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# ASPECTS OF ACCURACY, SCANNING ANGLE OPTIMIZATION, AND INTENSITY CALIBRATION RELATED TO NATIONWIDE LASER SCANNING

by

Eero Ahokas

Doctoral dissertation for the degree of Doctor of Science in Technology to be presented with the due permission of the School of Engineering for public examination and debate in Auditorium E at the Aalto University (Otakaari 1, Espoo, Finland) on the 14th of November 2013 at 12 noon.

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**Abstract**

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**Abstract**
Airborne laser scanning is a technique that produces three-dimensional coordinates of the Earth's surface as well as generating intensity values. Nationwide airborne laser scanning was launched in Finland in 2008 and some 180 000 km$^2$ had been scanned by the end of 2012. While the main goal in this endeavour is to produce an accurate digital elevation/terrain model (2 x 2 m$^2$ grid size) of the whole of the country, other applications, e.g. forestry, will benefit from the data as well. This study deals with the accuracy of airborne laser scanning, the optimization of the scanning angle, and the calibration of intensity.

Accuracy assessments of airborne laser scanning have shown that the geometric accuracy of the method can fulfill the accuracy requirements for producing a nationwide digital elevation model with a grid of 2 x 2 m$^2$.

When studying the effect of scanning angle and biomass on elevation modeling capability, it was found that it would be possible to increase the scanning angle applied in Finland's nationwide laser scanning. Even though the accuracy of the elevation model in the conditions prevailing in Finland allows increasing of the scanning angle, other applications would most probably not benefit from this. For example, these same data are sometimes used in nationwide forest inventory in Finland.

A method for relative and absolute calibration of airborne laser scanning intensity was developed. The portable reference targets have proved their usefulness for calibration purposes. An intensity correction method should be used in pre-processing the airborne laser data. As a result of this, the usability of the intensity values may increase in practical applications, such as in classification.

The studies constituting this dissertation have already impacted on the practical aspects of the nationwide airborne laser scanning dealing with accuracy assessment, the work done in the field of intensity calibration, and scanning angle analysis may have a further impact on nationwide laser scanning in the coming years. The optimization of airborne laser scanning flight parameters for multi-use nationwide laser scanning is a topic deserving further research.

**Keywords** airborne laser scanning, intensity, calibration, accuracy, scanning angle
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**Tiivistelmä**

**Tekijä**
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**Väitöskirjan nimi**
Tarkkuuden, keilauskulman optimoinnin ja intensiteetin kalibroinnin näkökulmia valtakunnallisen laserkeilauksen kannalta

**Yksikkö** Maankäyttötieteiden laitos

**Julkaisija** Geodeettinen laitos

**Sarja** Suomen Geodeettisen laitoksen julkaisuja

**Tutkimusala** Fotogrammetria ja kaukokartoitus

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**Yhdistelmäväitöskirja (yhteenveto-osa + erillisartikkelit)**

**Tiivistelmä**
Ilmasta tehtävä laserkeilaus tuottaa 3D-koordinaatteja maan pinnalta sekä intensiteettiarvoja. Suomen valtakunnallinen laserkeilaus aloitettiin vuonna 2008 ja noin 180000 km$^2$ oli keilattu vuoden 2012 loppuun mennessä. Vaikka päätarkoituksena on tuottaa tarkka digitaalinen korkeus/maastomalli (2 x 2 m$^2$ ruutukoko) koko maasta, muutkin sovellukset, kuten metsätalous, hyötyvät tästä aineistosta. Tämä tutkimus käsittelee ilmasta tehtävän laserkeilauksen tarkkuutta, keilauskulman optimointia sekä intensiteetin kalibrointia.

Laserkeilauksen tarkkuusarviointi on osoittanut, että menetelmän geometrinen tarkkuus täyttää valtakunnallisen digitaalisen korkeusmallin tuottamisen tarkkuusvaatimukset. Kun tutkittiin keilauskulman ja biomassan vaikutusta korkeusmallin tuottamiseen, huomattiin että olisi mahdollista kasvattaa valtakunnallisen laserkeilauksen havaintokulmaa. Vaikka korkeusmallin tarkkuus mahdollistaisi Suomen oloissa keilauskulman kasvattamisen, muut sovellukset eivät luultavasti hyötyisi tästä. Esimerkiksi tätä samaa aineistoa käytetään Suomen valtakunnallisessa metsien inventoinnissa.

Laserkeilauksen intensiteetin suhteellista ja absoluuttista kalibrointia varten kehitettiin menetelmä. Siirrettävät referenssikohteet osoittivat käyttökelpoisuutensa intensiteetin kalibroinnissa. Intensiteetin kalibrointimenetelmää tulisi käyttää laserkeilausaineiston esikäsittelyssä. Tämän tuloksena intensiteettiarvojen käyttökelpoisuus kasvaisi käytännön sovelluksissa, kuten luokittelussa.

Tämän väitöskirjan muodostaneet tutkimukset ovat jo käytännössä vaikuttaneet valtakunnallisen laserkeilauksen tarkkuusarvioinnissa. Intensiteetin kalibrointityö ja keilauskulman analysointi vaikuttanevat valtakunnalliseen laserkeilaukseen tulevina vuosina. Lisätutkimusta tarvitaan ilmasta tehtävän laserkeilauksen lentoparametrien optimoimiseksi monikäyttöistä valtakunnallista laserkeilausta varten.

**Avainsanat** Laserkeilaus, intensiteetti, kalibrointi, tarkkuus, keilauskulma

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## Preface

This doctoral dissertation is based on my work at the Finnish Geodetic Institute (FGI), at the Department of Remote Sensing and Photogrammetry, during the years 2002-2011.

I would like to thank Professor Juha Hyyppä and Dr. Sanna Kaasalainen for their guidance and valuable advice, and Professor Henrik Haggrén for his support during my post-graduate studies at the Aalto University, School of Engineering.

