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COMPARING THE ACCURACY OF LASER SCANNER WITH OTHER OPTICAL REMOTE SENSING DATA SOURCES FOR STAND ATTRIBUTE RETRIEVAL

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ABSTRACT

The laser scanners are capable to record a digital 3-dimensional surface model of targets, such as forests, providing calculation of detailed 3-dimensional tree height models. Imaging spectrometer is able to split the received spectrum into tens or hundreds of bands and may be of valuable use for the forest inventory. These advances have aroused a question: what is the accuracy of such airborne systems compared with existing satellite-borne data and requirements of operational forest inventory? This paper verified the explanatory power and information contents of several remote sensing data sources on the retrieval of stem volume and mean height, utilizing the following data sources: Landsat TM, SPOT Pan and XS, airborne data from imaging spectrometer AISA, and laser scanner TopoSys-1. This study is the first one to compare the laser-derived forest inventory estimates with estimates produced using other remote sensing data sources in a single test site. A total of 41 stands were assessed with manual field measurements, and multivariate regression analysis was applied. The results showed clearly that laser-derived stand attributes were more accurate than those obtained by other data sources, and that the laser scanner is the only sensor that satisfies the accuracy requirements of operational standwise forest inventory.

1. INTRODUCTION

The new laser scanner technology offers new possibilities for mapping purposes. At this moment, laser scanners can provide up to 83 000 distance measurements in a second, are capable to be operated at night time, and are capable to provide accurate DEM/DTM/DSM for various applications. In the near future, laser scanners may threaten the role of conventional photogrammetric measurements.

One of the most potential applications in Finland using high-pulse-rate laser scanners is the forest inventory at the stand level. Forest stand is the smallest description unit of forests and it represents a homogeneous forest area with respect to forest resources and treatments needed. The size of the forest stand varies, normally, between 0.5 and 5 hectares. Presently, forest inventory data is collected primarily by means of field surveys, which is both expensive and time-consuming. Important forest attributes, including stem volume per hectare, are then assessed to these stands by measuring sample plots and individual trees, and by using personal experience. At this level of planning, the accuracy requirements on forest data are very high, typically a 15 % error is tolerated (standard error divided by the mean). Typical costs per hectare range between 15 and 20 USD/Euro of which about 50-60 % is used for data acquisition and recording - tasks that can be substituted by remote sensing.

In order to reduce the costs of forest management planning in Finland, remote sensing techniques have be studied intensively for the last decades. The national forest inventory of Finland was the first of its kind utilizing satellite data (Tomppo, 1991). Satellite remote sensing has been shown to be an appropriate tool to assess and monitor large-area forest attributes with reasonable accuracy levels. Presently, optical satellite images are widely applied in national forest inventories. Concerning the stand level, no single remote sensing data acquisition method has been shown to be accurate and costeffective enough for operational forest inventory, despite intensive research utilizing both airborne and space-borne remote sensing techniques (Poso et al., 1984, 1987; Pussinen, 1992; Tokola and Heikkilä, 1997; Hyyppä et al., 1999a). The relative accuracy of volume estimates using visual aerial photo interpretation has been reported to be 14-45 % (Poso et al., 1987; Pussinen, 1992; Ståhl, 1992). Aerial photos have been widely accepted to assist in the process, but automatic derivation of stand parameters is constantly an aim of several research groups. Recently, promising results have been obtained by many authors using semi-automated forest inventory based on single tree crown delineation and aerial photos (Uuttera et al., 1998; Brandtberg and Walter, 1998; Dralle and Rudemo, 1996; Gougeon,1997) or laser scanner (Hyyppä and Inkinen, 2000).

The airborne laser scanner offers huge opportunities for rapid estimation of tree height, timber volume, and forest biomass over extensive forest areas. Previously, laser systems applied for forest studies were profiling sensors capable of data collection merely along the flight track, such as in Nelson et al. (1984, 1988) or the pulse rate of the laser scanner hindered the capability to detect individual trees (Nässet, 1997). The modern laser scanner is capable to produce three-dimensional tree height maps with high spatial and range resolution (Hyyppä et al., 1999b). However, the capability of laser scanner with respect to other remote sensing data sources has not yet been reported.

