area of single trees is one of the most important outputs from the segmentation step. The segmentation algorithm produces a raster file where pixels from the same tree crown are indicated by the same label. Crown area is calculated by adding up pixels with the same label. Verification of the crown area assessment was performed with the 78 correctly segmented spruces out of the 197 verification trees in Hohentauern. The crown areas of these spruce trees were measured by terrestrial means. The tree-wise comparison of the crown area of the correctly segmented trees and the crown area measured in the field showed that segmentation overestimates the crown area by 5 m² on average. However, measuring crown area in the field is not easy in steep terrain, thus resulting in an uncertainty in the verification data. Figure 6 presents the verification results.

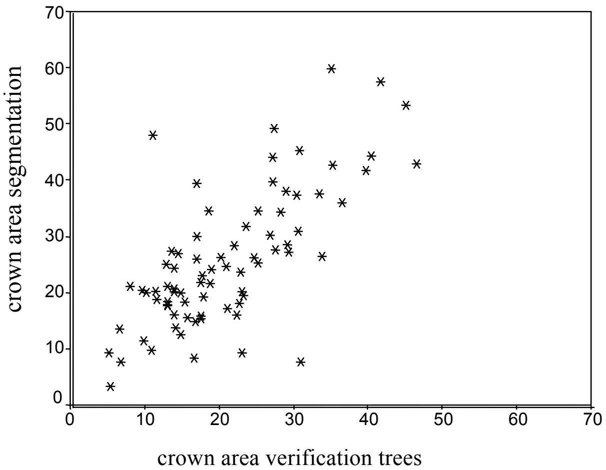

Figure 6: Crown area from segmentation versus crown area of verification trees (78 spruces, Hohentauern test site, crown area in m²)

Derivation of number of trees

The estimation of the number of trees is another output from the segmentation process. Figure 7 depicts the verification results concerning the number of trees for 23 stands selected representatively for the Hohentauern test site (each point in figure 7 represents on stand).

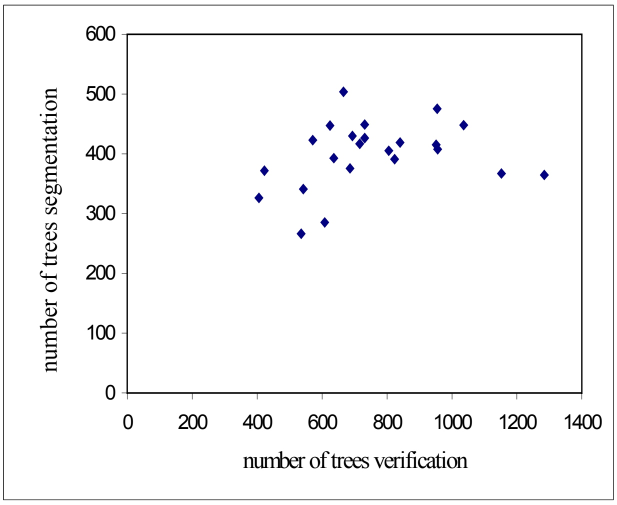

Figure 7: Verification in terms of number of trees (23 stands, Hohentauern)

The verification has shown that the number of trees is underestimated. On average the segmentation algorithm captured only 56 % of the trees within one stand with a standard deviation of 15 %. However, an uncertainty in the verification data must be considered, as the number of trees was not measured in the field but estimated from yield tables.

Derivation of tree height

After segmentation tree height is derived from laser scanner data by searching for the maxima within one crown segment. Figure 8 depicts the verification results of tree height measurements for the 78 correctly segmented spruce trees at Hohentauern (see verification crown area).

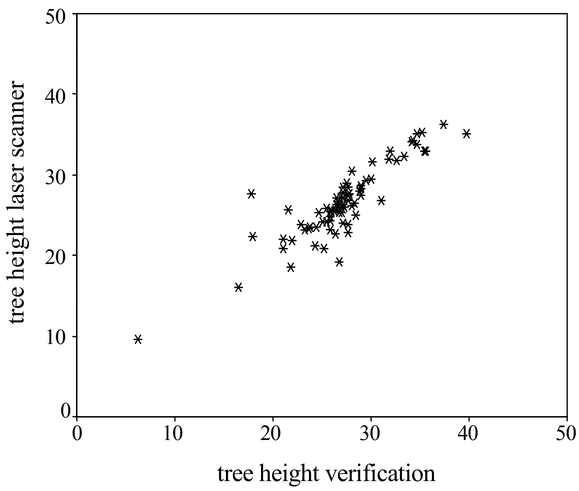

Figure 8: Tree height verification versus tree height from laser scanner data (78 spruce trees, Hohentauern test site, tree height in m)

The comparison has shown that the tree height calculated from laser scanner data is on average only 62 cm smaller than the tree height obtained by ground measurements.

Derivation of breast height diameter by empirical models

The breast height diameter (BHD) is one of the most important parameters in forest inventories. BHD is a direct function of the parameters tree height and crown diameter, which can both be measured by means of laser scanning data. An empirical BHD model for spruce was developed on the basis of field measurements of tree height and crown diameter at the Hohentauern test site. The calculated BHD model is shown below:

BHD (mm)
(h) tree height (in dm)
(c) crown area (in m²)

Spruce (1), Hohentauern, Alpine character: (1)
BHD = -31,96 + 1,33 * h + 5,19 * c

R^2 = 72 %, 165 trees

Based on this model BHD values can be calculated for each of the segmented trees. The statistical analysis of the BHD model for spruce shows that tree height (h) accounts for 2/3 and crown area (c) only for 1/3 of the BHD model, indicating that accurate height data are more important than accurate crown area data. This is important since tree height measurements by laser scanner data are very accurate, whereas crown segmentation still leaves room for improvement in terms of accuracy.