The pre-examiners of the thesis, Assistant professor, Ing. Markéta Potůčková, Ph.D., Department of Applied Geoinformatics and Cartography, Charles University in Prague, Czech Republic, and Dr.-Ing. Aloysius Wehr, Institute of Navigation, University of Stuttgart, Germany, are acknowledged for their reviewing and valuable comments on the manuscript.

I would also like to thank my co-authors of the original articles (see list of publications) Dr. Markus Holopainen, Dr. Eija Honkavaara, Prof. Juha Hyyppä, Juha Jaakkola, Lic. Sc., Harri Kaartinen, Lic.Sc., Dr. Sanna Kaasalainen, Anssi Krooks, M.Sc., Prof. Risto Kuittinen, Antero Kukko, Lic.Sc., Lauri Markelin, M.Sc., Kimmo Nurminen, M.Sc., Dr. Jouni Peltoniemi, Dr. Juha Suomalainen, and Dr. Yu Xiaowei for their help and co-operation. I also take this opportunity to express my gratitude to all members of staff at FGI, who have contributed to my work in any possible way.

Special thanks go to my family, wife Jaana, and children Aarne, Sampo, Siina, and Oili.

In Kirkkonummi, August 2013.

Eero Ahokas

**List of abbreviations**

| | |
|---|---|
| ADS | Airborne Digital Sensor |
| AGC | Automatic Gain Control |
| AGL | Above Ground Level |
| AHN | Dutch Elevation Model |
| ALS | Airborne Laser Scanning |
| ALTM | Airborne Laser Terrain Mapper |
| ANOVA | Analysis of Variance |
| BRF | Bidirectional Reflectance Factor |
| DBH | Diameter at Breast Height |
| DEM | Digital Elevation Model |
| DGM | Digitales Geländemodell |
| DN | Digital Number |
| DTM | Digital Terrain Model |
| EuroSDR | European Spatial Data Research |
| FGI | Finnish Geodetic Institute |
| FOV | Field of View |
| GLAS | Geoscience Laser Altimeter System |
| GNSS | Global Navigation Satellite System |
| GPS | Global Positioning System |
| ICAO | International Civil Aviation Organization |
| IMU | Inertial Measurement Unit |
| INS | Inertial Navigation System |
| ISPRS | International Society for Photogrammetry and Remote Sensing |
| LiDAR | Light Detection and Ranging |
| MLS | Mobile Laser Scanning |
| MODTRAN | MODerate resolution atmospheric TRANsmission |
| NLS | National Land Survey of Finland |
| NSIDC | National Snow and Ice Data Centre |
| PRF | Pulse Repetition Frequency |
| RGE | Référentiel à Grande Échelle |
| RMSE | Root Mean Square Error |
| RTK | Real-Time Kinematic |
| SME | Small and Medium Enterprises |
| TIN | Triangular Irregular Network |
| TLS | Terrestrial Laser Scanning |
| VRS | Virtual Reference Station |
| 3D | 3-dimensional |

## Contents

**List of publications**

This thesis is based on the following publications, which are referred to in the text by their Roman numerals:

I Ahokas, E., Kaartinen, H., Hyyppä, J. 2004. A quality assessment of repeated airborne laser scanner observations. *The International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences,* Istanbul, Turkey, Vol. XXXV, part B3, pp. 237-242. ISSN 1682-1750.

II Ahokas, E., Hyyppä, J., Kaartinen, H., Kukko, A., Kaasalainen, S., Krooks, A. 2010. The effect of biomass and scanning angle on laser beam transmittance. *International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences*, Vienna, Austria, Vol. XXXVIII(7A), pp. 1-6. ISSN 1682-1777. http://www.isprs.org/proceedings/XXXVIII/part7/a/pdf/1_XXXVIII-part7A.pdf

III Ahokas, E., Hyyppä, J., Yu, X., Holopainen, M. 2011. Transmittance of Airborne Laser Scanning Pulses for Boreal Forest Elevation Modeling. *Remote Sensing*. 3, 1365-1379. ISSN 2072-4292.
http://www.mdpi.com/2072-4292/3/7/1365/

IV Kaasalainen, S., Ahokas, E., Hyyppä, J., Suomalainen, J. 2005. Study of surface brightness from backscattered laser intensity: Calibration of laser data. *IEEE Geoscience and remote sensing letters,* Vol. 2, No. 3, pp. 255-259, ISSN 1545-598X.

V Ahokas, E., Kaasalainen, S., Hyyppä, J., Suomalainen, J. 2006. Calibration of the Optech ALTM 3100 laser scanner intensity data using brightness targets. ISPRS Commission I Symposium, Paris Marne-la-Vallee, 4-6 July 2006, ISPRS Volume XXXVI Part 1/A. pp. 14-20. CD-ROM publication. Also in *Revue Française de Photogrammétrie et de Télédétection*, No. 182, (2006-2), pp. 10-16.

VI Honkavaara, E., Peltoniemi J., Ahokas, E., Kuittinen R., Hyyppä, J., Jaakkola, J., Kaartinen, H., Markelin, L., Nurminen, K., Suomalainen, J. 2008. A Permanent Test Field for Digital Photogrammetric Systems. *Photogrammetric Engineering and Remote Sensing.* Vol. 74, No. 1, pp. 95-106.

Publications I and II are peer-reviewed conference articles. Publications III, IV, V, and VI are refereed journal papers.

**Author's contribution**

Prof. Juha Hyyppä supervised and provided advice in the sub-projects and helped in various ways as part of the typical supervision tasks of professors.

In **Publication I** the author processed the data, analyzed the results, and wrote the article. The field work in Espoo was done with Harri Kaartinen.

**Publication II** is a joint study. The author processed and analyzed the data, and was responsible for writing the article. All of the co-authors participated in the indoor experiment and made the measurements possible.

