FOREST INVENTORY BY MEANS OF SATELLITE REMOTE SENSING AND LASER SCANNING

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ABSTRACT

In this paper forest inventory methods which are based on satellite remote sensing and laser-scanner data will be introduced. It will be demonstrated in how far conventional terrestrial inventories at a scale of 1 : 10.000 to 1 : 25.000 can benefit from the synergetic use of both sensor types. The forest inventory parameters to be investigated are: tree height, timber volume, tree species, tree age, stand border, and basal area. The presented results are mainly derived from the following projects

→ HIGHSCAN (Assessing forest stand attributes by integrated used of high-resolution satellite imagery and laser-scanner), EU - DG XII, CEO, co-ordinated by the Helsinki University of Technology and financed by the EU,

→ ALPMON (Inventory of alpine-relevant parameters for an alpine monitoring system using remote sensing data and GIS), EU - DG XII, CEO, co-ordinated by Joanneum Research Graz

→ SEMEFOR, Satellite based environmental monitoring of European forests, EU-DG XII, Pilot Projects, co-ordinated by Swedish Environmental Institute, Stockholm

The projects are conducted in close co-operation with forest private and governmental management administrations. In this paper the results derived from different test sites will be presented.

1 INTRODUCTION

In the Austrian National Forests and those belonging to large forestry owners, forest inventories are performed every ten years on a stand-wise basis. In this inventories data are collected using cost-intensive field surveys in combination with yield tables. Inventory data for small forestry owners are mainly collected on the basis of questionnaires (Wood Felling Reports). Inventories of a similar intensity to those taken for the national forests and large forestry concerns are carried out only for those small forestry owners which have combined into agricultural associations. The proportion of small forestry owners participating in agricultural associations is very small, therefore field inventories are only carried to an very extensive extend.

In this paper the potential of satellite remote sensing and laser-scanner data will be introduced and discussed. According to the positive experiences in the field of satellite based forest inventories it can be stated that satellite remote sensing is an appropriate tool to inventor and monitor forest parameters at a small scale. However, not all inventory relevant parameters such as tree height, tree volume, vertical stand structure and under-storage can directly be derived from satellite remote sensing. To overcome this shortcomings new airborne laser-scanner data from TOPOSYS can be used additionally to satellite images. Doing this, the synergetic use of both laser-scanner data and satellite data will take advantage of the benefit from both sensor types.

Firstly, in this paper the potential of satellite remote sensing for the classification of forest parameters will be presented. Due to the lack of very high resolution the results will focus on the demonstration and evaluation of high resolution satellite data such as Thematic Mapper and SPOT IV data. Secondly, the ability to classify forest parameters by means of laser scanner data will be introduced. Finally, the information content of both data types will be compared and potential synergies outlined.

	Reference			
classified	forest	Non-forest	$\sum$points	% correct
forest	547	44	591	93
non-forest	2	403	405	100
$\sum$points	549	447	996	
% correct	99	90		95

Table 1: Error matrix: forest / non-forest

	Flat Terrain	Mountainous Terrain
Forest Types		
Deciduous Forests	> 90%	85 - 90%
Spruce	> 90%	85 - 90%
Pine	70 - 80%	to be investigated
Spruce/Pine	60 - 70%	to be investigated
Mixed Coniferous / Deciduous	80 - 90%	80 - 90%
Larch and Larch / Spruce	to be investigated	85-90 %
Swamp Forest	80 - 90%	Does not occur
Natural Age Classes		
Coniferous: 3 classes	80 - 90%	80 %
Deciduous: 3 classess	75 - 80%	to be investigated
Forest density Classes		
Coniferous 5 classes (20% steps)	> 85%	75 - 80%
Coniferous 3 classes (30% steps)	> 90%	>85 %

Table 2: Producer Accuracy of the classification of different forest types

2 POTENTIAL OF SATELLITE REMOTE SENSING FOR FOREST INVENTORY

The feasibility of satellite remote sensing for the classification of forestry parameters has been proven in the past by several studies. The following examples selected from the above listed projects are based on Thematic Mapper and SPOT and shall demonstrate the potential of available remote sensing data at the assessment of different inventory relevant forest parameters on a scale of 1 : 50.000 to 1 : 100.000. These studies were related to the classification of the parameters forest / non-forest, tree species types, age classes and forest density. For the classification of forest types the maximum likelihood method and for the stratification of forest and non-forest areas the threshold-level procedures was applied. The verification of the classification result was performed by means of independently selected verification areas.