The main objective of this study was to compare the laser-derived estimates with estimates produced by other airborne and satellite-borne remote sensing data on the retrieval of the following forest stand attributes: stem volume (m^3/ha) and mean tree height (m). The main emphasis was put on the retrieval of stem volume (per hectare) which is the most valuable attribute to be assessed in national forest inventory and also in operational inventory at the stand level. This paper verified the information content of the following data: Landsat TM, SPOT Pan and XS, airborne data from imaging spectrometer AISA and laser scanner TopoSys-1. This study is the first one to compare the laser-derived forest inventory estimates with estimates produced by using other remote sensing data sources in a single test site.

2. MATERIAL

2.1 Test Site

The boreal forest test site, Kalkkinen, is located in southern Finland, 130 km north of Helsinki. This rather typical boreal forest area was selected for the study in order to maximize the availability and adequacy of good field inventory data and remote sensing data. An intensive area of 100 hectares (2-km-by-0.5-km) was selected for the detailed study. The test site is dominated by minor hills, otherwise it is flat and situated about 110 m above sea level. The main tree species are Norway spruce and Scots pine.

2.2 Field Inventory Data

The study was based on conventional forest inventory carried out by local forestry center from August – October 1996. From that data, 41 stands were used for the study. Conventional forest inventory was based on sample plot measurements and visual estimation. Mean tree height (m), basal area (m^2/ha), and stem volume per hectare (m^3/ha) were obtained for each stand basically as means of the sample plot values.

The descriptive statistics of ground truth data is depicted in Table 1. The average stem volume was 174.7 m^3/ha with a variation of 115.4 m^3/ha (coefficient of variation 66.0 %). The mean tree height was 16.9 m with variation of 7 m. The mean age of stands was 73 years whereas the oldest stands were 109 years old. The mean diameter was 20.4 cm and mean number of stems per hectare was 1551 pc/ha. The average stand size was 1.21 ha. The tree species proportions from intensive area were spruce (54 %), pine (29 %) and birch (17 %).

Table 1. Descriptive Statistic of the Field Inventory Data

Character	*Mean Height*	*Basal Area*	*Volume*
Mean Value	16.9 m	19.4 m^2/ha	174.7 m^3/ha
Standard Deviation	7.0 m	10.5 m^2/ha	115.4 m^3/ha
Minimum Value	3.0 m	0.3 m^2/ha	1.0 m^3/ha
Maximum Value	24.2 m	34.3 m^2/ha	361.4 m^3/ha

In order to verify the accuracy of the field inventory data, field checking was performed in Kalkkinen forest area for other 40 spruce-dominated and mixed stands independently from stand measurements. Field checking was based solely on systematic sample plots by measuring about 10 relascope sample plots in each stand. Tree species and the diameter at breast height (dbh) were recorded for each measured tree, determined with a relascope factor of 1. Age, diameter at breast height, and height were measured for the basal-area-median-tree of each sample plot. From these data, mean tree height (m), basal area (m^2/ha), and stem volume per hectare (m^3/ha) were obtained for each stand basically as means of the sample plot values. Since the ichecking was performed carefully devoting one man-day for the checking of each stand, one can assume it as a reference determining the accuracy of the checking and conventional forest inventory. Accuracy of the standwise field inventory compared to the intensive checking measurements is depicted in Table 2. The estimated accuracy of field inventory was better than that reported in (Hyyppä et al. 1999a) since the stand size of the applied material was higher than that used earlier. The effect of the stand size was corrected according to the results reported by Hyyppä and Hyyppä (2000).