In **Publication III** the author was responsible for analyzing the data and for writing the article, Yu Xiaowei helped with the forest data, and Markus Holopainen contributed comments.

In **Publication IV** the author was responsible for designing the portable test targets and for preparing the article. Sanna Kaasalainen was the lead author and Juha Suomalainen participated in the laboratory measurements.

In **Publication V** the author carried out the laser data processing, analysis, and writing of the article. Juha Suomalainen carried out the field work. Sanna Kaasalainen contributed comments.

In **Publication VI** the author was one of the major builders and maintainers of the test field. The author developed methods for testing analogue systems and for radiometric testing of digital sensors. Eija Honkavaara conducted and participated in calibration and development of the testing method, and in conducting the analysis, and she compiled this article. Jouni Peltoniemi supervised the BRF measurements and processed and analyzed the BRF data.

Author's additional publications within the topic of this dissertation are Ahokas et al. (2000, 2001, 2002, 2003, 2005, and 2008), and Kaasalainen et al. (2008, 2009a). The main material of Ahokas et al. (2008) is presented in Chapter 4. The number of references in the Google Scholar is 561 (April 22, 2013).

# 1. Introduction

## 1.1 Motivation

Airborne laser scanning (ALS) is a method based on laser (LiDAR, Light Detection, and Ranging) range measurements from an aircraft, and the precise orientation of these measurements between a sensor (the position of which is known by the use of a differential-GPS technique) and a reflecting object, the position of which (x, y, z) is to be defined. In addition to ALS, an increasing number of terrestrial laser scanners (TLS) have been mounted on tripods and even on moving platforms (MLS, Mobile Laser Scanning). The output of the laser scanner is a georeferenced point cloud, i.e., 3D coordinates to each observed hit and the intensity and possibly waveform information corresponding to the return. An overview of ALS can be found in Wehr and Lohr (1999), Petrie and Toth (2009), and Wehr (2009).

LiDAR instruments have been operated also from space. The first LiDAR instrument for continuous observations of the Earth was the Geoscience Laser Altimeter System (GLAS). It was launched in 2003 and the instrument on board is the ICESat operated by the National Snow and Ice Data Centre (NSIDC). The footprint of this LiDAR was 70 m in diameter and they were spaced at 170 m intervals on the ground (ICESat 2012). The study conducted by Meng et al. (2011) involved comparing GLAS measurements and ALS data. The regression model with detected outliers removed yielded an RMSE value of 0.66 m and an R-squared value of 0.99. A spaceborne LiDAR for high resolution topographic mapping is also under development. The purpose of this mission is to map topography and vegetation at a spatial resolution of 5 m. The orbit altitude will be about 400 km (Yu et al. 2010). With these spaceborne LiDARs global and national coverage is possible but spatial resolution is limited compared to airborne instruments.

In Finland, airborne laser scanning has been in use since the late 1990s for both forestry and elevation model purposes (Hyyppä and Hyyppä 1999, Hyyppä and Inkinen 1999, Hyyppä et al. 2000). FGI initiated ALS-based quality analysis research in 2000 resulting in studies on the quality of the accuracy of laser-based elevation and target models (Ahokas et al. 2001, 2002, 2003, 2005 and Hyyppä et al. 2005 and Publication I). There was then an increasing demand for more accurate terrain height information than what the existing DEM with a grid of 25 m could provide, and National Land Survey (NLS) launched the densification of the 25 m elevation model in 2001 using manual stereophotogrammetry with a grid of 10 m (Vertanen et al. 2006). This densification was completed in 2011. In addition, the International Civil Aviation Organization (ICAO) accepted the new Guidelines for Electronic Terrain, Obstacle and Aerodrome Mapping (ICAO, ICAO 2004) and the European Union issued a directive on the assessment and management of flood risks in 2007 (Directive 2007). These both had the impact of further to improving the on-going 10 m grid elevation model process. The cooperation between the Finnish Geodetic Institute and the National Land Survey in the field of ALS began in 2003. First it consisted of using ALS to analyze the homogeneity of NLS DEM production (Oksanen and Sarjakoski 2006) and in 2005 the two organizations made preparations for nationwide ALS collection. The accuracy of ALS in the context of national production was analyzed by NLS/FGI by means of tests in the Salo-Suomusjärvi area (conducted in 2006-2007). The nationwide airborne laser scanning of Finland carried out by the National Land Survey began in 2008 and the production of the new 2 x 2 $m^2$ elevation model was assumed to take 10-15 years. However, about 180 000 $km^2$ was covered by laser point clouds already by the end of 2012. The official height accuracy of the model is 30 cm and 15 cm for laser points on hard surfaces. The point density is 0.5 points/$m^2$. The main goal is to produce an accurate digital elevation/terrain model for the whole of Finland, but other applications will benefit from the valuable data as well. Examples of other applications are forest inventory and forestry (e.g. Hyyppä et al. 2009), virtual reality, 3D city models, hydrology, flood prevention, geology, map updating, and land-use data base. The automated detection of buildings and changes in buildings for updating of maps using ALS data has been studied by Matikainen et al. (2003, 2009, 2010).