Derivation of timber volume

Timber volume (vs) which is a direct function of BHD and tree height (h) can be calculated by known increment models from forestry (Pollanschuetz, 1974).

BHD (in cm)
h (tree height in m)
(form value) constant value for different management procedures

vs = (BHD / 100)² * 3,141593 / 4 * h * form value (2)

The timber volume derived from laser scanner data is calculated by using equations (1) and (2) described above. The timber volume assessment was tested for the 197 verification trees in the Hohentauern test area. Figure 9 presents the correspondence of timber volumes measured in the field and timber volume calculated on the base of laser scanner data separately for each of the 197 trees.

Figure 9 shows that for some trees the values derived from both measurements (laser and terrestrial) do not correspond. However, when summing up the timber volumes of the single trees, the timber volume derived from laser scanner data is only slightly below the actual value (3.3 % of verification timber volume). In this comparison all trees were considered, even if they had been merged in the segmentation process. Thus, the result indicates that the underestimation of the number of trees by the segmentation algorithm is compensated by an overestimation effect due to the merging of various trees into one big tree, which results in an overestimation of timber volume for this "one" big tree.

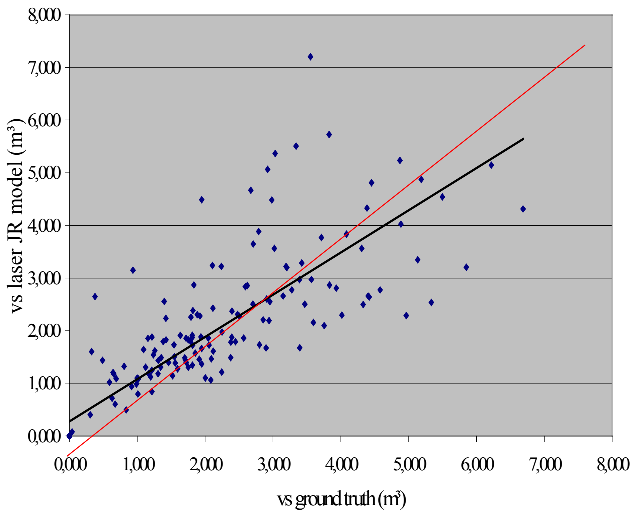

Figure 9: Timber volume verification trees versus timber volume derived from laser scanner data.

In a further investigation the dependence of timber volume accuracy on merging effects was analyzed on the basis of the 197 verification trees. This investigation has shown that an increase of the number of merged trees is associated with a decrease of timber volume derived from laser scanner data (see Figure 10).

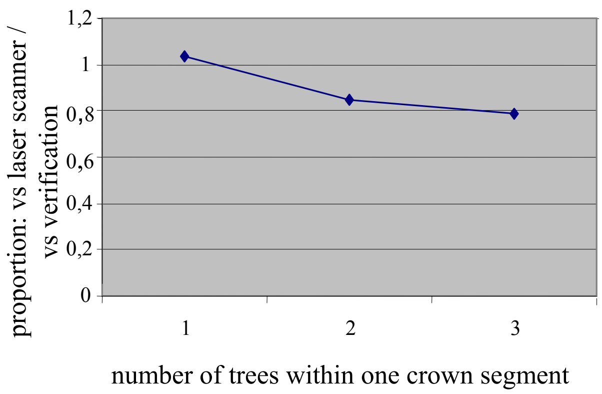

Figure 10: Dependence of timber volume assessment on correctly segmented crowns (3 means 3 or more trees)

5. SUMMARY AND CONCLUSION

The results of the study show that laser scanning is a potential valuable tool in forest inventories. Both the tree-wise approach and the statistical stand-wise approach produced reliable results. For instance, the timber volumes derived from laser scanner data deviated from the timber volumes measured in the field by less than 10%. It must be noted that the segmentation methods for the tree-wise approach were developed exclusively for spruce stands. It must be expected that the methods developed within the scope of this project are not suitable for deciduous tree species which are characterized by a more complex canopy structure. The statistical stand-wise approach should thus be chosen for deciduous tree stands. Another restriction is that the algorithms have been developed on the basis of a limited forest region. Further investigations will be required to verify whether these methods can also be applied to other forest areas with different stand structures, in particular to mixed forest areas.

It can be expected that improved algorithms and more detailed data will result in a further improvement of the methods developed.

Improvements in algorithms:

- Knowledge - based tree top detection and segmentation considering minimum distances of tree tops depending on tree species and tree height (age)
- Fusion methods to combine laser scanning data with other data sources (e.g. very high resolution optical data, intensity values of the laser signal or existing forest maps)

Improvements in data:

- Availability of multispectral data acquired simultaneously (TopoSys II)
- Availability of intensity values
- Better ground resolution in order to detect smaller trees and trees in dense stands

The advantages of laser scanning based inventories can be summarized as follows:

- Laser scanning provides a quick overview of forested areas
- Automated assessment of inventory data in an objective manner
- Multiple use of the data: e.g. DTM for road construction and planning of harvesting activities, assessment of forest parameters as basis for forest management activities
- Data can be shared with other users, e.g. administration and planning offices, hydrology
- Alternative to yield tables, which are of limited use as an inventory tool (Hasenauer et al. 1994)

In spite of the high potential of laser scanning for forest inventories, laser scanning will most likely not substitute the field work of foresters, since not all information can be derived by means of this new method.

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