Table 2. Accuracy of Applied Ground Truth Data

Field Inventory	*Mean height*	*Basal Area*	*Volume*
Random error	1.7 m	3.0 m^2/ha	35.8 m^3/ha
Systematic error	+ 0.57 m	0.0 m^2/ha	+19.3 m^3/ha

2.3 Satellite-borne and Airborne Remote Sensing Data

The remote sensing data set included satellite and airborne data: SPOT Pan & XS, Landsat TM, and airborne data from imaging spectrometer (AISA) and laser scanner (TopoSys-1). Table 3 summarizes the acquisition of the data in detail.

Optical satellite data - Optical satellite images were rectified using base maps and ground control points.

Imaging spectrometer AISA - The radiometric and geometric corrections of the imaging spectrometer measurements were carried out at Finnish Forest Research Institute (Metla). Radiometric correction converts obtained numerical values into radiance without any atmospheric correction. The intensity slope across the flight track in AISA data due to the BRDF and the viewing geometry was corrected with an algorithm utilizing the common area between adjacent flight lines. Geometric correction is based on the recording and modeling of the platform location and attitude and on the central projection imaging model for each raw image row. For each row, there are six orientation parameters, x, y, z, roll, pitch and yaw, respectively. These parameters allow the computation of ground location for each pixel.

The initial values of the orientation parameters are computed from the differential GPS and three angular velocity sensors. The digital terrain model was also used in the correction.

Table 3. Applied Remote Sensing Data

Platform/Instrument	**Description of Data Acquisition**
Laser scanner	Measured 2-3 September 1998 using TopoSys-1 laser scanner of TopoSys GmbH from the altitude of 400 m resulting in measurement density more than 10 measurements per m^2. Due to the survey altitude applied, the swath width was about 100 m. Both the first and last pulse modes were used.
Imaging Spectrometer	Measured on 10 June 1996 using the AISA imaging spectrometer of the Finnish Forest Research Institute (METLA), resolution 1.6 m (across-track) and 2.4 m (along-track), geometric and radiometric rectification was done by METLA, spectral range 466-870 nm. All together 30 spectral channels were recorded. The whole image was constructed from 600 m wide parallel strips. Atmospheric absorption bands between that range were omitted in channel selection.
Spot XS and Pan	Acquisition date 24 August 1996, data obtained under totally cloud-free conditions, processing level 1B, image size 60 km by 60 km, pixel size: 10 m (PAN), 20 m (XS).
Landsat TM	Acquisition date 24 August 1996, data obtained under totally cloud-free conditions, system corrected image, image size 50 x 50 km^2, pixel size 30 m (except for the channel 6: 120 m).

The pre-processing of remote sensing data was carried out accordingly.

Laser scanner data – The data was calibrated with the calibration flight from cross-tracks over the Kalkkinen area. The captured data of the flights were transformed into the Finnish co-ordinate system KKJ-3. The systematic errors occurred in the transformation were corrected using ground control points of summer cottages, road junctions and the base map. Laser scanner survey provided a cloud of points, the x, y and z co-ordinates of which are known. They form a digital surface model (DSM), which includes terrain points, vegetation points, and points reflected from buildings. By processing the data and classifying the points to terrain and vegetation points, it was possible to produce digital terrain model (DTM) and digital vegetation model (DVM). When only the top of the vegetation was included in the model, was called digital crown model (DCM). The difference between the DCM and DTM was called in this study a digital tree height model (DTHM), 3-dimensional representation of the tree heights within the target forest area. The digital tree height model was processed as explained in (Hyyppä and Inkinen, 2000).

3. METHODS

The rectified and pre-processed image data were analyzed using image processing, GIS and statistical software. The stand boundaries were imported to the GIS system. The stand boundary map was used to produce standwise estimates from the remote sensing data. The stands were decreased in size by removing a zone about 6 m wide around the perimeter of each stand. This removed some of the problems with mixed pixels at stand boundaries, and eliminated errors related to stand boundary map. From each stand, statistical standwise features were extracted to explain the variation of stem volume.