The main flight parameters in ALS are scanning angle, pulse rate, scan rate, flying altitude, swath width, beam divergence, laser footprint, and point density. The scanning angle is one parameter that affects the economy of the nationwide laser scanning. In Finland, forests cover 77% of the total land area; indeed, Finland is the only country in Europe where this percentage is over 70% (Tilastokeskus 2007). In forested areas it is important to know what scanning angles can be used in elevation modeling. It is important to recognize the effect of forest (e.g., pulse transmittance to the ground) on elevation modeling. The density of the forest plays a significant role in laser pulse penetration to the ground through the foliage, and this needs to be recognized when optimizing the elevation modeling process. At the time of the advent of airborne laser scanning, the shadowing problem was considered to be a serious challenge. The TopoSys airborne laser scanner was designed to embody a scanning angle of ±7º off-nadir in order to minimize shadow formation (Lohr, 1997). Since then, laser scanning has been applied to tasks such as the creation and updating of nationwide elevation models and standwise forest inventories where data covering large areas need to be collected cost-efficiently. Presently, scanning angles of ±15º have been generally accepted in operational work, but larger scanning angles are also being applied, e.g., in nationwide airborne laser scanning in Finland and Sweden, the corresponding scanning angle is ±20º. Optimization of the scanning angle (i.e., of the field of view) is an important aspect of nationwide airborne laser scanning. Significant savings in flying time (and thus in costs) can be achieved by increasing the scanning angle and flight altitude if the quality of the end product does not deteriorate too much considering the demands. The initial results obtained using scanning angle analysis (Ahokas et al. 2005) have shown that the scanning angle impacts on the accuracy of DEMs, but that other factors, such as forest density, dominate the process.

In addition to point clouds, ALS provides intensity of the backscatter or full-waveform (intensity as a function of range). Intensity values contain information about the target and this information should be used in the future in the automatic classification of objects. The intensity of each recorded airborne laser point has been mainly used only as an aid for classification purposes (e.g., Holmgren and Persson 2004), for matching laser scanner data with aerial images, and for lidargrammetry (Fowler et al. 2007). Intensity can also yield information on the optical properties of the target, such as snow (Kaasalainen et al. 2006). Intensity values have not been fully utilized, partly because the techniques for calibrating them were lacking before the present dissertation work began (before 2004). Since nationwide laser scanning in Finland will be repeated, calibrated intensity is an important feature to be used, e.g., in the detection of change. Since laser scanning is also evolving towards multi- and hyperspectral sensing (e.g., Kaasalainen et al. 2007, Suomalainen et al. 2011), intensity calibration is a topic of increasing importance. Figure 1.1 shows the variation of ALS intensity data on two different dates. As the laser point coordinates of nationwide laser scanning are in a uniform coordinate system over Finland, the intensity values should be presented in a uniform scale for further use.

Figure 1.1. ALS data on two different dates were used in the above. The differences in intensity values are clearly evident.

## 1.2 Hypothesis

The basic hypothesis in the present study was that airborne laser scanning is a technique accurate enough to be used for the current nationwide elevation modeling, calibration of intensity can be done, and the transmittance of laser pulses to the ground surface is affected by the forest biomass.

## 1.3 Objectives

The objective was the preparation of Finnish nationwide laser scanning acquisitions with regard to the following aspects:

1) Is the accuracy of ALS good enough for nationwide elevation modeling (activity launched in 2002)?
2) What is the effect of scanning angle and biomass on elevation modeling capability (activity launched in 2004)?
3) To demonstrate that the intensities of ALS surveys can be radiometrically corrected (activity launched in 2003).

This dissertation can be regarded as an empirical one and it is also a review of the historical development of nationwide laser scanning research in Finland. FGI launched preparations for nationwide elevation modeling in 2000 by studying elevation model accuracy on all land cover types. In 2005, it became clear that nationwide laser scanning will actually take place. Publications I and Ahokas et al. (2008) related to Objective 1 are examples of these preparations. Height and planimetric errors along the flight strips are considered in Publication I. Ahokas et al. (2008) is a presentation of a mobile accuracy assessment method for larger areas. Objective 1 was also conducted in close cooperation with National Land Survey of Finland. The activity was launched in 2008, and FGI also participated in the auditing of the new elevation model process.

Objective 2 relates to the capability of ALS to penetrate through forest cover with increasing scanning angles due to cost-effectiveness considerations. Publications II and III are responses to Objective 2. The effect of the scanning angle of ALS on accuracy has been debated. Publication II describes a controlled indoor experiment on how biomass and scanning angle affect beam transmittance. Publication III extends the scope to an airborne experiment looking into the effect of the scanning angle on laser pulse transmittance in connection with boreal forest elevation modeling.

Intensity calibration is based on a concept developed at FGI in 1996 (Kuittinen et al. 1996 and Ahokas et al. 2000) in which test site gravel and portable targets can be used to calibrate the DN of aerial images. Publications IV and V are responses to Objective 3. Field methods for calibrating the intensity of ALS did not exist at the time when the paper was published. The objective in Publications IV and V was to develop an intensity calibration method using portable brightness targets. Systematic laboratory measurements of backscattered laser intensity were presented for these targets. These targets have been used many years as part of the Sjökulla photogrammetric test field for testing the radiometry of aerial digital cameras (e.g., Markelin et al. 2008). The calibration of intensities could open up new possibilities for using intensity values for the classification of airborne laser scanner data. Synergy from previous work in the field of aerial image calibration was benefited from (Ahokas et al. 2000). Publication VI provides an overview of the possibilities of the permanent test field and highlights also the history of portable test targets.

## 2. The state of the art in nationwide ALS surveys

The focus in descriptions of the state of the art is on what had been published before the individual papers of this thesis were published. As regards the accuracy of laser scanning and the accuracy of the nationwide elevation model, quite a number of other papers have been published in the field. In regard to scanning angle optimization and intensity calibration, relatively few papers had been published prior to this work. Especially the matter of intensity calibration is currently a major research topic, whereas at the time when Publications IV and V where published, only a few articles had been published on this topic. Papers contributed after Publications IV and V on intensity calibration are referred to in more detail in Section 5 Discussion.

