# Evaluation of Remote Sensing Techniques for Estimation of Forest Variables at Stand Level

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# Abstract

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There is a continuous need for accurate forest description. Forest data at stand level is required in forestry planning, in particular when scheduling treatments within the next few years. Collection of forest data is typically acquired with subjective surveying methods in the field. However, field work is labor intensive and therefore an expensive method. An alternative to surveying methods in the field is to use remotely sensed data acquired by, *e.g*. optical, radar, and laser sensors.

In the present thesis, different remote sensing techniques for estimation of forest variables at stand level have been evaluated. All studies were performed in hemi-boreal coniferous dominated forest at a test site in southern Sweden (lat. 58°30'N, long. 13°40'E), enabling a detailed comparison. Remotely sensed data were related to field data using regression analysis. The root mean square error (RMSE) of the average stem volume using airborne laser scanning data, CARABAS-II radar data, aerial photo-interpretation, and multi-spectral optical satellite data was found to be 13%, 19%, 21-24%, and 24-32%, respectively. The analyses clearly demonstrate that airborne laser scanning is the single remote sensing technique of those investigated that gives the most accurate stem volume and tree height estimates at stand level. The estimates from laser scanning data are better than commonly achieved with subjective surveying methods in the field. The accuracy of forest variable estimation using aerial photo-interpretation of Z/I DMC images was found to be in agreement with the results using conventional film-based panchromatic photos. Hence, the results indicate that photo-interpretation of Z/I DMC images using a digital photogrammetric workstation could replace photo-interpretation of film-based photos using analog or analytical stereoplotters without loss of accuracy.

Combining two or more data sources which are complementary gives the possibility of improving estimation accuracies. Here, two particularly successful approaches were found. A combination of multi-spectral optical satellite and tree height data improved the RMSE of stem volume estimation to 11-12%. Using a combination of multi-spectral optical satellite and CARABAS-II radar data improved the RMSE to about 15%.

The application of the investigated remote sensing techniques in the forestry sector is restricted to the costs and the availability of remotely sensed data. In Sweden, airborne laser scanning data might be supplied by several companies operating in a pure commercial market. The National Land Survey has the mission of aerial photo mapping on a regular basis, but aerial photo mapping is also performed by commercial companies. For multi-spectral optical satellite and CARABAS-II radar data the governmental policy effects in practice what is offered to the users.

*Keywords*: Forest inventory, stem volume, regression models, combined estimation, aerial photography, multi-spectral optical satellite, laser scanning, synthetic aperture radar (SAR).

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# Contents

# Appendix

## Papers I-V

The present thesis is based on the following papers, which will be referred to by their Roman numerals:

I. Magnusson, M. & Fransson, J.E.S. 2004. Combining airborne CARABAS-II VHF SAR data and optical SPOT-4 satellite data for estimation of forest stem volume. *Canadian Journal of Remote Sensing 30(4)*, 661-670.

II. Magnusson, M. & Fransson, J.E.S. 2006. Evaluation of airborne low-frequency SAR and multi-spectral optical satellite data in combination and aerial photo-interpretation for forest stem volume estimation. *Submitted*.

III. Magnusson, M., Fransson, J.E.S. & Olsson, H. 2006. Aerial photo-interpretation using Z/I DMC images for estimation of forest variables. *Submitted*.

IV. Magnusson, M. & Fransson, J.E.S. 2005. Estimation of forest stem volume using multispectral optical satellite and tree height data in combination. *Scandinavian Journal of Forest Research 20(5)*, 431-440.

V. Magnusson, M., Fransson, J.E.S. & Holmgren, J. 2006. Effects on estimation accuracy of forest variables using different pulse density of laser data in combination with multi-spectral optical satellite data. *Submitted*.

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# Introduction

The continuous need for data in the process of forest management planning varies and depends on the user's requirement. Collection of forest data is typically acquired with subjective surveying methods in the field. The managed forest land in Sweden is primarily coniferous dominated and covers about 23 million ha (Anon., 2005a). The ownership of the forest land is divided among different categories, where about 50% of the forest is either public or owned by a few forest companies and the other half owned by non-industrial private forest owners with in general small forest holdings (Anon., 2005b). To support collection of forest data remote sensing has been used for decades by means of aerial photography. Forest companies apply methods including interpretation and tree height measurement in aerial photos using analog or analytical photogrammetric instruments (*i.e.* stereoplotters). A number of forest variables can then be estimated and the labor related to field survey reduced. For small scale private forest holdings aerial photos are typically used to delineate the forest into stands and used as a background image to a forest map. Besides aerial photography, data from several other remote sensing techniques are now available showing potential for forest variable estimation. These techniques are based on optical, radar, and laser sensors that could either be satellite or airborne. By combining two or more data sources there are also possibilities to improve estimation accuracies. In the present thesis, the performance of forest variable estimation at stand level using a combination of different remotely sensed data and field data has been examined.

## Forestry

### *Forest management planning*

The use of forest involves forest management planning to meet the objectives of the landowners and the society (Davis *et al*., 2001). In the planning process decisions among possible alternatives which contribute to the objectives are made and implemented. The objectives in forestry can be, *e.g.* economic return, nature conservation, biodiversity, recreation, social considerations, and aesthetic values (Andersson *et al*., 2005; Sallnäs, 2005). A starting point in the planning process is the current state of the forest. In order to meet the different objectives, data describing the forest are required and criteria to meet the objectives have to be settled. In general, forest maps and stand records are available for forest holdings (Davis *et al*., 2001). The forest map is divided into stands, typically about 0.5-20 ha in size, which primarily coincide with the treatment units. A stand is considered to have homogenous tree cover and uniform site conditions. The stand records usually include variables such as stem volume, tree height, tree species composition, site index, and age. An illustration of a general and simplified view on events in timber-oriented forestry is shown in Fig. 1.

| Inventory → | Forest management planning → | Forestry operations → | Transport → | Industry → | Product |
|---|---|---|---|---|---|
| - field survey<br>- remote sensing | - decision | - regeneration<br>- cleaning<br>- thinning<br>- clear cutting | - truck<br>- train | - pulp mill<br>- saw mill | - paper<br>- board |

*Fig. 1.* Chain of events in timber-oriented forestry.

Distinction into a strategic, tactical, and operational level of the planning process is typically made by forest companies (Duvemo & Lämås, 2006). In the strategic planning or long term planning dealing with scenarios of up to about 100 years, forest growth, thinning, and harvesting volumes are focused upon. At this level it is important to have accurate information of the entire forest holding to make a proper strategic decision. Here, objective methods for data collection of a sample of stands can be applied to obtain unbiased and accurate estimates (*e.g.* Jonsson *et al*., 1993). Preferably, the forest map and the stand records can be used for stratification prior to objective inventory. For forest planning on a time horizon of 5-10 years, *i.e.* tactical level, forest data are required for all stands in order to select appropriate harvesting areas, particularly with respect to the available road system. Full spatial coverage information has frequently been collected using photo-interpretation of aerial photos together with subjective field surveys (Åge, 1985). A number of stands selected for the tactical level, corresponding to an established harvest volume, are then in detail planned for cutting or other treatments in the near future, *i.e.* operational planning. Using field computers together with GPS equipment, detailed field data can be collected efficiently (Eriksson & Holmgren, 1997).

Forest management planning systems are valuable tools for analysing production possibilities, stand management practices, and forest economics. Existing planning systems, *e.g.* the forest management planning package (FMPP) (Jonsson *et al*., 1993), MELA (Siitonen, 1993), and AVVIRK2000 (Eid & Hobbelstad, 2000), are therefore used by forest companies and other owners with large forest holdings. These deterministic systems mainly focus on timber production for long term forest management planning. Inventory data to the FMPP and MELA planning systems originate from measurements on single trees. A forest management system operated on single tree models is assumed to have a higher resolution for estimates of stem volume and timber quality, reveals better predictions on multi-layer stands, and is more adaptable to deal with other utilities such as biodiversity and recreation in comparison to systems operating on models developed on standwise estimates (Lämås & Eriksson, 2003). To achieve the objectives of forestry the net present value (NPV) is commonly optimized. It is difficult, however, to predict future timber prices and rate of interest. In addition, unexpected events such as wind damages, insect attacks, and diseases in the forest are necessary to consider in decision analysis systems (Kangas & Kangas, 2004). Resources that do not have a market value, *e.g.* nature conservation, biodiversity, recreation, social considerations, and aesthetic values, are difficult to value in monetary terms (Boman & Mattsson, 1999). Thus, in a forest management planning system it is common to apply, *e.g.* area restrictions of old or deciduous forest within a forest holding. In Sweden, the forest companies have considered multiple objectives by applying an ecological landscape planning approach (Fries *et al.*, 1998).

For the non-industrial private forest owners the objectives of forest management are often different in comparison to forest companies. While the forest company's primary objective is purely economical other utilities may be important for the private forest owner, which imply that the forest is not managed optimally for timber production on parts of the holding (Karppinen, 1998; Ingemarson *et al.*, 2006). The forest company needs an even flow of timber to supply the industry and steady revenues over time from forestry. In contrast, the private forest owner often has the possibility to sell timber when the prices are temporarily high. To support decisions for the private forest owner a forest management plan consisting of a map and stand records is commonly used. Experience, common sense, and attitude play a significant role for the private owner when choosing treatments or activities in the forest (*e.g.* Karppinen, 2005).