Table 4 describes the extracted features, such as mean, standard deviation, and median of intensity, spectral band ratios, principal component transforms, linear transforms (such as tasseled-cap), channel differences and shape of the histograms, for each data source. Extracted features were compared with the field-measured data. The criterion to eliminate and include variables was that all variables in the models should be significant ($p<0.05$). The maximum allowed number of features (predictors) in one model was 4. All data were used for model development. Using derived statistical features, the best-subset regression method was applied.

The parameters of the regression model were estimated by the method of least squares. In the least-squares procedure, the estimated line of regression was selected in a way that the sum of squares of the residuals was minimized. The term residual refers here to the vertical distance from a remote sensing-derived and field-measured value to the estimated line of regression. The sum of the squares of the residuals is called the sum of squares error and is denoted by *SSE*.

$$SSE = \gamma_1^2 + \gamma_2^2 + \gamma_3^2 + \ldots + \gamma_N^2 \tag{1}$$

where N represents the number of samples.

The mean squared error MSE corresponds to

$$MSE = \frac{SSE}{N-k-1} \tag{2}$$

where k refers to the number of internal sum of squares. In the case of simple linear regression, $k=1$.

The squared root of the MSE, denoted by RMSE (root mean squared error) corresponds to accuracy of the model and can be divided in to the bias and random error. Since all the data was used in the model development, the bias can be assumed as zero.

As a reference material, conventional forest inventory depicted in Section 2 was applied. Since the accuracy of the conventional forest inventory affects the evaluation, the accuracy of the conventional inventory was assessed and the errors due to the inaccuracy of the field inventory were removed from the mean squared errors. Since these two errors can be assumed as independent, the corrected root mean squared error can be expressed as

$$RMSE_c = \sqrt{MSE - \frac{1}{l}\sum_{i=1}^{l} Var(\delta_i)}\ , \tag{3}$$

where $Var(\delta_i)$ refers to variance of conventional field inventory error δ_i for stand i. The accuracy of field inventory measurement was verified in earlier study (Hyyppä et al. 1999a) by measuring carefully 40 stands in a near-by area (unfortunately laser mission could not cover them) spending one man-day to each stand. The accuracy of the intensive stands could be calculated from the variance of the plot data. Comparing that data against the conventional field inventory data and taking into account the internal variance of the intensive checking, the standard error of the conventional inventory was obtained. The systematic error of conventional field inventory was obtained by assuming that there is no bias in intensive field checking.

Table 4. Extracted Features

Platform/Instrument	**Extracted Features***
Laser scanner	Arithmetic and weighted mean of the laser-derived tree heights Canopy coverage percentage using the tree height model and assuming heights of bigger than 2 or 5 m to be as crown hits
Imaging Spectrometer	Intensity of 30 narrow spectral channels First three principal components Ratios of principal components NDVI-like ratios of channels Channel differences Channel ratios of type ch1/ch2/ch3
Spot PAN	Intensity
Spot XS	Intensity of all three channels NDVI-like ratios Channel differences Squared sum of all channels Channel ratios First three principal components
Landsat TM	Intensity of all seven channels NDVI-like ratio of channels for all channel combinations Channel difference of all channel combinations Squared sum of all channels Tasselcap transformation: brightness, greenness and wetness Channel ratios First three principal components

*Standwise means, medians and standard deviations were calculated for all above described features

The coefficient of determination (R^2) and adjusted R^2 (denoted by R_a^2) were calculated for the models. The R^2 tends to be an optimistic estimate of how well the models fit the population. The adjusted coefficient of determination attempts to correct this problem and reflect the goodness of fit of the model more closely.

The coefficient of determination R^2 was obtained from the corrected standard error of regression RMSE_c and the variance of the forest attribute data explained by the mean, denoted by V

$$R^2 = 1 - \frac{RMSE_c^{\ 2}}{V} \tag{4}$$

Adjusted R^2 is given by (Norusis, 1992)

$$R_a^2 = R^2 - \frac{k(1-R^2)}{N-f-1} \tag{5}$$

where f is the number of independent variables and N is the number of cases. In this study the adjusted R^2 was used.