### 2.1 Physics of laser scanning

The word *laser* stands for light amplification by stimulated emission of radiation. The emission of light occurs when photons are excited to higher energy level and this excitation state discharge. ALS transmitters are usually semiconductor diode lasers or solid-state lasers. Airborne laser scanners work in the optical domain and usually in the wavelength region between 800 nm and 1600 nm (Wehr et al. 1999). The emitted laser light is coherent and monochromatic. When the laser light is transmitted from the light source this light remains coherent over a certain distance which is called the coherence length. Coherence creates a speckle phenomenon when the laser pulse is scattered from diffuse surface (Hecht 1992). Atmospheric absorption and scattering attenuate the laser pulse. Water vapour and aerosols are the main factors for this attenuation. The ALS receiver contains an optical detector that is a semiconductor photodiode. Photodiodes can be avalanche or PIN (positive-intrinsic-negative) photodiodes. The incident optical signal is converted into an electrical current output in the receiver (Wehr et al. 1999).

Range from the sensor transmitter to the target is determined by measuring the time of the laser pulse travelling this path down and up. Range $R$ can be calculated from

$$R = \frac{vt}{2} \qquad (2.1)$$

where $v$ is the velocity of the pulse and $t$ is the measured down-and-up time of the pulse. The accuracy of the determination of time $t$ is important for obtaining accurate range values. The echo detection algorithm is also an important factor that affects the accuracy of the range measurement. Standard pulse detection methods are threshold, center of gravity, maximum, zero crossing of the $2^{nd}$ derivative, and constant fraction. In the threshold method a pulse is triggered if the rising edge of the signal is bigger than the threshold. In the center of gravity method a fixed threshold exists and all the points above it are used for center of gravity calculation. The maximum method detects local maxima of the pulse. Zero crossings of the $2^{nd}$ derivative give the possible turning points of the pulse curve. In the constant fraction method a specified fraction (e.g. 50%) of the peak amplitude times the leading edge. The first two pulse detection methods are vulnerable to the signal amplitude and width. Amplitude variations do not affect the latter three methods.

The radar/lidar equation explains the signal strength of laser. The recorded intensity is related to the received power, which can be given in the form (Wagner et al. 2006):

$$P_r = \frac{P_t D_r^2}{4\pi R^4 \beta_t^2} \cdot \eta_{sys} \eta_{atm} \cdot \sigma \tag{2.2}$$

where $P_r$ is the received signal power [W], $P_t$ is the transmitted signal power [W], $D_r$ is the diameter of receiver aperture [m], $R$ is the range from sensor to target [m], $\beta_t$ is the laser beamwidth (beam divergence) [radian], $\eta_{sys}$ is the system transmission factor, $\eta_{atm}$ is the atmospheric transmission factor, $\sigma$ is the target backscatter cross section [$m^2$]. The target backscatter cross section $\sigma$ is

$$\sigma = \frac{4\pi}{\Omega} \rho A_s. \tag{2.3}$$

where $\Omega$ corresponds to the directional properties of the scattering, $\rho$ is the reflectivity of the target surface and $A_s$ is the receiving area of the scatterer (Jelalian 1992). Directional properties of the scattering, target reflectivity and the receiving area of the scatterer affect the backscattering characteristics of a target. The recorded intensity is proportional to $R^2$ for homogenous targets filling the full footprint, to $R^3$ for linear objects, and to $R^4$ for individual scatterers.

## 2.2 Accuracy of nationwide ALS surveys

Nationwide ALS surveys and/or DEM collection have also been carried out or are currently under way in the Netherlands, Switzerland, Denmark, Sweden, and the United States. In the Netherlands, laser altimetry has been used for computing the new Dutch elevation model (AHN) starting in 1996 and it was completed in 2003. The decision to launch the production of the 2nd generation DEM (AHN2) was made in 2008 and it is due to be completed in 2013 (Swart 2010). The point density in AHN2 is approximately 9 points/$m^2$ (Eurosense 2011). In Switzerland, nationwide laser scanning was launched in 2000. It consisted of five periods with the last period ending in 2005 (Artuso et al. 2003). The Earth's surface with vegetation and buildings below 2000 m a.s.l. were modeled applying an accuracy of ±0.5 m (1σ) in open areas and ±1.5 m (1σ) in vegetated areas. The Digital Terrain Model represents the ground surface without vegetation and buildings. Its accuracy is ±0.5 m (1σ). The laser point density is about 1 point/2$m^2$. In addition, a 2 m grid is produced (Swisstopo 2011). The laser point data is updated applying a cycle of 6 years. In Denmark, the whole country was scanned and the new DEM (Denmark's Height Model) with 1.6 m grid was ready in 2008. The laser point density was 0.45 points/$m^2$ (KMS 2011). In Sweden, the production of the new nationwide elevation model using airborne laser scanning was launched in 2009. The nationwide laser point coverage is due to be ready in 2013, and the elevation model is due to be ready in 2015. The point density is 0.5 – 1 points/$m^2$ and the maximum scanning angle is ±20° (Lantmäteriet 2011 and 2010). In the USA, the nationwide LiDAR dataset remains a future goal. There is no consensus on the detailed data specifications, and the roles and responsibilities of the partners. At the state level, laser data are being acquired and statewide elevation models are being created (Stoker et al. 2008). Federal instructions could result in the following advantages for state level laser scanning: standardized data processing, uniform quality analysis and control, seamless data along state borders, and authoritative data sources (Parrish 2009). Laser datasets have been compiled in Connecticut, Delaware, Iowa, Louisiana, North Carolina, Ohio, and Pennsylvania. Partial coverage applies to Florida, Illinois, Kansas, Maryland, Massachusetts, Minnesota, New Jersey, North Dakota, South

Dakota, Oregon, Texas, Utah, Wisconsin, and Wyoming (Wikipedia 2011). In France, ALS is used in producing RGE ALTI products in flood risk areas. In coastal areas the Litto3D and the RGE ALTI are identical. The specifications for ALS require 2 points/$m^2$ on average (SHOM, IGN 2009). RGE ALTI DTM is available in 1 m and 5 m grids (IGN 2011). ALS has made it possible to create accurate nationwide elevation models using 5 x $5m^2$, 2 x $2m^2$, and even 1 x $1m^2$ grid sizes. In Germany, the production of height models (DGM) is organized at state level. Table 2.1 shows roughly the geometric accuracy of nationwide ALS.