### *Forest inventory*

Collection of standwise forest data covering an entire forest holding is typically acquired with subjective surveying methods, *e.g.* ocular inspection in the field, relascope measurements on plots that are judged to be representative for the stand, and by aerial photo-interpretation (Ståhl, 1992). The estimation accuracy obtained from subjective methods depends on the skill of the surveyors or interpreters. Consequently, the estimates are often biased and vary widely. Fixed-area plot sampling is common when performing objective forest inventories at stand level (Lindgren, 1984). Typically, circular sample plots are positioned in a systematic grid superimposed on the stand (*e.g.* Jonsson *et al.*, 1993). In contrast to subjective methods, the accuracy can be estimated in objective inventories. Thus, objective inventories on a sample of stands can effectively be used when collecting data for the strategic planning carried out by forest companies to reduce the risk of erroneous strategic decisions. The cost for objective inventories is often considerably higher in comparison to subjective inventories.

Estimation accuracy of forest variables depends on the chosen inventory method. At stand level, subjective methods are often less accurate in comparison to objective inventories. Generally, the cost increases and the accuracy improves with increasing intensity of the inventory (Ståhl, 1992). However, high accuracy in forest variable estimates is not an objective in itself. It is the accuracy that gives the highest utility that should be found. The cost-plus-loss approach is a method to optimize the utility for the forest owner where the resources can be quantified in monetary terms. By minimizing the sum of the inventory cost and the inoptimality losses due to erroneous decisions (expressed in NPV) the optimal inventory effort or method could be found (Fig. 2). Several studies have focused on the effect of estimation accuracies by means of a cost-plus-loss analysis using forest inventory data. Typically, erroneous data have been compared with forest data considered to be free from errors for a chosen forest management planning system using simulations (*e.g*. Sprängare, 1975; Larsson, 1994; Eid & Hobbelstad, 2000). Using an analytical approach, Ståhl *et al*. (1994) examined when it is optimal to carry out an inventory.

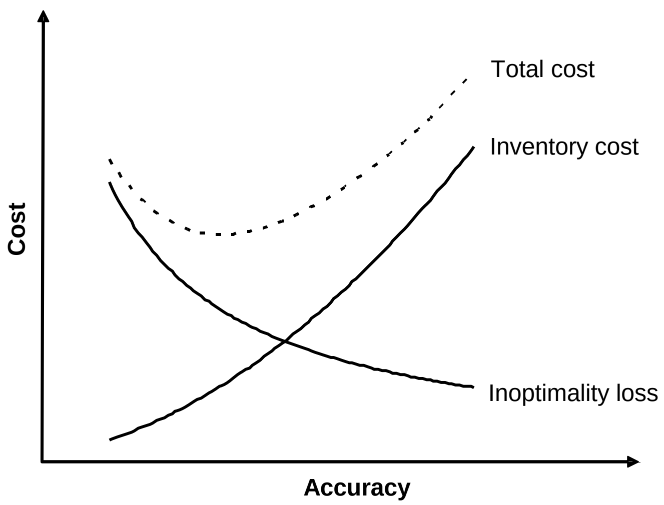


*Fig. 2*. The relation between inventory cost and estimation accuracy in forest inventory (Cochran, 1977). The dashed line is the total cost, *i.e*. sum of inventory cost and inoptimality loss.

The need of forest inventory is also addressed when a forest holding is bought or sold and when forest companies purchase timber in order to supply their industries. Given the multi-functionality of forests and the different actors and stakeholders there is an obvious need for accurate forest data from the perspective of the society as well as for the forest company and the non-industrial private forest owner.

## Remote sensing techniques

A sample of plots or stands is most often required for establishing the relationship between field data and remotely sensed data from optical, radar, and laser sensors. These types of sensors are based on different physical principles. Each specific sensor also has unique spatial, radiometric, and geometrical properties (*cf*. Kramer, 2002). A brief presentation of the remote sensing techniques used in the thesis follows together with image examples from the test site.

*Optical sensors*

Optical sensors measure passive reflected solar radiation and depend on relatively clear skies. Differences between acquisitions related to changes in atmospheric conditions (*e.g*. haze and clouds), sun elevation angle, view angle, and phenology, affect the optical image.

The first experiments using aerial photography were conducted in 1920s (Loetsch & Haller, 1973). In Sweden, the first successful trial of photo-interpretation in forest inventories was performed in Markaryd in the county of Småland in 1930 by a company from Germany (Anon., 1930; Danielsson, 1930). Since then aerial photo-interpretation has been widely used. Film-based aerial photos are captured using mapping cameras, *e.g*. Wild RC30 and Zeiss model TOP 15. Images acquired by digital mapping cameras, *e.g*. Zeiss/Intergraph Digital Mapping Camera (Z/I DMC) and Vexcel Ultracam-D, are now replacing the traditional film-based photos (Fig. 3). These digital images have lower spatial resolution and better radiometric resolution in comparison to the traditional film-based aerial photos. At a typical flight altitude of 5 km the spatial resolution in aerial photos or digital images allows single trees to be visible. The relation between the flight height and the size of the imaged region (side length) is about 1:1. In the aerial photos or digital images acquired with central projection, the variation in terrain elevation will result in scale variation and radial displacements.

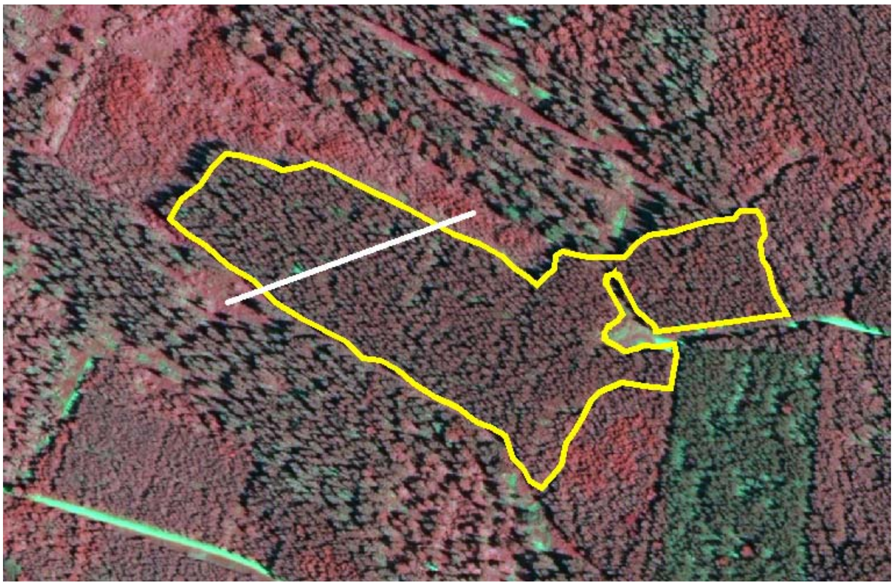

*Fig. 3*. A pansharpened color infrared image from the airborne Z/I DMC sensor acquired at a flight altitude of 4,800 m above ground, with a pixel size of 0.48 m. The imaged area covers about 600×400 m. The stand boundary, superimposed on the image, is outlined in yellow color. The white line shows the transect used to visualize laser data in Fig. 6.

A common product from mapping cameras is the orthophoto. Orthophotos do not contain the scale, tilt, and relief distortions characterizing aerial photos or digital images. Thus, it can readily be interpreted like a map on which true distances, angles, and areas can be measured directly. Using analog or analytical photogrammetric instruments, or a digital photogrammetric workstation, measurements of terrain elevation and tree height can be performed in aerial photos or digital images.

The first civilian optical land monitoring remote sensing satellite was launched in the beginning of 1970s and ever since there has been at least one multi-spectral satellite with medium spatial resolution in operation (Roller, 2000). This type of sensor onboard satellites such as SPOT-4, SPOT-5, Landsat 7, and ALOS, measure radiance with a radiometric resolution of 256 digital levels in wavelengths representing the visible and infrared range (Fig. 4). These satellites revisit the same area, typically, after a couple of weeks and each image cover large areas, *e.g.* 60×60 km in the case of SPOT-4 HRVIR and SPOT-5 HRG, and 185×170 km for Landsat 7 ETM+. The large coverage results in low cost per unit area (Roller, 2000). The relation between the flight height (about 700-800 km) and the size of the imaged region is about 5:1 – 10:1. The narrow field of view implies that the angle effects in a satellite image are small. Medium spatial resolution multi-spectral satellite images have lower resolution than aerial photos, typically 10-30 m. Hence, each pixel represents several trees. The satellite images can be geometrically precision corrected with an error of about half the spatial resolution.