Forest/Non-forest

Investigations in alpine regions on the stratification of Forest and Non-Forest Areas on the base of SPOT / PAN data has shown that an accuracy of more that 95% can be obtained. The nomenclature definition of forests in this case defines forest as an area with more than 10% crown cover. The accuracy assessment was performed by comparing the forest mask with 1054 sample points. These sample points (in a regular grid of 100m by 100m steps) were visually categorized into forest / non-forest / forest-border by the use of CIR-ortho- photos. Table 1 displays the error matrix for the forest / non-forest points.

Comparable results have been achieved in flat and mountainous test sites have been achieved by investigations carried out by (M. Schardt, 1990) and (Keil et al., 1990)

Tree species types, age classes and density classes

Investigations carried out by (M. Schardt, 1990, M. Schardt, 1995) in four German test sites as well as the experiences made with the forest mapping in Alpine regions carried out within the EU-projects ALPMON and SEMEFOR (Schardt and Schmitt, 1996) proved that the classification of the major tree species groups is possible with a satisfactory accuracy. The separable forest types and the average approximate accuracy values achieved in these projects are summarized in table 2:

Shortcomings

According to the positive experiences in the field of satellite based forest classifications quoted above it can be stated that satellite remote sensing is an appropriate tool to inventor and monitor forest parameters at a small scale with reasonable accuracy levels. However, in consideration of intensive large scale inventories on stand and district level some significant shortcomings were identified when using Thematic Mapper and SPOT data:

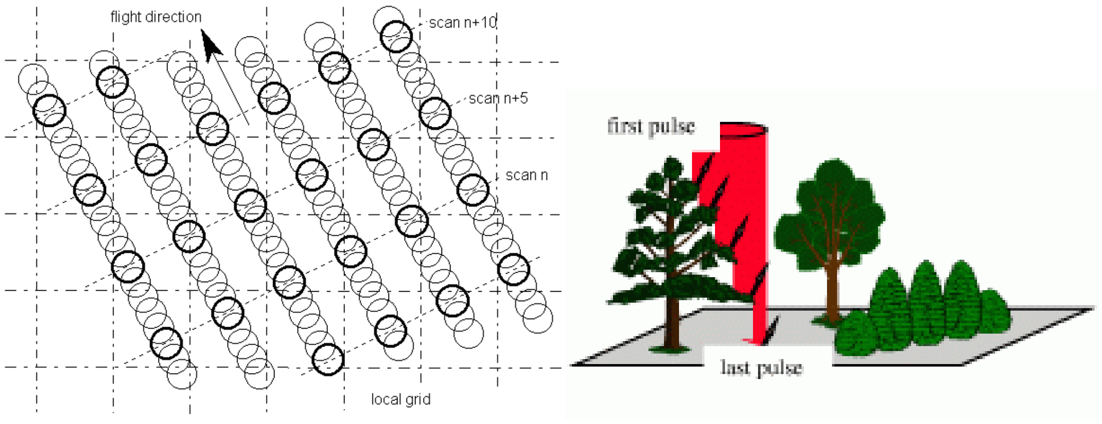

Figure 1: TopoSys laser scanner principles, scan pattern (left) and first and last pulse mode (right)

1. The assessment of information on stand level is only possible in very large and homogeneous stands due to limitations in geometrical resolution of sensor types available at this time.

2. The attained accuracy level is suitable for small scale inventories at a scale of 1 : 50.000 and less but not for detailed inventories on stand and district level (1:10.000 to 1:25.000).

3. Not all inventory relevant parameters such as tree height, tree volume, vertical stand structure, under-storage, etc. can be derived directly from satellite remote sensing.

Nevertheless, it can be expected that in future with the availability of very high resolution satellite systems such as IKONOS or SPOT V the assessment of information on stand and district level will be possible with the thematic accuracy depicted in table 2.

3 APPLICATIONS OF LASER SCANNING FOR FOREST INVENTORY

Measurement principle of a laser scanner

Laser scanning allows the measurement of the distance between aircraft and the earth's surface. The scanning mechanism sweeps the laser beam across the flight line. By knowing the position and orientation of the sensor in the aircraft, the measured distances can be converted into elevations (see figure 1). The position of the sensor can be measured with an accuracy of about 0.1 m with sensitive and noise suppressing kinematic DGPS receivers, additionally a corresponding reference station must be placed within or close to the surface area. Sensor's orientation is obtained with a better accuracy than 0.2 mrad using a precise measurement device (INS)(Hyyppä et al., 1999, Samberg et al., 1999).