Relative accuracy, i.e. standard error in percentages, denoted by SE%, was obtained by dividing the standard error by the mean value of the stand attribute data and converted into percentage values

$$SE\% = \frac{SE}{x}100\% \tag{6}$$

where x is the mean value for corresponding stand attribute data.

4. RESULTS AND DISCUSSION

The adjusted coefficient of determination, the corrected standard error of the model, and the standard errors in percentage were calculated for each data source utilizing the principles and methods described in Section 3. All the data was used for the model development. Figure 1 depicts the obtained standard errors in percentages with the best model for mean height and stem volume. As can be seen, the data sources in the estimation of tree height in the decreasing order of explanation power were the laser scanner, imaging spectrometer AISA, Landsat TM, Spot XS and Spot Pan and in the estimation of stem volume the corresponding order was the laser scanner, imaging spectrometer, SPOT XS, Landsat TM and Spot Pan. The SE% obtained in the stem volume estimation for laser was 13.5% compared to 49.6 % for Spot Pan. Laser scanner was the only data source of equivalent or better accuracy with the traditional forest inventories.

In order to better understand the order of explanatory power of different data sources, the previous regression quality variables were computed as a function of predictors in a model. Figure 2 shows the coefficients of determination versus number of predictors used and the Figure 3 shows equal standard errors in percentage.

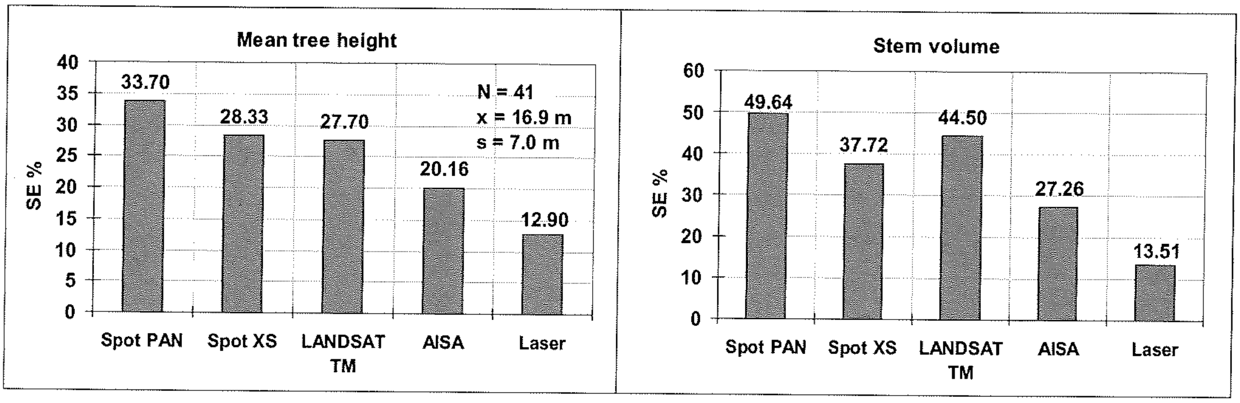

Figure 1. Obtained standard errors in percentages with the best models for mean height and stem volume.

Figures 2 and 3 clearly demonstrate the superior performance of the laser scanner when using a single predictor, i.e. laser-derived weighted mean height obtained from digital tree height model. The use of other laser predictors did not improve the model significantly. When comparing the results obtained with one predictor, the difference between other remote sensing data sources was tremendous. The results also indicate that imaging spectrometer can improve its performance due to the large number of predictors which could be generated from 30 channels. With one predictor, the estimation accuracy was comparable with satellite-borne sensors implying that the resolution does not have a significant effect in this spectral range for forest inventory. However, one should keep in mind that the radiometric quality of imaging spectrometer is poorer than that of satellite imagery. For the mean height estimation, there was no big difference regarding the type of satellite data sources utilized. For the stem volume estimation, SPOT satellite seemed to provide higher quality than Landsat. The better results obtained with the Landsat in comparison to Spot Pan can be explained by the number of predictors.