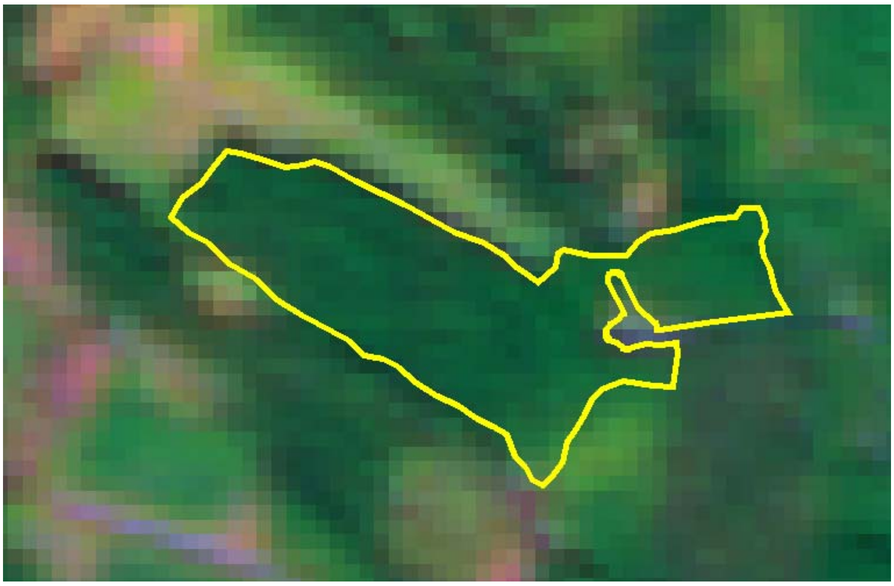

*Fig. 4.* A multi-spectral satellite image from the optical HRG sensor onboard SPOT-5, with a pixel size of 10 m. The imaged area covers about 600×400 m. The image is displayed in the red, near infrared, and short wave infrared wavelengths corresponding to the blue, green, and red channel, respectively.

*Synthetic aperture radar sensors*

Radar is an acronym for radio detection and ranging and is an active remote sensing technique. The synthetic aperture radar (SAR), in which an artificially extremely long antenna is synthetically created using a moving small antenna, is the most common remote sensing technique used for radar imaging. The first spaceborne radar system came into operation in the late 1970s (Leckie & Ranson, 1998). The imaging radar sensors are side looking and energy is transmitted to and received from objects within the sensors' incidence angle range. In contrast to optical sensors, the radar has the capability to generate images independently of weather conditions and sun illumination. Radar sensors are partly characterized by their operating frequencies corresponding to wavelengths ranging from centimeters to meters, *e.g.* 3.75-7.5 cm (C-band), 15-30 cm (L-band), and 3.3-15 m (VHF-band). The energy is also transmitted and received with a well-defined polarization, usually either horizontal (H) or vertical (V). The physical and the electrical properties of the illuminated object affect the backscattered energy. Typically, a physical object has to be at least the size of half the wavelength in order to be visible in the radar image. Hence, for an old coniferous forest, needles, twigs, and smaller branches will constitute the major scatterers when using the C- or L-band, whereas for the VHF-band the main scatterers are the larger branches and tree trunks. The image resolution generated from C-band SAR sensors onboard satellites such as Envisat and Radarsat-2, and L-band onboard ALOS, varies from a few meters to one or several hundred meters depending on sensor mode, but is typically about 20-30 m. The unique airborne CARABAS-II sensor is developed by the Swedish Defence Research Agency and operates in the VHF-band with a ground resolution of about 3 m (Hellsten *et al.*, 1996) (Fig. 5).

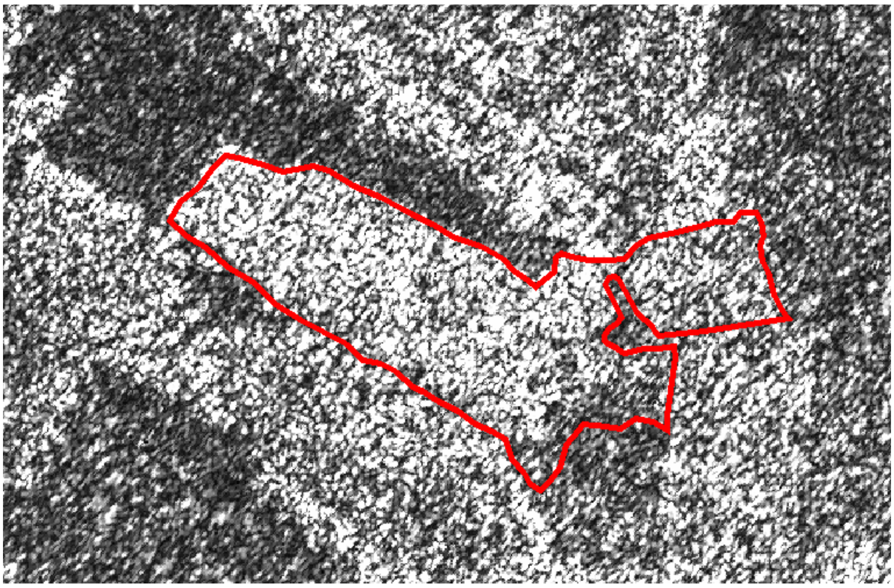

*Fig. 5.* A radar image from the airborne CARABAS-II VHF SAR sensor acquired at a flight altitude of about 3,400 m above ground, with a pixel size of 1 m. The imaged area covers about 600×400 m. Bright areas indicate high intensity (high stem volume) and dark areas low intensity (low stem volume) of backscattered energy.

## *Laser sensors*

Laser is an acronym for light amplification by stimulated emission of radiation and is an active remote sensing technique. A powerful highly directional optical light beam is transmitted and received, enabling accurate range measurements. The use of laser for determination of terrain elevations began in the late 1970s (Lillesand & Kiefer, 2000). These initial systems were equipped with a profiling device that measured the elevation directly under the track of the aircraft. In airborne laser scanning, pulsing lasers are combined with a scanner mechanism. The laser measurements are then distributed on the ground through the scan movement together with the forward motion of the aircraft. Hence, three-dimensional (3D) coordinates of reflection locations from the ground surface and the tree canopy can be generated, giving accurate measurements of tree height (Fig. 6). The beam divergence and the flight altitude above ground determine the laser beam diameter on the ground, commonly referred to as laser footprint diameter. Airborne laser scanner sensors such as TopEye, Optec ALTM, TopoSys Falcon, are typically operated at flight altitudes of about 200-2,000 m above ground and produce small footprints (diameter of about 0.1-4.0 m) and a pulse density of about one or more laser measurements per square meter (Næsset *et al*., 2004). Sensor characteristics, *e.g*. pulse density, number of pulse returns, flight height, and scan angle as well as the forest type influence the estimation of forest variables. Due to the relatively low flight altitudes the use of airborne laser scanning is associated with a relative high cost per unit area.

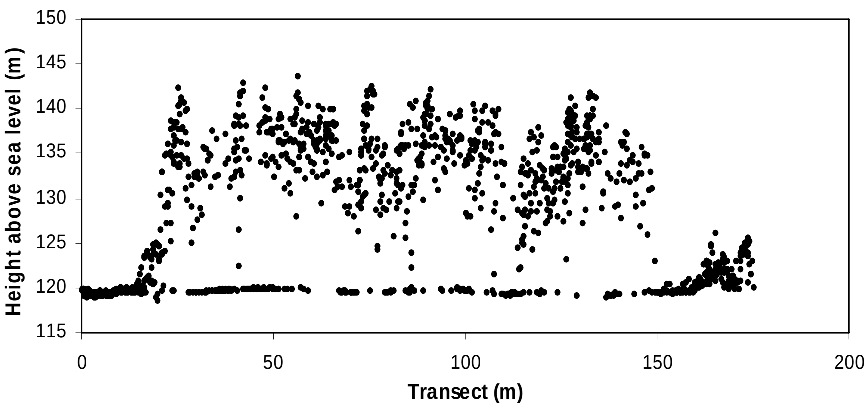


*Fig. 6*. Laser data from the airborne TopEye sensor acquired at a flight altitude of about 400 m above ground, with a pulse density of about 2.5 measurements per square meter. Each pulse is displayed as a black point plotted along a five meter wide transect through a forest stand (see Fig. 3).

## Estimation of forest variables at stand level

A review of literature that pertains to the estimation of forest variables using remotely sensed data follows. The review includes studies using remotely sensed data from various data sources separately or in combination together with field measurements. Unless stated otherwise, the studies have been carried out for coniferous dominated boreal forests and performed at stand level.

### *Aerial photo-interpretation*

Film-based aerial photos have been used extensively in support of forest management planning and methods for aerial photo-interpretation using analog or analytical photogrammetric instruments have been developed (*e.g.* Åge, 1985; Spencer & Hall, 1988; Eid, 1996). In Sweden and Norway, forest inventories have frequently been carried out with photo-interpretation of large-format film-based aerial photos, where stands are delineated and forest variables estimated. Through manual interpretation of aerial photos using a photogrammetric instrument, stand delineation, assessment of tree species composition, and stand density can be performed. The photogrammetric instrument also allows accurate tree height measurements of stands provided that the ground is visible in the photos. Using interpreted stand density and measured tree height, standwise stem volume can then be estimated through tree species specific empirical functions (*e.g.* Jonson, 1914; Tomter, 1988). To improve forest variable estimation and finally determine stand boundaries, a subsequent subjective field inventory is often performed. The interpretation and the subsequent field inventory are based on manual work and rely on the expertise of the personnel involved. To assess the data quality, the aerial photo-interpretation is often combined with an objective inventory performed at a limited number of randomly chosen stands within the forest holding. This two-phase sampling procedure makes it possible to correct for systematic errors in the subjective estimates (Thompson, 2002).