All data presented in this study have been recorded for the EU-project High-Scan. Investigations are carried out in two Austrian test sites, a mountainous (Alpine) test site characterized by high relief energy and steep slopes (ranging from 1200 - 1700 m) and a test site located at the south-eastern border of the Alps with typical small structured hilly terrain characterized by moderate height differences (ranging from 250 - 400 m) and small troughs and hillocks. Concerning tree species the Alpine test mainly consists of spruce (94 %), the main tree species within the hilly test site are beech (30 %), spruce (30 %) and pine (15 %).

The laser scanner campaigns were carried out with the scanner from TopoSys because of its high measurement density, steep viewing angle and capability to provide both the first and last pulse mode, see figure 1. High measurement density was required in order to be able to have a good separation within individual trees. Steep viewing angle enable to have good number of ground points hitted (Hyyppä et al., 1999, Samberg et al., 1999). The two different modes - first pulse and last pulse - are necessary to get ground information (last pulse) on the one hand and information from the crown surface on the other hand

Pre-processing of laser scanner data

The original data from the laser scanner - last pulse and first pulse - is originally in a format (raw data) where corresponding x, y and z coordinates were listed in rows. The data was transformed into the local coordinate system.

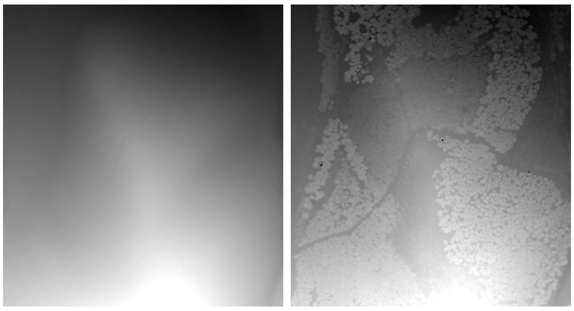

Figure 2: 1x1 m forest floor DEM (left) and 1x1 m crown DEM (right) - Alpine test site

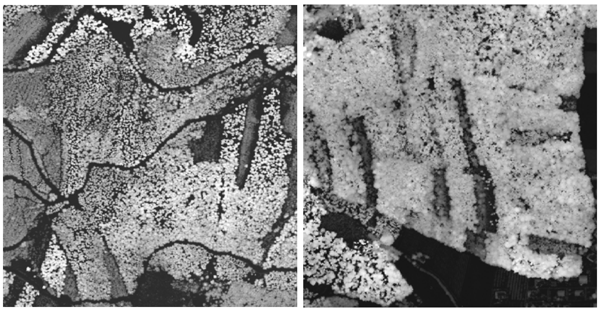

Figure 3: 1 x 1 m final tree height maps - cut-out from Alpine test site (left) and hilly test site (right)

Forest floor DEM

Because of difficult terrain conditions (steep slopes and small structured relief) high attention was turned to the question of generation accurate forest floor DEMs. Raw data (last pulse if available) was processed in a regular grid of 1 x 1m by means of a multi-resolution method in combination with an improvement by gradient, figure 2.

The method searches for the minimum within the respective resolution and increases the minimum by an appointed amount as a function of the gradient within the neighborhood. Within every resolution step smoothing and thresholding algorithms are performed. Thus, pixel values are resulting within every resolution step. The method starts with a rough 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 to get forest floor information 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 rough or better resolution are made by thresholding - assures to take ground results from better resolutions whenever there is a ground signal, in other cases (dense stands) the value from the rough resolution is taken. The obtained accuracy varies between 18 and 100 cm (Ruppert et al., 2000).

Crown DEM

The processing of crown DEMs followed through a simple algorithm, which searches for maximum values within 1 x 1 m for the regular grid. Smoothing and thresholding algorithms were performed, figure 2.

Tree height map

The final tree height maps were calculated as the difference between the crown DEMs and the final forest floor DEMs as shown in figure 3 and were appropriated for the further investigations.