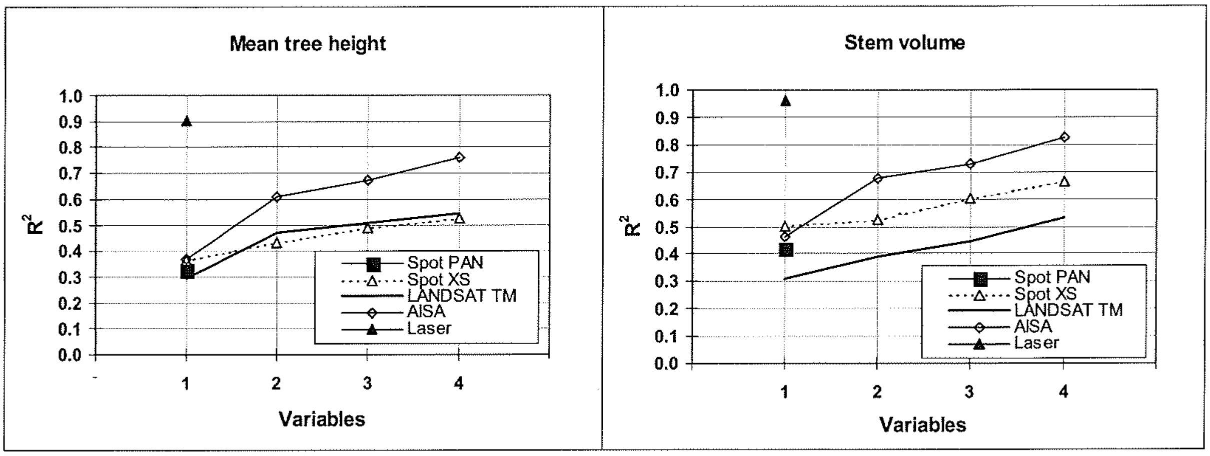

Figure 2. Adjusted coefficients of determination versus number of predictors.

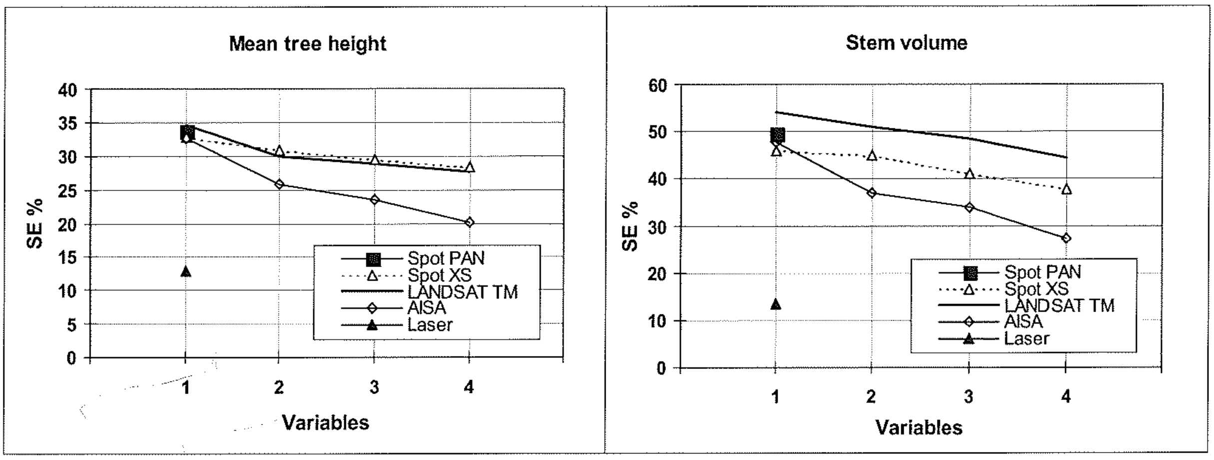

Figure 3. Standard errors in percentage versus number of predictors.