A number of studies using aerial photo-interpretation for stem volume and tree height estimation in large-format film-based photos have been carried out in Scandinavia. In Sweden, stem volume estimation in panchromatic photos (*e.g.* Ericson, 1984; Ståhl, 1992) and color infrared photos (*e.g.* Ståhl, 1988) in the scale of 1:30,000 have been investigated at different test sites. Ericson (1984) reported a standard error of 19% of the average stem volume in the range of 60-425 $m^3$ $ha^{-1}$ (average 189 $m^3$ $ha^{-1}$) for a test site located in the central part of Sweden. On two other test sites, located in northern and southern Sweden, with stem volumes ranging from 70-350 $m^3$ $ha^{-1}$ and 80-500 $m^3$ $ha^{-1}$, the standard errors were 13.5% and 26%, respectively (Ståhl, 1988, 1992). Norwegian studies using either panchromatic or color infrared aerial photos in the scale of 1:15,000 show a standard error in the range of 13-33% for stem volume estimation (Eid, 1996; Næsset, 1996; Eid & Næsset, 1998). In the Swedish studies, stand density was represented by volume density, *i.e.* actual standing stem volume in relation to a fully stocked stand according to Jonson (1914), and in the Norwegian studies by crown closure. Moreover, for tree height estimation the standard error was found to be in the range of 7-10% (Ståhl, 1992; Eid, 1996). All studies were performed in analog photogrammetric instruments.

In digital photogrammetry the interpretation and measurements are performed in digital images that are computer visualized. Until recently, large-format digital images were mainly produced from scanned film-based photos. At present, several large-format digital aerial cameras are being introduced for standard photogrammetric applications, *e.g.* Z/I DMC, Leica ADS40, and Vexcel Ultracam-D (Cramer, 2005). In 2004, the National Land Survey (NLS) of Sweden procured a Z/I DMC digital mapping camera. According to a new government policy, an area corresponding to one third of Sweden (about 15 million ha) will be photographed annually. From 2007 only digital images will be acquired by NLS and the standard altitude is planned to be 4,800 m above ground.

### *Multi-spectral optical satellite images*

Several studies have investigated the relationship between stem volume and multi-spectral optical satellite images. The optical bands in SPOT and Landsat show a general inverse relationship with stem volume, *i.e.* a decrease in the measured radiance with increasing stem volume (*e.g.* Ripple *et al.*, 1991; Trotter *et al.*, 1997). The correlation between the spectral data and stem volume tends to be stronger for younger stands than for older stands (*e.g.* Franklin, 1986; Horler & Ahern, 1986). This is probably a consequence of the fact that once the canopy closes the spectral reflectance saturates and the relationship between spectral radiance and stem volume becomes weak. Hence, stem volume is more difficult to estimate accurately for dense forests.

Stem volume estimates in the range of 0-305 $m^3$ $ha^{-1}$ (average 129 $m^3$ $ha^{-1}$) using images from SPOT-1, 2, and 3 resulted in a root mean square error (RMSE) between 24% and 38% of the average stem volume (Fransson *et al.*, 2001). Hagner (1990) estimated stem volume using Landsat 5 satellite data at plot level and performed the evaluation at stand level. The RMSE was found to be 26% for the investigated stands in the range of 70-350 $m^3$ $ha^{-1}$ (average 177 $m^3$ $ha^{-1}$). The above studies were carried out using regression analysis. Estimation of stem volume has also been performed by applying the *k* nearest neighbor (*k*NN) method (Tomppo, 1990). Holmström & Fransson (2003) used the *k*NN method and found an RMSE of 30% using SPOT-4 data in the stem volume range of 0-430 $m^3$ $ha^{-1}$ (average 169 $m^3$ $ha^{-1}$). Other *k*NN studies using Landsat 5 data have reported an RMSE of 38% and a standard error of 36% in the stem volume range of 0-360 $m^3$ $ha^{-1}$ (average 149 $m^3$ $ha^{-1}$) and 0-480 $m^3$ $ha^{-1}$ (average 156 $m^3$ $ha^{-1}$), respectively (Nilsson, 1997; Holmgren *et al.*, 2000). However, Nilsson (1997) evaluated the stem volume estimation at plot level.

### *Synthetic aperture radar*

The correlation between radar backscattering and stem volume has been investigated (*e.g.* Le Toan *et al.*, 1992; Leckie & Ranson, 1998; Fransson, 1999). The sensitivity of radar backscattering to stem volume increases when the radar wavelength increases. Using C-band SAR satellite data from ERS-1 the backscattered radar signal saturates at a stem volume of about 60 $m^3$ $ha^{-1}$ in comparison to L-band data from JERS-1 with a saturation level of about 140 $m^3$ $ha^{-1}$ (Fransson & Israelsson, 1999). No signal saturation for the airborne CARABAS-II VHF SAR sensor has been observed up to about 1000 $m^3$ $ha^{-1}$ (Melon *et al*., 2001).

The CARABAS-II sensor operates at extremely long wavelengths (3.3-15 m). As a consequence, the wavelengths are able to penetrate the forest canopy. Hence, the dominant scattering mechanism is the ground-trunk or trunk-ground interaction (dihedral reflection) as described through physical modeling (Smith & Ulander, 2000). Empirical studies at stand level support the physical model, showing a linear relationship and a strong correlation between radar backscattering amplitude and stem volume in coniferous forest on near-horizontal ground (slope < 4°). For stem volume in the range of 80-625 $m^3$ $ha^{-1}$ (average 339 $m^3$ $ha^{-1}$) the results showed an RMSE of about 20% of the average stem volume (Fransson *et al*., 2000). However, in stands with low stem volume (< 100 $m^3$ $ha^{-1}$) the possibility of accurate stem volume estimation is limited due to the noise floor of the CARABAS system. Another problem influencing the accuracy of stem volume estimation is the decrease in backscattering amplitude caused by sloping terrain. A first method to adjust for this effect has been developed using data from several flight directions, *e.g*. formed in a square pattern, and using the maximum backscattering amplitude (Fransson *et al*., 2004). The results after correction for topography are in agreement with previous studies on near-horizontal ground.

### *Airborne laser scanning*

Features from airborne laser scanning data describing the distribution of canopy tree heights and forest density is commonly used to relate laser data to forest variables (*e.g*. Holmgren, 2003). Pulse densities of approximately one or more laser measurements per square meter have been used in several studies for standwise estimates (*e.g*. Hyyppä *et al*., 2001; Næsset, 2002; Holmgren, 2004). Standard errors for mean tree height, basal area, and stem volume were estimated to 1.8 m (9.9% of the mean tree height), 2.0 $m^2$ $ha^{-1}$ (10.2%), and 18.5 $m^3$ $ha^{-1}$ (10.5%), respectively, with stem volume in the range of 2-335 $m^3$ $ha^{-1}$ (Hyyppä *et al*., 2001). In a study based on stem volumes ranging from 91-415 $m^3$ $ha^{-1}$, stands were divided into three strata according to age class and site quality prior to evaluation. The standard deviations of the differences between predicted and ground-truth values of mean tree height, basal area, and stem volume were found to be 0.6-1.2 m, 2.3-2.5 $m^2$ $ha^{-1}$, and 18-32 $m^3$ $ha^{-1}$ (corresponding to 11.4-14.2% of the average stem volume), respectively (Næsset, 2002). In the study by Holmgren (2004), laser data were used to predict mean tree height, basal area, and stem volume, resulting in an RMSE of 0.59 m (3% of the mean tree height), 2.7 $m^2$ $ha^{-1}$ (10%), 31 $m^3$ $ha^{-1}$ (11%), respectively, with stem volume in the range of 0-600 $m^3$ $ha^{-1}$ for the best case investigated.

### *Combined estimates*

There are many possibilities to improve the accuracy in stem volume estimation by combining different data sources, *e.g.* combining image data from a single sensor with field data (*e.g.* Hagner, 1990; Nilsson, 1997; Holmgren *et al*., 2000), combining images acquired at different times from the same sensor (*e.g.* Santoro *et al*., 2002; Rauste, 2005) or combining images from different sensors (*e.g.* Holmström & Fransson, 2003).

Variance weighting is one method where the included data sources are weighted by the inverse of their variances (Meier, 1953). The combined estimate is then supposed to give better accuracy than any of the separate data sources. For the combined estimate to be efficient the variance of the data sources should be of the same magnitude and the random errors should be independent or, even better, negatively correlated. However, negatively correlated random errors between data sources from forest inventories are not likely to occur. If the difference in variances between the data sources is large or the correlation of random errors is positive, the improvement of the estimate accuracy is marginal (*cf.* Ståhl, 1992). Furthermore, it is not obvious that the weights between the data sources could be correctly determined in the variance weighting procedure. With incorrect weights, the effect on estimation accuracy could be the opposite as one desires, resulting in decreased estimation accuracy in comparison to using the best single data source separately. Combined estimates using variance weighting for stem volume estimation at stand level (*e.g.* Santoro *et al*., 2002) and at plot level (*e.g.* Poso *et al*., 1999; Tuominen & Poso, 2001) have been performed, showing significantly improved estimation accuracies compared with that using the best single data source only.