4 STAND-WISE APPROACH USING LASER SCANNER

Assessment of tree heights

For the stand-wise assessment of tree heights a maximum filter (window size 3 x 3) was applied to the tree height maps to smooth the tree heights with regard to the estimation of top heights from forest inventories. The processed tree height maps were analyzed using stand-wise forest inventory data. The stand boundaries were obtained from the end users, digitized and imported to GIS system. The boundary information was visually checked by means of aerial photos and laser data.

	number of stands	mean difference weighted top heights - h	Standard deviation of differences
Alpine test site	139	- 0.3256	5.1259
hilly test site	49	- 0.9099	5.2412
both test sites	188	- 0.4949	5.0520

Table 3: Statistics for the assessment of tree heights

	R Square	Std. Error of Estimation
Alpine test site	0.633	3.9833
hilly test site	0.823	3.0045
both test sites	0.715	3.8018

Table 4: Statistics for the fitted top height models

The following features were extracted for each stand from the maximum filtered laser data (max laser):

→ arithmetic mean of the laser-derived tree heights (h)

→ crown closure, assuming heights of more than 6 m to be crown hits (c)

The stand-wise average tree height values were compared with weighted top heights (one top height for different top heights from different tree species within one stand) from forest inventory data. Table 3 depicts the statistics for each test site alone and for both test sites together.

The assumed dependence on crown closure is shown in figure 4 for both test sites. In cases where the crown closure is below 65 %, the laser-derived tree heights (h - from max laser) are significantly lower than the weighted top heights from forest inventory. Hence, weighted top heights were predicted by laser-derived tree heights (h - from max laser) and crown closure (c) for the Alpine test site 1, the hilly test site 2 and both test sites together 3

$$\text{predicted top height} = 16.16 + 1.35 * h - 29.3 * c \quad (1)$$
$$\text{predicted top height} = 12.366 + 1.619 * h - 31.889 * c \quad (2)$$
$$\text{predicted top height} = 15 + 1.43 * h - 29.5 * c \quad (3)$$

Table 4 depicts the statistics for the fitted top height models and figure 5 shows the predicted top heights for both test sites using equation 3.

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 with the same model for different test site conditions concerning tree species mixture and terrain. However, mean errors from forest floor model between 18 and 100 cm, deteriorating the tree-height map, have to be considered. Assuming that forest floor DTMs can be improved (Ruppert et al., 2000), accuracy for laser-derived mean tree heights cannot be stated as the final results in this study.

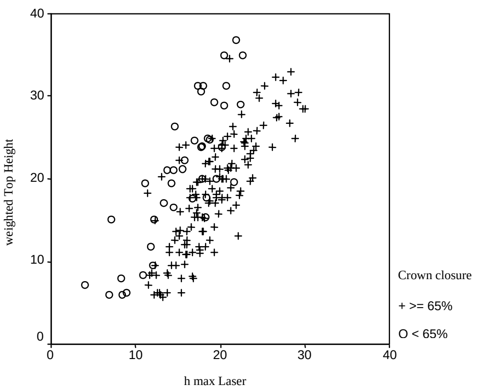

Figure 4: Weighted top heights vs. laser-derived tree heights in two crown closure classes.

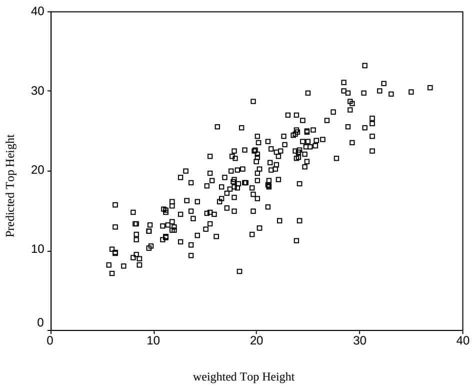

Figure 5: Predicted top heights vs. weighted top heights for both test sites using equation 3

	h	hf
timber volume	0.779	0.85

Table 5: Correlation coefficient between laser-derived features and timber volume

Assessment of timber volume

Assessments of timber volume were carried out within the hilly test site. The following features have been taken into account:

→ predicted top heights by equation 2 (hf)

→ laser-derived mean tree-heights (h - from max laser)

Table 5 depicts the correlation coefficient between laser-derived features and timber volume from forest inventories. Clearly, it can be seen that the fitted top height (hf) was 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 6.