Since all the available data was used for teaching of the models and the field inventory error was reduced from the final results, the presented results described an optimistic view of the capacity of all remote sensing data sources, even though tree species classification and each tree species modeled separately were not accomplished. The effect of tree species represent at the maximum about 10 % of standard error. Since all the data sources were treated equally, the comparison of the data sources reflect the usefulness of each data source. Therefore, the results clearly showed that laser scanners can provide a huge potential for forest inventory and that they are far more accurate than any other data source tested, including the imaging spectrometer AISA.

As the predictors selected for the laser scanner were not ideal, therefore, more predictors with a physical behavior should be developed and tested in near future. In Hyyppä and Inkinen (2000), a segmentation-based method to retrieve parameters related to single trees was tested with reasonably good results. It was shown that tree heights of individual trees in the dominating storey can be obtained with less than 1 m standard error. In addition, the following standard errors were obtained for mean height, basal area and stem volume at stand level: 2.3 m (13.6 %), 1.9 m^2/ha (9.6 %), and 16.5

m^3/ha (9.5 %), respectively. The study was based on the same data set and, therefore, the comparison of the results was seemingly easy. The use of parameters related to single trees improved the stem volume estimates from 13.5 % to 9.5 %.

Comparing the results with the previous non-scanning laser studies, such as Nelson et al. (1988), a remarkable difference can be found. Nelson et al. (1988) stated an R^2 value of 0.52 and standard error of 69 m^3/ha (field-measured mean volume was 190.4 m^3/ha) between the laser-derived and field-measured stem volume per hectare. Their study was based on sample plots which can be assessed with a rather high accuracy. Hyyppä (1993) obtained improved results for plot assessment using ranging scatterometer: an R^2 value of 0.8 and a standard error of 45 m^3/ha (field-measured mean volume 223 m^3/ha) were obtained. At the stand level, Hyyppä (1993) obtained an R^2 value of 0.85 and a standard error of 31.3 m^3/ha (26.5 % relative accuracy). The error at the stand level was increased due to incomplete coverage and errors of field inventory which are higher than in sample plot inventories.

In Hyyppä et al. (1999a), different remote sensing data sources were compared at the stand level in Kalkkinen area using 483 stand in the analysis. For ranging radar, the obtained standard error after removing the field-inventory error was 37.7 m^3/ha (relative error 24.1 %). The order of the data sources in the decreasing order of explanation power were ranging radar, imaging spectrometer AISA, Spot XS, Spot Pan and Landsat TM. Comparing the results of this study, the order of Spot Pan and Landsat TM has been changed. This difference can be mainly explained by the number of predictors used in the modeling.

The new laser-derived stem volume estimates confirm well with the previous studies done by simulation (Hyyppä, 1996). Approximately a 10 % standard error was estimated for scanning ranging radar capable to provide both the crown top and ground hits.

The results suggest that new methods for forest inventory should be developed utilizing fully the capability of the laser scanner and integrating the laser scanner with other useful data sources. Additionally, the cost-effectiveness of laser-based surveys should be calculated. The breakpoint when laser-based surveys are more economical than the present methods should be found with respect to stand attributes, survey parameters (height, scan angle, number of pulses per m^2, sampling rate) and historical data applied.

5. CONCLUSION

This paper verified the explanatory power and information contents of several remote sensing data sources on the retrieval of stem volume and mean height, utilizing the following data sources: Landsat TM, SPOT Pan and XS, airborne data from imaging spectrometer AISA, and laser scanner TopoSys-1. This study is the first one to compare the laser-derived forest inventory estimates with estimates produced using other remote sensing data sources in a single test site. 41 stands were assessed with manual field measurements, and multivariate regression analysis was applied. The results showed clearly that laser-derived stand attributes were more accurate than those obtained by other data sources, and that the laser scanner was the only sensor that is capable to threaten the operational standwise forest inventory, at least as far as accuracy of stand attribute estimates is concerned. The obtained standard error after removing the error of field inventory was 23.6 m^3/ha (13.5 %) with an R^2 value of 0.96 for stem volume and 2.2 m (12.9 %) with an R^2 value of 0.9 for mean height.

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