Another way to carry out combined estimates is to use multiple regression analysis. The weights for each data source are then determined in the regression analysis. Hagner (1990) applied regression analysis to combine stem volume estimates from Landsat 5 data and pure ocular field observations performed by forestry professionals. For the combined estimate, the RMSE was improved to 18% in comparison to 26% and 24% using Landsat 5 data and ocular field observations, respectively.

Using the *k*NN method Holmström & Fransson (2003) estimated stem volume based on a combination of SPOT-4 and CARABAS-II data. The estimate resulted in an RMSE of 30% using SPOT-4 data that improved to 22% when both data sources were used. In Holmgren *et al*. (2000) stem volume was estimated by combining Landsat 5 and field data. By adding site index, age, and tree height as ancillary data the standard error was found to be 17% compared to 36% using Landsat 5 data only. At plot level, Landsat 5 data in combination with tree height data showed an improvement of the RMSE from 38% to 25% (Nilsson, 1997).

## Objectives

The objective of this thesis is to evaluate remote sensing techniques for estimation of forest variables at stand level. Optical, radar, and laser remotely sensed data acquired by satellite or airborne sensors were investigated. In particular, the performance of stem volume estimates using a combination of different remotely sensed data and field data has been examined. A detailed comparison between the techniques was possible as all studies were performed at a single test site, consisting of intensively managed coniferous dominated forest.

The specific objectives for the papers I-V are:

I. To evaluate the accuracy of stem volume estimation at stand level using airborne CARABAS-II radar data, multi-spectral optical SPOT-4 satellite data, and the combination of these two data sources.

II. To evaluate the accuracy of stem volume estimation at stand level using (a) a combination of airborne CARABAS-II radar data and multi-spectral optical Landsat 7 ETM+ satellite data and (b) aerial photo-interpretation of film-based panchromatic photos.

III. To evaluate the accuracy of stem volume estimation, tree height, and tree species composition at stand level using aerial photo-interpretation of pansharpened color infrared images acquired by the airborne Z/I DMC sensor. In particular, two different base-to-height ratios of 0.26 and 0.39 were evaluated.

IV. To evaluate the accuracy of stem volume estimation at stand level using a combination of multi-spectral optical satellite (SPOT-4 and Landsat 7) and tree height data. Furthermore, computer-generated random errors were added to tree height data to examine the response in accuracy for the combined stem volume estimates.

V. To evaluate the effect on accuracy of stem volume and tree height estimation at stand level using different pulse density of airborne TopEye laser scanning data. Two different approaches for deriving laser variables based on a grid and a stand approach were investigated. In particular, stem volume accuracy assessment was evaluated using a combination of laser derived variables and multi-spectral optical SPOT-5 satellite data.

# Material and methods

## Test site

Forest field data for all studies in this thesis have been collected at the Remningstorp test site (lat. 58°30’ N, long. 13°40’ E), located in the south of Sweden (Fig. 7). The forest holding covers about 1,200 ha of productive forest land divided into 340 stands. The prevailing tree species are Norway spruce (*Picea abies* (L.) Karst.), Scots pine (*Pinus sylvestris* L.), and birch (*Betula* spp.). The dominant soil type is till (*i.e*. a mixture of glacial debris) with a field layer consisting of a different herbs, blueberry (*Vaccinium myrtillus* L.), and narrow thinned grass (*e.g*. *Deschampsia flexuosa* (L.) Trin.). In denser old spruce stands the field layer is absent. The ground elevation is moderately varying between 120 and 145 m above sea level. The Remningstorp estate is owned by the Forestry Society’s Estate Management Company and further descriptions of the property are presented by Ahlberg & Kardell (1997).


*Fig. 7*. Location of the Remningstorp test site.

## Field data

Stands were selected through a stratified random procedure for the objective field inventory using the forest map and stand records available. The stratification procedure was carried out to ensure that the entire stem volume range was represented. The criteria of coniferous stem volume > 70% and soil type till were used in the selection of stands in papers I-V. Besides these criteria, the criterion of ground slope < 4° was used in papers I, II, and IV. Prior to field inventory, stand boundaries were checked using aerial orthophotos.

Collection of standwise forest data was carried out by fixed-area plot sampling according to the routines in the forest management planning package (Jonsson *et al.*, 1993). In each stand, plots with a radius of 10 m were placed in a quadratic grid with a random starting-point. On each plot, all trees were callipered at breast height (*i.e.* 1.3 m above ground) and tree species determined. For sample trees, selected with a probability proportional to tree basal area, tree heights were also measured on the plots. On average about ten sample plots were inventoried in each stand. Hence, field data were collected using an objective and unbiased method.

The estimates from the field inventory included forest variables such as tree species composition, stem diameter, tree height, and stem volume. Stem volume corresponds to the trunk volume per unit area ($m^3$ $ha^{-1}$) excluding branches and stumps, and tree height represents the basal area weighted mean tree height (m). The growth functions in Söderberg (1986) were used to adjust field data to match the forest conditions at the time of remote sensing data acquisition (Table 1).

Table 1. Forest data collected from objective field inventories.

| Paper | Number of stands | Stem volume range ($m^3$ $ha^{-1}$) | Average stem volume ($m^3$ $ha^{-1}$) | *Relative standard error (%) | Tree height range (m) | Average tree height (m) | **Relative standard error (%) | Average stand size (ha) |
|---|---|---|---|---|---|---|---|---|
| I, II, IV | 61 | 15-585 | 266 | 9 | 5-27 | 18 | 2 | 3.5 |
| III | 56 | 35-628 | 300 | 8 | 7-28 | 20 | 2 | 3.0 |
| V | 70 | 30-620 | 286 | 9 | 6-28 | 19 | 2 | 2.9 |

* square root of the average sampling variance of stem volume
** square root of the average sampling variance of tree height

## Remote sensing data

Data from aerial mapping camera, multi-spectral optical satellite, airborne radar, and laser scanning sensors have been analysed. System parameters and sensor characteristics are outlined in Table 2. Stand boundary vector data from the forest map were used for extraction of remote sensing data and the Swedish National Grid was used as reference coordinate system in all papers I-V.

Aerial photos (papers II and III) were acquired during the late spring (April 22) and summer (June 28) by the National Land Survey (NLS) of Sweden. Film-based panchromatic aerial photos were captured using a wide angle Wild RC30 camera at an altitude of 4,600 m above ground, corresponding to a scale of about

1:30,000. Contact diapositives were used in the aerial photo-interpretation. Pansharpened color infrared images were captured using the Z/I DMC sensor (Tang *et al.*, 2000; Schiewe, 2005). The flight altitude was 4,800 m above ground, corresponding to a pixel size of 0.48 m. The 12 bits digital aerial images were used in the photo-interpretation.

Data from the multi-spectral optical satellites (papers I, II, IV, and V) were captured during the vegetation season (May 8 – July 3). The optical images were cloud free over the test site investigated. The sensors onboard SPOT-4 and 5 measure the radiance in the green, red, near infrared, and short wave infrared wavelength band with a ground resolution of 10 or 20 m. Besides these wavelengths the sensor onboard Landsat 7 also measures radiance in the blue and in an additional short wave infrared wavelength band with a ground resolution of 30 m. Each wavelength band in the satellite images is represented by digital numbers (DNs), which are proportional to the measured radiance, and has a radiometric resolution of 256 digital levels. The images were geometrically precision corrected by the NLS with a geometrical error of about one half of the ground resolution (level 2C). The extraction of multi-spectral optical satellite data from the images was performed by averaging the pixel values of DNs at stand level for each wavelength band. Finally, the average DNs were radiometrically adjusted by subtracting the DN calculated over open water bodies, *i.e.* dark objects in the image located close to the test site (*cf.* Chavez, 1996). Meteorological data were presented (papers IV and V) as background information about the weather conditions at the dates of image acquisition.

Radar images from the airborne CARABAS-II sensor (papers I and II) were acquired from four different flight directions forming a square around the test site. The low-frequency CARABAS-II VHF SAR sensor operates at 20 to 90 MHz, corresponding to a wavelength between 3.3-15 m, using HH-polarization (Hellsten *et al.*, 1996). The images were captured at an altitude of about 3,300-3,500 m above sea level with incidence angles in the range of 35-75°. At these angles, the incidence angle is assumed to have a small effect on the radar response (Ulander *et al.*, 1999). In order to perform radiometric calibration of the SAR images a trihedral reflector was imaged outside the test site and used for radiometric calibration. The calibration accuracy for the SAR images is better than ±1 dB (Ulander *et al.*, 1999). The ground resolution of the CARABAS-II images is about 2.5 m. The SAR processing resulted in complex slant range images with a pixel size of 1 m. The images were automatically transformed into the reference coordinate system with a geometrical error of about 3-4 m (Walter *et al.*, 1999). The extraction of radar data from the images was performed by averaging the pixel backscattering amplitude values at stand level. Finally, for each stand the maximum backscattering amplitude from the four radar images was used in the analysis to reduce variations due to topography (Fransson *et al.*, 2004).