Laser-derived predicted top heights explain 72% of the variability of timber volume in forest inventory data (R square = 0.72). The corresponding obtained standard error is $76\frac{m^3}{ha}$. Typically, stand-wise forest inventory is carried out with 15 - 30 % error concerning main forest attributes. In this case an error of $55\frac{m^3}{ha}$ for timber volume is assumed. That error affects the outcome of the previous analysis, deteriorating the obtained R square and standard error. Assuming that these two errors 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,

$$\sqrt{76^2 - 55^2} \tag{4}$$

which is slightly better than the error of the conventional forest inventory ($s = 52.5\frac{m^3}{ha}$). (Hyyppä et al., 1999) stated a corrected laser-based error for timber volume assessments by means of laser data of $27.5\frac{m^3}{ha}$. This result is due to nearly homogenous spruce stands.

In the Austrian case the hilly test site is characterized by a mixture of coniferous and broad-leaved trees with differences in top height between 1 and 3 meters within one stand, summarized within the weighted top heights. Tree species information from satellite data (e.g. with an resolution of 10 m) could provide the necessary information to decrease the standard error. Another problem in the Austrian test sites occurs, as within stands with high trees and low crown closure laser-derived mean tree heights, even predicted top heights (laser-derived), underestimate top heights from forest inventory significantly, see figures 4 and 5. In order to solve this problem and to increase the estimation accuracy for timber volume, algorithms for segmentation of single trees were developed.

However, this study demonstrates that the stand-wise assessment of timber volume for the forest inventory is feasible with good accuracy by means of laser scanner data.

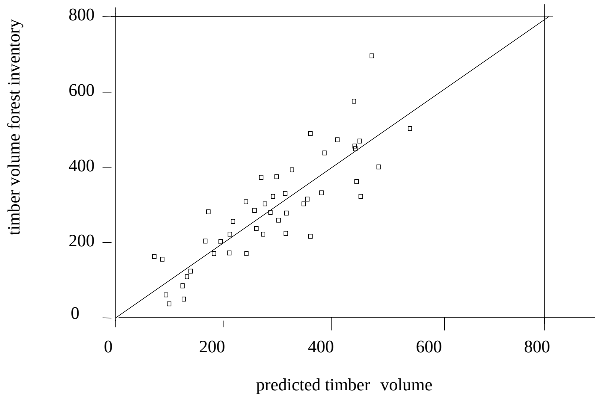

Figure 6: Timber volume from forest inventory vs. predicted timber volume - hilly test site

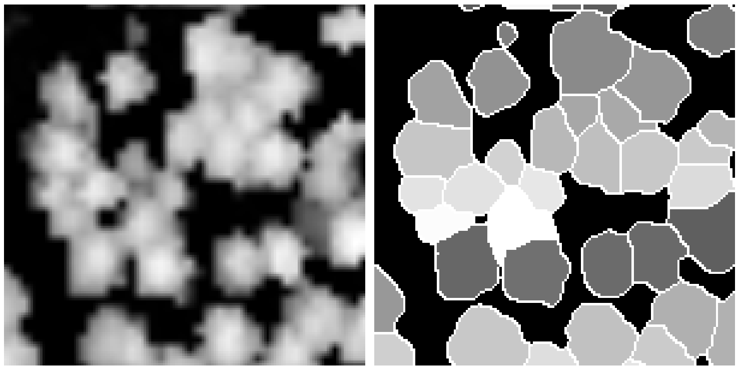

Figure 7: Tree height image (left) and segmentation result (right)

5 SINGLE-TREE SEGMENTATION BASED ON LASER SCANNER DATA

In this section a method for delineating single trees in laser scanner data is presented. The key part of this method is a watershed segmentation algorithm. In order to get meaningful segmentation results, the processed tree height map demands some further preprocessing before being applied to the watershed algorithm. The whole processing chain and the constraints implied by the used algorithms is explained in (Ziegler et al., 2000).

Results

Figures 7 and 8 represent segmentation results from the Alpine test site. Figure 7 shows a 40 x 40 meter section of the tree-heights image generated from the laser scanner data and the result of the single tree segmentation method presented in (Ziegler et al., 2000). For validation purposes the same plot was surveyed by ground measurements. The exact position of the single trees was determined by the use of a differential GPS system and accurate terrestrial measurements (within 15 cm accuracy in x, y). For every tree in the plot a map of the tree crowns was created (reference tree crowns). In figure 8 these crown maps were overlaid to the original tree height image. As it can be seen, the maps do not exactly match with the tree height image. The determination of the size and shape of a crown map is based on terrestrial distance measurements but also on visual interpretations. Therefore a typical error for terrestrial measurements of about 20% has to be assumed. Although this is not very accurate the maps provide a good estimation, which is useful for verifying the segmentation results. The second image of figure 8 compares the outlines of the segments calculated by the watershed approach (light lines) with the crown maps (dark lines).