Table 2.1. Accuracies/specifications of ALS and derived DEM in some countries. The values for Germany are presented by states.

| | ALS planimetric accuracy, m | ALS vertical accuracy, m | Product | DEM planimetric accuracy, m | DEM vertical accuracy, m |
|---|---|---|---|---|---|
| Denmark | | 0.15 | 1.6 m grid | | |
| Finland | | 0.15 | 2 m grid | | 0.3 |
| France | 0.5 MSE | 0.2 | | | |
| Netherlands | | | | 0.5 | 0.05 SD 0.05 syst.error |
| Sweden | 0.4 SD | 0.1 | 2 m grid | | 0.5 |
| Switzerland | | | 2 m grid | | 0.5 |
| Germany | | | | | |
| Baden-Württemberg | | <±0.15 (σ) | | | |
| Bavaria (*Bayern*) | | | DGM1 | ±0.5 | ±0.2 |
| Berlin | | | DGM2 | | ≤0.2 |
| Brandenburg | | | DGM1 | | <0.3 |
| Bremen | | | DGM5 | | ±0.25 |
| Hamburg | | ±0.15 | | | |
| Hesse (*Hessen*) | ≤±0.3 | ≤±0.15 | DGM1 | | ≤0.4 (2σ) |
| Mecklenburg-Vorpommern | | ±0.2 | DGM2 | | |
| Lower Saxony (*Niedersachsen*) | | | DGM5 | | ±0.5 |
| North Rhine-Westphalia (*Nordrhein-Westfalen*) | | | DGM1 | | ±0.2 |
| Rhineland-Palatinate (*Rheinland-Pfalz*) | 0.3 | 0.15 | | | |
| Saarland | | | DGM1 | | <±0.15 |
| Saxony (*Sachsen*) | | | DGM2 | | ±0.2 |
| Saxony-Anhalt (*Sachsen-Anhalt*) | | | DGM1 | | ±0.15 |
| Schleswig-Holstein | | | | ≤0.3 | ≤0.15 (2σ) |
| Thuringia (*Thüringen*) | | | DGM5 | | ±0.5 |

It can be seen from Table 2.1 that the planimetric accuracy of the nationwide ALS point cloud is 0.3-0.5 m and that elevation accuracy is 0.1-0.2 m. The planimetric accuracy of the national DEM derived from ALS data is typically 0.3-0.5 and elevation accuracy is 0.05-0.5 m, depending on the size of the model grid. Methods for checking the quality of elevation models can be found e.g. in Kraus et al. (2004) and Höhle et al. (2011).

The process of the production of the 2m x 2m grid DEM in Finland started in 2008, and has five basic steps; airborne laser scanning, basic laser data processing, quality control, automatic ground classification, and interactive work in a stereo environment. ALS is carried out either by consultant small-and-medium-sized enterprises (SMEs) or by the National Land Survey (NLS). Basic laser data processing includes system calibration and project calibration (strip adjustment + georeferencing). The result of these steps is an unclassified georeferenced point cloud. Quality control focusing on the laser points includes checking holes, low and high points, strip overlap, point density, accuracy of the strip adjustment in height and planimetry (along track and cross track), and checking the absolute reference height by control point fields and planimetry by stereomodels. Automatic ground classification produces four point classes: unclassified, low vegetation, ground, and low points. Interactive work in a stereo environment produces the final point cloud with three new point classes: water, stream, and bridge.

Figures 2.1 and 2.2 depict ALS coverage in Finland (2012) and Sweden (2012).

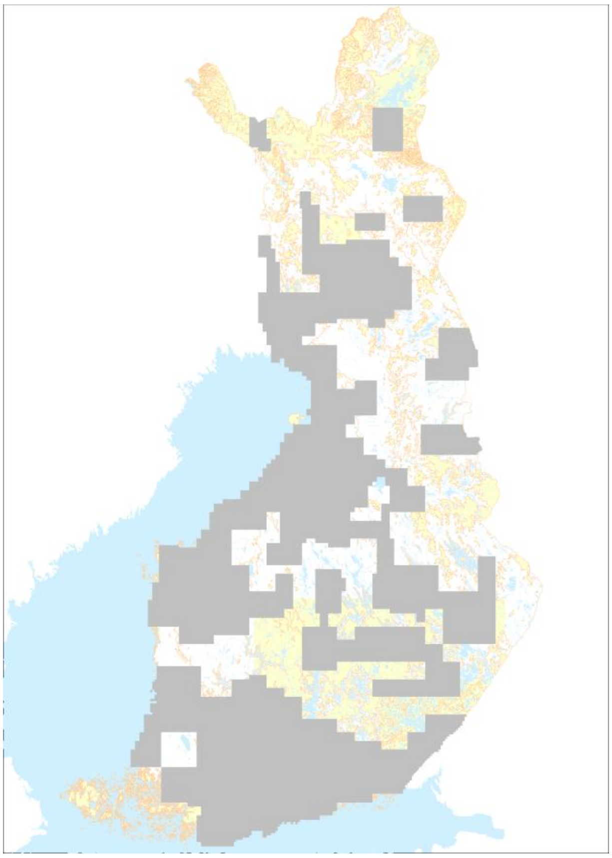

Figure 2.1. The status of the nationwide ALS collection in Finland in 2012. The scanned areas are marked in grey. Image courtesy of Heli Laaksonen, NLS.