Laser data from the airborne laser scanning system TopEye (paper V) were collected from an altitude of 430 m above ground. The laser data used were acquired with a beam divergence of 1.0 mrad, a wavelength of 1064 nm, a pulsing frequency of 7,000 Hz, a scan frequency of 17 Hz, and a scan angle of ± 20 degrees. The geometrical error of three-dimensional reflections from objects is about one or a few decimeters (Sterner, 1997). Approximately 2.5 laser measurements per square meter were registered with a variation of measuring density depending on overlapping swaths. The first and last pulse returns were recorded. Standwise laser variables were derived consisting of height percentiles, mean height, and the ratio between the number of vegetation returns and the total number of returns (in the following referred to as canopy density) (Means *et al*., 2000; Næsset, 2002; Holmgren, 2004).

Table 2. Description of sensors and parameters used in papers I-V.

| | Multi-spectral optical satellites | | | Aerial photo | | Radar | Laser |
|---|---|---|---|---|---|---|---|
| Paper | I, IV | V | II, IV | III | II | I, II | V |
| System | SPOT-4 | SPOT-5 | Landsat 7 | Digital pansharpened color infrared | Film-based panchromatic | Airborne VHF SAR | Airborne laser scanning |
| Sensor | HRVIR | HRG | ETM+* | Z/I DMC | Wild RC30 | CARABAS-II | TopEye |
| Agency (Country) | CNEC (France) | CNEC (France) | NASA (U.S.) | NLS (Sweden) | NLS (Sweden) | FOI (Sweden) | TopEye AB (Sweden) |
| Launch date | 1998 | 2002 | 1999 | 2004 | 1995 | 1996 | 1997 |
| Altitude (km) | 822 | 822 | 705 | 4.8 | 4.6 | 3.4 | 0.4 |
| Spectral bands (µm) | | | | | | VHF-band: 3.3-15 m, HH-polarization | |
| Blue | | | 0.45-0.52 | 0.40-0.58 | | | |
| Green | 0.50-0.59 | 0.49-0.61 | 0.53-0.61 | 0.50-0.65 | | | |
| Red | 0.61-0.68 | 0.61-0.68 | 0.63-0.69 | 0.59-0.67 | | | |
| Near infrared | 0.78-0.89 | 0.78-0.89 | 0.78-0.90 | 0.68-0.85 | | | 1.06 |
| Short wave infrared | 1.58-1.75 | 1.58-1.75 | 1.55-1.75 | | | | |
| Short wave infrared | | | 2.09-2.35 | | | | |
| Panchromatic | Not used in this thesis | Not used in this thesis | Not used in this thesis | No information available | 0.35-1.00 | | |
| View angle | ±27° | ±27° | Nadir | Nadir | Nadir | | |
| Field of view | ±2° | ±2° | ±7° | ±35° cross track, ±22° along track | ±45° | Incidence angle: 35-75° | Scanning angle: ±20° |
| Ground resolution (m) | 20 | 10 (short wave infrared 20) | 30 | 0.48 (panchromatic), 2.3 (color) | 0.4 | 2.5 | Footprint diameter: 0.43, Pulse density: 2.5 $m^{-2}$ |
| Image size (km) | 60×60 | 60×60 | 185×170 | 6.6×3.7 | 6.9×6.9 | Strip width: 6 | Strip width: 0.3 |
| Orbital cycle (days) | 26 | 26 | 16 | | | | |
| Radiometric resolution (digital levels) | 256 | 256 | 256 | 4096 | | | |
| Approx. cost relation | 0.01 | 0.01 | 0.01 | 1 | 1 | 1 | 10 |

* instrument failure due to scan mirror anomalies in 2003

## Methodology

The analyses were performed by using conventional statistical methods, including regression analysis (papers I, II, IV, and V) and variance weighting (papers I and II). A backwards elimination procedure was used to develop multiple linear regression models for multi-spectral optical satellite and laser data. Initially, remote sensing variables known from the literature to be applied as predictors were included in the analysis. Strongly correlated variables were removed. The number of predictor variables included in the models was also kept to a limited amount. The selection of predictor variables included in the regression models were also based on ordinary statistical measures including significance levels of the regression coefficients, adjusted coefficients of determination, and residual plot studies. In the radar studies, simple linear regression analysis was used to estimate the regression coefficients for a physically based model (Smith & Ulander, 2000). The regression coefficients were estimated by means of ordinary least squares. To ensure that the regression functions were not overfitted, cross-validation was performed. In order to evaluate the performance of the functions for forest variable estimation, the root mean square error (RMSE) was used as the accuracy measure. The effects of the sampling errors were removed from the mean sum of squared residuals by subtracting half of the mean squared standard error calculated from field measurements (single plot values) (*cf*. Lindgren, 1984; Fransson *et al*., 2001).

In papers I and II, models for estimating stem volume from SPOT-4 and Landsat 7 data were developed using regression analysis (*cf*. Tomppo, 1987; Hagner, 1990). A regression function was created, describing the relation between stem volume and maximum backscattering amplitude from CARABAS-II data (Fransson *et al*., 2004). To combine radar and optical satellite data a regression analysis was performed using the estimated stem volume from each sensor as predictor variables after applying a weight proportional to the inverse variance (MSE) calculated sensorwise.

In papers II and III, aerial photo-interpretation of film-based panchromatic photos using an analytical stereoplotter and Z/I DMC pansharpened color infrared images using a digital photogrammetric workstation were performed. Measurements of tree height and interpretation of volume density and tree species composition were conducted by three (paper II) and four (paper III) professional aerial photo-interpreters, independently. The standwise stem volume was estimated using tree species specific empirical functions (Jonson, 1914). To assess the stem volume accuracy, the differences between stem volume from photo-interpretation and stem volume from field measurements were used to calculate the standard deviation, bias, and RMSE for each interpreter separately. The differences between stem volume from photo-interpretation and stem volume from field measurements were calculated in absolute terms in paper II and in relative terms in paper III. To test for individual systematic error in stem volume estimation a two-sided *t*-test was performed for each interpreter. Then, to correct for systematic error different estimators were investigated. Accuracy assessment of tree height measurements was also carried out. In paper III, accuracy evaluation of tree species composition was performed using a method based on fuzzy sets (Gopal & Woodcock, 1994). Here, a linguistic measurement scale is defined using a reasonable number of classes to quantify the accuracy of tree species composition. Furthermore, two different base-to-height ratios of 0.26 and 0.39 were used in order to evaluate the vertical exaggeration effect on the estimation accuracy.

In paper IV, stem volume regression models were developed using tree height data combined separately with SPOT-4 and Landsat 7 data. In order to further investigate the accuracy of stem volume estimation, the stands were stratified with respect to tree height. The stratification was performed into three strata with tree heights < 15 m, 15-22 m, and > 22 m to obtain approximately an equal number of stands in each stratum. The accuracy in each stratum was estimated using the residuals from the derived regression functions. To examine the response in accuracy for the combined stem volume estimates random errors, normally distributed with zero expectations, were added to tree height data. Simulations were performed 100 times separately for random errors with standard deviations of 1, 1.5, and 2 m. Applying the developed stem volume regression models using tree height data combined separately with SPOT-4 and Landsat 7 data, new regression coefficients and residuals were estimated in the simulation procedure. Accuracy assessments were carried out by calculating the square root of the average MSE over the simulations.

In paper V, regression analysis was used to relate stem volume and tree height to laser derived variables. In order to evaluate the estimation accuracies of stem volume and tree height, regression models were developed using a pulse density of about 2.5 pulses $m^{-2}$. The developed regression models were then used in a sensitivity analysis of estimation accuracy, where the pulse density was reduced (referred to as thinned laser data). Altogether, 15 different thinning levels were performed by removing laser returns from the initial laser dataset. The thinning was carried out by allowing a minimum horizontal distance of 1, 2,…, 15 m between adjacent laser returns. Two different approaches, *i.e.* grid and stand approach, for extraction of laser derived variables were investigated. Furthermore, stem volume regression models were developed using SPOT-5 data and the combination of SPOT-5 and laser data. Two different combined stem volume regression models were developed; optical satellite data combined with laser derived height and optical satellite data combined with laser derived height and canopy density. In addition, for each thinning level in the sensitivity analysis, both a digital elevation model (DEM) created from the initial laser dataset and a DEM created from the thinned laser data were investigated.