The segmentation method found 17 out of 19 trees in this plot. One very small tree in the upper left quarter of the image was merged with the neighboring trees. Examining the same area in the tree heights image it is also impossible to find this tree by visual interpretation. In this case the resolution of the laser scanner data was to low or the one meter raster grid to coarse to generate a image feature for this tree. The top left quarter also shows two trees merged. In the tree height image these two trees are separated only by a hardly identifiable valley. This valley gets blurred in the smoothing step and the regions representing the two trees merge. Choosing the best smoothing scale is therefore the most sensible part of the method. A high smoothing scale will end up in a merging of trees standing dense but too low smoothing scales will split up single trees into several segments.

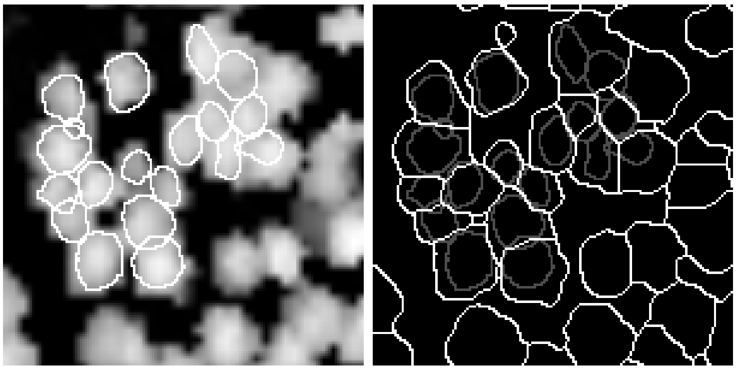

Figure 8: Crown maps (left) and segmentation - light lines - vs. crown maps - dark lines - (right)

	clipping of Alpine test site
segmented trees / reference trees	17 / 19
mean of differences reference trees - laser-derived maxima	0.42 m
standard deviation	1,17 m

Table 6: Statistics for laser-derived tree heights based on segmented tree height map

Further, test showed that the method works quite well for trees standing not to dense. Especially coniferous trees were segmented correctly in most of the cases. In dense areas the method tends to merge tree crowns. The only sensible parameter of the whole method is the smoothing scale. The optimal scale depends on the crown sizes of the trees in the examined area. Especially when there exists a variety of crown sizes it is difficult to find a optimal scale. Due to this fact future work will focus on adaptive blurring and scale space approaches to improve the smoothing part of the method.

Nevertheless, statistics for segmented trees concerning tree heights are better or at least within the accuracy of field-based measurements assumed to be $\pm 0.5m$, table 6.

6 CONCLUSION

Advantages of High and Very High Resolution Satellite Data

It is to be expected that the new very high resolution represents a major breakthrough, allowing the utilization of the above discussed forest parameters derived from satellite images in regions characterized by small stand size, as it is typical in most of the Austrian forests and especially in the test sites to examined in the proposed investigation. This is especially true for inventories in forest areas, which are managed in an natural manner. Thus, by using very high resolution satellite data the weaknesses of Thematic Mapper and SPOT data listed under section 1 and 2 can be surmounted.

In spite of the advantages of very high resolution satellite data it is not to be expected that the parameters listed under table 2 which are of predominant importance for forest inventories can be assessed. This is due the fact that it is not possible to derive 3 - dimensional information out of the signature of the satellite images. Considering the state of the art concerning digital photogrammetry and satellite stereoscopy the extraction of precise 3D - forest information from existing or future satellite systems seems not to be feasible.

Advantages of laser-scanner data

Forest inventories based solely on laser-scanner data are not feasible since parameters such as tree species types and age classes cannot be extracted from these data. Nevertheless these data can be used to compensate the general drawbacks of satellite imagery by providing supplementary information on parameters that cannot be classified by means of satellite remote sensing. Thus, synergies resulting from the usage of both sensor types will significantly increase the performance of remote sensing based forest inventories. The potential of laser-scanner data for the assessment of forest inventory data has already been proved by several investigations (Nässet, 1997, Hoss, 1997).

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