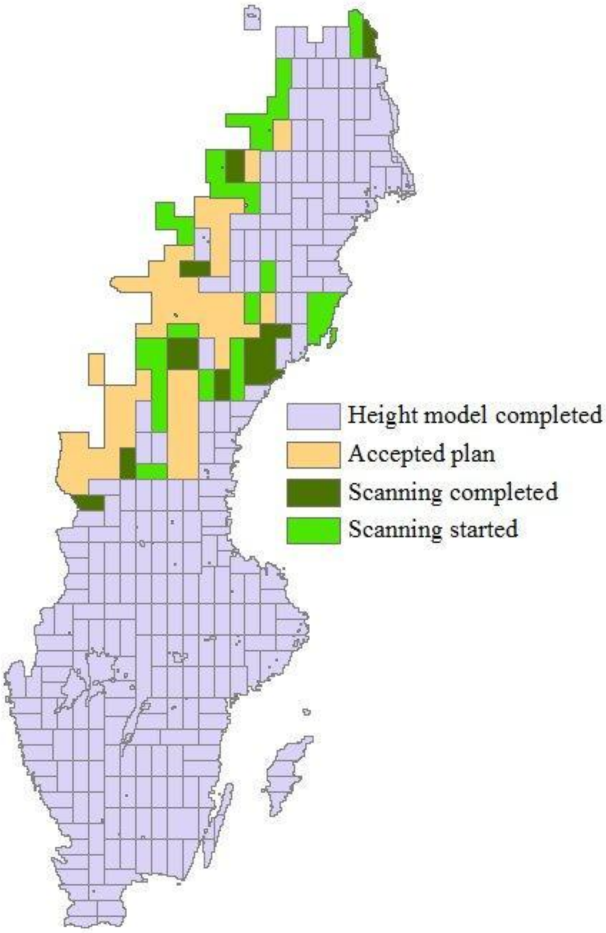


Figure 2.2. The status of the nationwide ALS in Sweden on November 8, 2012 (Lantmäteriet 2013). The scanned areas include the new height model areas (blue) and scanning-completed areas (dark green). The fell areas along the western border have a low scanning priority.

A number of factors impact on the quality of the airborne laser scanning derived DTM. These factors may be divided into four categories:

1. Errors caused by the laser system (instrument, GPS and IMU).
2. Effect of flight and scanning parameters. The collected data have various characteristics, namely first and last pulse, point density, flying altitude, and scan angle.
3. Effect of data processing and its parameters related to interpolation, filtering, break line detection, segmentation, and smoothing create errors.
4. Effect of target characteristics such as type of terrain, flatness, and canopy density.

**System errors** – Earlier studies of system errors have been published by Schenk (2001) and Crombaghs et al. (2002). Schenk (2001) modeled and analyzed systematic errors in airborne laser scanning. The error sources can be divided into laser scanning system errors (range and scan angle errors), mounting errors (laser scanner and GPS mounting error), INS errors, systematic GPS errors, errors in geoid normal, and time basis (synchronization and interpolation error). Crombaghs et al. (2002) assessed the height precision of laser DEMs and quantified the effects of different error components; errors per point, errors per GPS observation, errors per strip, errors per block. These include errors from measuring uncertainty, GPS, INS, and ground control.

**Effect of flight and scanning parameters** – Csanyi May and Toth (2007) have listed the various LiDAR system factors impacting on point positioning accuracy. Simulations have revealed that the standard deviation in elevation was 10 cm at 2000 m and 15 cm at 3000 m when the scan angle was 25º. Planimetric errors have been observed to increase more than elevation errors with increasing flight heights. Horizontal point positioning accuracy decreases more than vertical as the flying altitude increases. This happens especially when applying smaller scan angles. An Optech 3100 scanner was used in a study by Goulden and Hopkinson (2010). External error sources such as terrain and land cover were not included in this study. Simulations showed that when the flying altitude and scan angle are increased, horizontal and vertical random errors increase as well. Constant 3 cm horizontal and 5 cm vertical GPS errors were assumed in this study. Csanyi et al. (2007) presented a method for how to improve LiDAR data accuracy using LiDAR-specific ground targets that are circular in shape (radius 1 m) and elevated from the ground. Scan angle (10º and 20º) was one of the parameters to be studied. The test results showed that LiDAR data containing errors greater than 10 cm horizontally and 2-3 cm vertically can be detected and corrected with these targets. The flying altitude was about 700 m above ground level and the footprint size was 21 cm. Dense point clouds enable the delineation of linear objects, for example, from airborne laser scanner data on the ground. In the study by Zhou and Vosselman (2012) curbstones were detected and modeled from airborne and mobile laser scanner data. The flying altitude was 275 m above ground and the point density was 20 points/$m^2$. In the ALS data, the planimettric geometrical accuracy was as follows: extracted road sides, bias 0.06 m and standard deviation 0.09 m around this offset. The RMS value of the distances between the GPS points measured from the ground survey and the extracted road sides was 0.11 m in ALS data.

**Effect of data processing** – Sithole et al. (2004) tested the performance of bare-earth extraction filters provided by eight individuals or groups taking part in the ISPRS Working Group III/3 test. Axelsson (2000) developed a progressive TIN densification method, which is implemented into the Terrascan software. In addition, filtering methods have been studied; e.g., by Chen et al. (2007), Zhang et al. (2003, 2005), Kraus et al. (1998), and Shan et al. (2005).

**Effect of target characteristics** – The best time for ALS for DEM production has been found to be the leaf-off period in forested areas. Raber et al. (2002) studied the impact of leaf-on and leaf-off situations on the digital elevation models acquired with LiDAR. The leaf-off conditions were found to be more applicable to terrain mapping than leaf-on conditions. Reutebuch et al. (2003) got the following results under a conifer forest canopy. The mean DTM error was 0.22 ±0.24 m. The DTM elevation error for clear-cut tree canopy cover class was 0.16±0.23 m, for heavily thinned 0.18±0.14 m, for lightly thinned 0.18±0.18 m, and for uncut 0.31±0.29 m. According to Su et al. (2006), vegetation was the biggest error source in the LiDAR-derived elevation model and airborne laser scanning should be done in early spring or late autumn to reduce the effects of vegetation. Forest cover determines the accuracy of ALS ground points. In the boreal forest zone, random errors of less than 20 cm can be achieved in most conditions if the terrain is not steep and if the pulse density is greater than 2 points/$m^2$. The complexity and density of the forest are the most important factors when determining the accuracy of LiDAR surveys (Hyyppä et al. 2005).