# Results

## Single remote sensing data source estimates

The main results using single sensor data for stem volume estimation at stand level are outlined in Table 3. The relationship between the stem volume and the estimated stem volume from various single remote sensing data sources is shown in Fig. 8. The best estimation accuracy for stem volume was obtained by using laser data (paper V) with an RMSE of about 13%. CARABAS-II data (papers I and II) gave an RMSE of 49 $m^3$ $ha^{-1}$, corresponding to a relative error of about 19% of the average stem volume. Aerial photo-interpretation of film-based panchromatic photos (paper II) gave an RMSE of 56 $m^3$ $ha^{-1}$ after correction for systematic error, corresponding to about 21% of the average stem volume (range of 17-24% between the interpreters). Using photo-interpretation of pansharpened color infrared images (paper III) no significant difference in the estimation accuracy using different base-to-height ratios was found. Furthermore, the accuracy in terms of relative RMSE, corrected for systematic error, was about 24% (range of 17-39%). However, calculated in absolute terms, the stem volume accuracy of pansharpened color infrared images (expressed in percentage by dividing the accuracy estimate with the average stem volume) was equal to the accuracy obtained from film-based panchromatic photos. Data from SPOT-4, SPOT-5, and Landsat 7 (papers I, II, IV, and V) gave RMSEs of stem volume estimation in the range of 24-32%.

Table 3. The accuracy in terms of root mean square error (RMSE) of the average stem volume at stand level using single sensor and combined data sources.

| | Paper | RMSE of average stem volume (%) | Improvement compared to best single sensor used (%) |
|---|---|---|---|
| **Single** | | | |
| SPOT-4 | I, IV | 24 | |
| SPOT-5 | V | 32 | |
| Landsat 7 | II, IV | 25 | |
| Wild RC30, film-based panchromatic photos | II | 21* | |
| Z/I DMC, pansharpened color infrared images | III | 24* | |
| CARABAS-II | I, II | 19 | |
| TopEye (tree height and canopy density) | V | 13 | |
| **Combined** | | | |
| SPOT-4 + CARABAS-II | I | 16 | 15 |
| Landsat 7 + CARABAS-II | II | 14 | 23 |
| SPOT-4 + tree height | IV | 11 | 53 |
| Landsat 7 + tree height | IV | 12 | 52 |
| SPOT-5 + TopEye (tree height) | V | 20 | 38** |
| SPOT-5 + TopEye (tree height and canopy density) | V | 12 | 5 |

* corrected for systematic error, ** compared with SPOT-5 data only

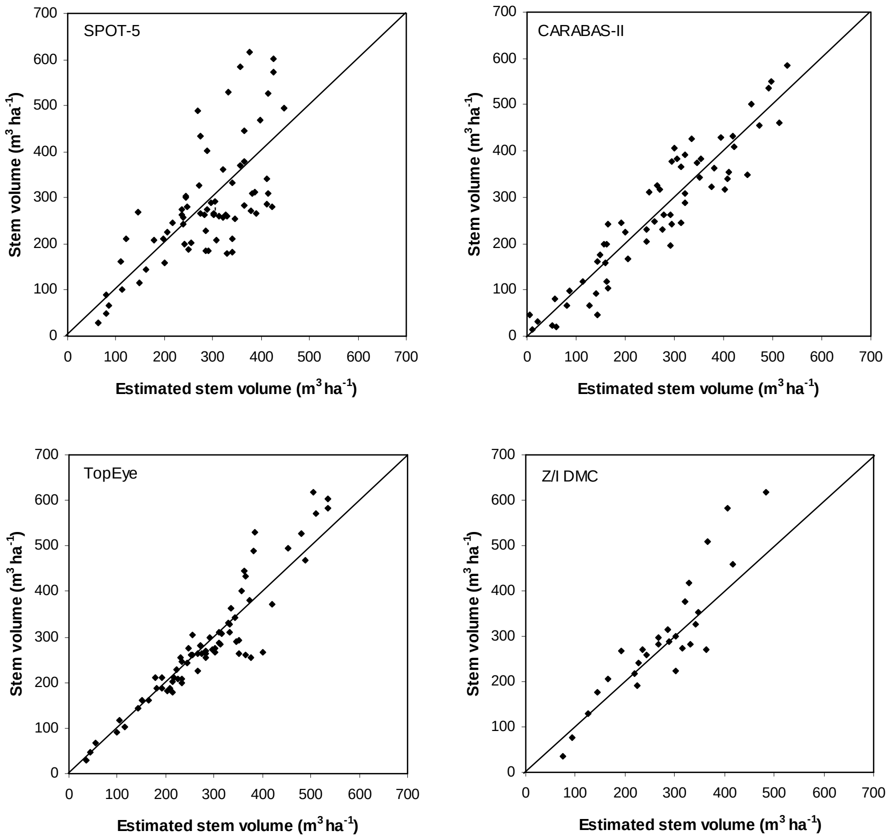


*Fig. 8*. Field measured stem volume plotted against estimated stem volume at stand level from single sensor data; SPOT-5 (paper V), CARABAS-II (papers I and II), TopEye (paper V), and Z/I DMC (paper III, Fig. 2 (B)) data. The plots are shown with reference lines.

Estimation of tree height (basal area weighted mean tree height, m) at stand level using single sensor data was investigated in papers II, III, and V. The best accuracy was obtained by using laser data (paper V), where the tree height estimation accuracy was found to be 0.6 m in terms of RMSE. Using aerial photo-interpretation of film-based panchromatic photos (paper II) the RMSE of tree height estimation was 1.5 m (range of 1.3-1.8 m). The corresponding accuracy of pansharpened color infrared images (paper III), corrected for systematic error, was 1.4 m (range of 0.9-1.6 m). Furthermore, the tree species composition accuracy assessment (paper III) using a fuzzy set evaluation procedure showed that 95% of the stands were correctly classified. For comparison, the standard error of the dominating tree species (spruce) was also calculated and found to be about 15% of the average proportion.

In paper V, the estimation accuracy of stem volume and tree height using thinned laser data was examined. By reducing the pulse density from 2.5 to 0.004 returns $m^{-2}$ the RMSE for the stem volume and tree height estimation increased from about 13% to 29% and 0.6 to 1.9 m, respectively. Overall, the grid approach compared to the stand approach revealed small differences in estimation accuracies. However, with inclusion of data from an accurate high resolution DEM (derived from the initial laser dataset instead of creating the DEM using thinned laser data) the estimation accuracies at low pulse densities were significantly improved. The results show that relative low pulse density laser data can be used for stem volume estimation at accuracies that can be obtained using, *e.g.* aerial photo-interpretation (papers II and III).

## Combined remote sensing data source estimates

Papers I, II, IV, and V focus on evaluating estimation accuracy of stem volume at stand level using a combination of data sources (Table 3). The largest improvement of accuracy was obtained by combining multi-spectral optical satellite data and tree height data (paper IV). The RMSE was about 11% of the stem volume using a combination of SPOT-4 data and field measured tree height data (see Fig. 9) compared to about 24% using SPOT-4 data only. Using Landsat 7 data in combination with tree height data the accuracy improved to about 12%. In paper V the RMSE was about 20% using SPOT-5 and laser derived tree height data in combination compared to about 32% using SPOT-5 data only. The RMSE for the combined regression function was even further improved to about 12% by adding the canopy density derived from laser data as a predictor variable. This demonstrates that the canopy density from laser data (with about 2.5 pulses $m^{-2}$) is superior to the SPOT-5 data by means of capturing the horizontal structure of the forest stands. Thus, SPOT-5 data contributed only marginally to improve the stem volume estimation accuracy in combination with laser data (including tree height and canopy density). In papers I and II, a significant improvement of stem volume estimation was achieved by combining multi-spectral optical satellite data and CARABAS-II data. The improvement using the combined estimate was found to be 15% (paper I) and 23% (paper II, see Fig. 9) over the full range of stem volumes investigated compared with that using CARABAS-II data only. The random errors between stem volume estimates from CARABAS-II and SPOT-4 data (paper I) are positively correlated with a correlation coefficient of 0.22, whereas the corresponding value is 0.04 for CARABAS-II and Landsat 7 (paper II). This may contribute to the slightly better improvement for the combined estimate in paper II in comparison to paper I.

The stem volume estimation accuracy using a combination of multi-spectral optical satellite data and tree height data was further investigated (paper IV). The analysis was performed by adding random errors with standard deviations of 1, 1.5, and 2 m to tree height data. The results showed that the RMSE increased with increasing random tree height error to 15%, 18%, and 20% using SPOT-4 data and 16%, 19%, and 21% using Landsat 7 data. This trend of decreasing accuracy with increasing tree height error was consistently observed for all tree height strata. Furthermore, the RMSE for the stem volume estimate using tree height data was also evaluated and found to be in the same order as for the estimates using optical satellite data only. Thus, the vertical and the horizontal structural data yielded about equal accuracies.

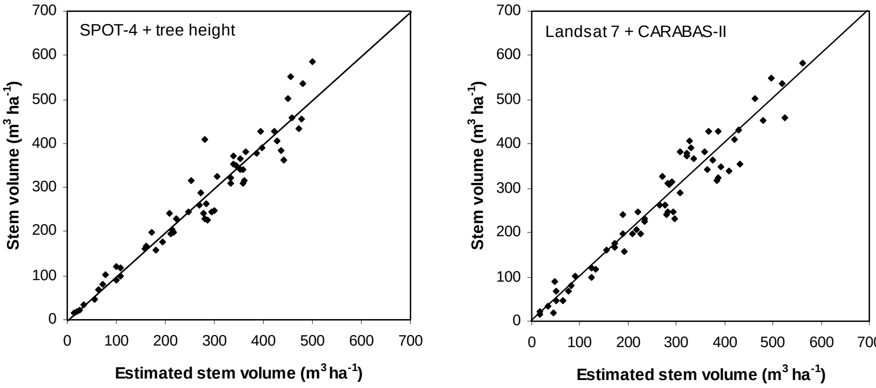


*Fig. 9*. Field measured stem volume plotted against estimated stem volume at stand level from combined sensor data; SPOT-4 and tree height (paper IV), Landsat 7 and CARABAS-II (paper II). The plots are shown with reference lines.

For the combination of SPOT-5 and thinned laser data the RMSE increased from about 20% to 27% and 12% to 25% using the two different combined stem volume regression models (paper V). Moreover, at a thinning level of ≥ 12 m (≤ 0.006 returns m$^{-2}$), the combination of SPOT-5 and laser derived tree height data has about the same estimation accuracy compared with that using thinned laser data only.

# Discussion and conclusions

In this thesis results from five papers demonstrate the applicability of using remotely sensed data for forest variable estimation at stand level. The experiments showed that stem volume estimates are feasible to perform in coniferous forest using optical, radar, and laser scanning data from either satellite or airborne sensors. The analyses were performed at a single test site and revealed three major findings:

- Airborne laser scanning data is the single sensor data source of those investigated that gives the most accurate stem volume and tree height estimates

- The results indicate that aerial photo-interpretation of Z/I DMC images using a digital photogrammetric workstation could replace photo-interpretation of film-based photos using analog or analytical stereo-plotters without loss of accuracy

- The combination of multi-spectral optical satellite and CARABAS-II radar data, and multi-spectral optical satellite and tree height data improve the stem volume estimation accuracy

## Single remote sensing data source estimates

The analyses clearly demonstrate that airborne laser scanning data is the single sensor data source of those investigated that gives the most accurate stem volume and tree height estimates at stand level (paper V). The estimates from laser data are better than commonly achieved with subjective surveying methods, *e.g.* relascope inventory and conventional aerial photo-interpretation with estimation accuracies in terms of standard error of about 15-25% of stem volume and about 10% of tree height (Ståhl, 1988, 1992). The results from laser data are in line with previous studies by Næsset (2002) and Holmgren (2004).

Few studies have examined the effect of reducing the pulse density in laser data on the accuracy of forest variable estimation (*e.g.* Holmgren, 2004; Lovell *et al.*, 2005). In Holmgren (2004) small differences in prediction errors for stem volume and tree height estimation was found when the pulse density was reduced from about 4 to 0.1 returns $m^{-2}$. At plot level, Lovell *et al.* (2005) revealed that the accuracy of tree height estimation decreased from about 0.05 to 0.11, in terms of normalized difference, when the pulse density was reduced from about 6 to 0.6 returns $m^{-2}$. The previous studies differ from paper V in that the reduction of pulse density was relatively modest and performed by a time sequential selection of laser returns.

As expected, a linear relationship and a strong correlation between CARABAS-II radar backscattering amplitude and stem volume were observed together with a constant variance about the stem volume regression function (papers I and II) (*cf.*

Fransson *et al*., 2000; Smith & Ulander, 2000). Consequently, stem volume estimation using CARABAS-II data is more accurate, in relative terms, for stands with high stem volume than for stands with low stem volume. The better performance of using CARABAS-II data in comparison to optical or laser data for stem volume estimation at high stem volumes is illustrated in Fig. 8.

The stem volume estimation accuracy using SPOT-4, SPOT-5, and Landsat 7 data (papers I, II, IV, and V) showed RMSEs in the range of 24-32%, which is in agreement with previous results using multi-spectral optical satellite data (*e.g*. Hagner, 1990; Fransson *et al*., 2001). Data from nearby meteorological stations show similar weather conditions at the time of image acquisitions. However, significant differences in the view angle, sun elevation angle, and phenology among the images may explain the variation in the estimation accuracy results. In particular, the view angle between the SPOT-4 image (papers I and IV) and the SPOT-5 image (paper V) differs by as much as 45°. Hence, stem volume estimation accuracy using multi-spectral optical satellite data is scene specific.

The traditional film-based photos are now being replaced by images acquired by digital mapping cameras. The results showed that the accuracy of forest variable estimation using aerial photo-interpretation of Z/I DMC images (paper III) was in agreement with the results using conventional film-based panchromatic photos (paper II). The results from this pioneer study indicate that photo-interpretation of Z/I DMC images using a digital photogrammetric workstation could replace film-based photos using analog or analytical stereoplotters without loss of accuracy.

## Combined remote sensing data source estimates

A combination of optical satellite data and other remotely sensed data or ancillary field data can improve stem volume estimation significantly (papers I, II, IV, and V). By combining multi-spectral optical satellite and CARABAS-II radar data (papers I and II) the RMSE was improved to about 15% of the average stem volume. The accuracy was found to be even better when combining multi-spectral optical satellite and tree height data (paper IV) (*cf*. Nilsson, 1997). Consequently, in this case, tree height was more successful than CARABAS-II as ancillary data. However, for a combination of SPOT-5 and laser derived tree height data (paper V) the accuracy was found to be about 20%. The high correlation between tree height and laser derived tree height (correlation coefficient of 0.99) indicates that the poorer accuracy for the combined estimate in paper V compared to paper IV is explained by the SPOT-5 data.

As expected, the results from the simulations in paper IV showed that the RMSE for the combined stem volume estimates increased consistently with increasing tree height error. This trend was observed for all investigated tree height strata and indicated that the number of simulations used in this study was appropriate to reveal reliable statistics. The similar trend has also been found by combining Landsat 7 and tree height data using the *k*NN method at plot level (Nilsson, 1997).

## Stand level analysis

In the present thesis the analyses were performed at the stand level. The mean value of all measurements in the remote sensing data was used as an unbiased estimator of the stand value. By using stand level instead of plot level in the analysis, the effects of spatial correlation are eliminated. Geometrical and measurement errors in the remote sensing data are then stabilized and expected to be small. The different spatial resolutions of the remote sensing data used are not assumed to have implications on the estimation results. The standard error in the field data was on average 8-9% of the stem volume and 2% of the tree height, at stand level (Table 1). Adjustment for the sampling error improved the estimation accuracy in terms of RMSE marginally. This indicates that the effects on the precision of additional sample plots in the field inventory are marginal compared to, *e.g*. measurement errors produced by a sensor or a photo-interpreter.

All studies were performed at a single test site in coniferous forest located on relatively flat ground and with comparable population distributions (Table 1). Therefore, a detailed comparison between the remote sensing techniques was enabled. However, applying the techniques in deciduous or peat land dominated forests and forests in mountainous terrain would affect the stem volume estimation accuracy.

## Applications in forestry sector

The application of the presented remote sensing techniques in the forestry sector is restricted to the costs and the availability of remotely sensed data. In Sweden, airborne laser scanning data might be supplied by several companies operating in a pure commercial market. The National Land Survey (NLS) has the mission of aerial photo mapping on a regular basis, but aerial photo mapping is also performed by commercial companies. For multi-spectral optical satellite and CARABAS-II data the governmental policy effects in practice what is offered to the users.

The large coverage capacity of multi-spectral optical satellite data makes the cost per unit area small. In Table 2, the relation between the costs per unit area of different remote sensing data has been approximated. However, cost for collection of field data and work for processing or interpretation of data should also be accounted for when comparing the techniques. Eid *et al*. (2004) have shown that the total cost, including inventory costs and economic losses (*cf*. Fig. 2), for estimation of basal area, dominant tree height, and number of trees per hectare is lower using laser scanning (25 euros $ha^{-1}$) compared to aerial photo-interpretation (54 euros $ha^{-1}$). In Næsset *et al*. (2004) it was concluded that although slightly different procedures and instruments can be used, airborne laser scanners using a pulse density of one or more measurements per square meter and small footprints (about 0.1-4.0 m) are very useful in practical inventories over large areas.

The practical implications given the estimation accuracy, availability, and cost aspects for the techniques used are in conclusion that:

- Airborne laser scanning data, available on a commercial market, yield forest variable estimation accuracy in relation to cost that most likely motivates operational use in forest inventories for companies at a tactical level and perhaps even at an operational level

- Z/I DMC images, acquired on a regular basis with complete coverage over Sweden every 3rd year by the NLS, will be available. Here, the NLS price policy for purchasing images will affect the use. It is foreseen that images will be available at a reasonable cost, in particular, for the benefit of forest owners with small forest holdings. Aerial photo-interpretation of Z/I DMC images using a digital photogrammetric workstation has potential to be widely used for forest variable estimation

- CARABAS-II radar data can be used for stem volume mapping in support of forest management planning. The technique is not commercial today, but with governmental financial support of data acquisition, CARABAS-II has potential to be extensively used. Combining CARABAS-II and multi-spectral optical satellite data for stem volume estimation, accuracies can be achieved that are equal to or better than subjective surveying methods

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“Do not cut down a tree, that gives you shadow.” (Arabic saying)
”Fäll inte ett träd, som skänker dig skugga.” (Arabiskt ordspråk)