Planimetric and vertical accuracy assessments of ALS measurements have been carried out in various ways. If accuracy better than 10-15 cm is needed, special attention has to be paid for organizing the measurement campaign. LiDAR-specific ground targets should be used. Then the vertical accuracy can be just 2 – 3 cm. One example is the mapping of a 1000 km segment of the San Andreas Fault using the Optech ALTM 3100 LiDAR in May 2005 (Toth et al. 2006). Using short GPS base lines, about 10 km spacing of reference stations, and 50% overlap of flight lines, white circular LiDAR-specific targets and profiles for ground control, a vertical accuracy of 3 cm was achieved between the LiDAR-measured and GPS-measured targets. The average horizontal coordinate differences were 7 cm to 12 cm, and the standard deviations were 18 cm along the X axis and 3 cm along the Y axis. Accurate identification of targets for LiDAR calibration and control measurements has been a problem and consequently the use of LiDAR-activated phosphors and infrared retro-reflectors has been studied by Anderson et al. (2010). These targets were clearly visible on the ground and could be separated from complex backgrounds. Vosselman (2012) investigated the automated planimetric quality control in high-accuracy ALS surveys. He verified the accuracy using the ridge lines of gable roofs in strip overlaps. This method gives results for the relative planimetric accuracy of the strips and there exists also the need for absolute accuracy assessment with ground-based control points. It was found that in 393 of 403 checked overlaps the theoretical maximum planimetric mapping error was ≤0.5 m. Moreover, in the case of 397 of 403 evaluated strip overlaps the systematic height error was less than 5 cm and the standard deviation was less than 5 cm. Höhle (2013) made an assessment of the positional accuracy ALS in urban areas. His method is based on the plane surfaces of building roofs, and they are derived from laser footprints. Three roof planes can be intersected to form a check point. The same points can be measured from digital aerial images. RMSE values of 53 check points in east, north, and height were 27 cm, 24 cm, and 14 cm. Articles of Höhle (2011) and Höhle et al. (2010) deal with the same accuracy assessment theme and use the original point cloud of the new DEM of Denmark. Ressl et al. (2008) presented an automatic method for checking the geometric accuracy of ALS points using statistics of strip differences. The difference of the DEMs of overlapping strips is computed. The 3D shifts on the overlapping area indicate the accuracy of ALS data in planimetry and height. So far only relative accuracy can be checked with their method.
Geodetic survey marks (with vertical accuracy of ±3 cm) have been used to assess the accuracy of LiDAR elevation data. Different methods were used to derive the elevations at the locations of the checkpoints. In open terrain, 80 check points gave an RMSE accuracy of 0.27 m for inverse distance weighting, 0.25 m for Kriging, 0.26 m for local polynomial, 0.27 m for TIN, and 0.29 m for nearest laser point. Optech ALTM 3025 data had an average point spacing of 2.2 m (Liu 2011). Vehicle-based VRS GPS observations for evaluating ALS height data have been used in two studies. Open field areas were excellent for this kind of mobile reference point measurement. The resulting 10 cm standard deviation of the laser points (random error), was about double that obtained when using static reference point measurements (Ahokas et al. 2008). The overall height differences (VRS-ALS) were ±5.9 cm (standard deviation) in the study by Dahlqvist et al. (2011).

It is difficult to compare various studies, because the parameters and scanner hardware used have been different. In simulations, measurement parameters can be selected and external effects (vegetation and terrain) can be neglected. In practical work it is normally possible to achieve vertical accuracies of 10 to 15 cm including GPS and IMU errors, which are the main factors in the error budget. When dealing with special targets, XY accuracies of 10 cm and 3 cm in Z can be achieved. In boreal forested areas, an accuracy of 20 cm can be achieved when the terrain is not steep.

### 2.3 Effect of scanning angle

The scanning angle and terrain slope also affect accuracy. The TopoSys airborne laser scanner was designed so that the scanning angle was fixed to ±7º off-nadir in order to minimize shadow formation at the borders of the scan (Lohr, 1997). It was also found that shadowing due to individual trees increases significantly when the scanning angle exceeds 5º. Holmgren et al. (2003) simulated the effects of LiDAR scanning angle on estimation of mean tree height and canopy closure. They found that the effect of the scanning angle is more evident in stands of spruce than in stands of pine. Simulations have shown that laser height percentiles and the proportion of canopy returns changed more with increased scanning angle for spruce when compared to pine. Alharthy et al. (2004) analyzed the vertical and horizontal accuracies of Optech ALTM 1210 data applying a flying altitude of 600 m and a point density of 1 point/m$^2$. The random errors in height were 20 cm. They found that the planimetric accuracy was 60 cm at the end of the swath width (=swath edge) and 30 cm in the middle of the swath, and that it varied along the swath width due to changes in the scanning angle. An Optech 2033 airborne laser scanner was used for data collection in the Sammatti area on June 29, 2004 in leaf-on conditions. The flying altitude was 2000 m and the scanning angle was ±15º. The classified ground point density was 0.2 points/m$^2$. The effect of the scanning angle was studied on agricultural field and forests. It was found that scanning angles up to 15º are usable in high altitude laser scanning in the boreal forest zone. However, the results appeared to be highly dependent on the density of the forest (Ahokas et al. 2005). Su et al. (2006) analyzed the influence of vegetation, slope, and LiDAR sampling angle on DTM accuracy. The mean DEM error was +0.02 m and RMSE was 0.59 m. Laser data were acquired using an Optech ALTM 2025 scanner. The flying altitude was about 1005 m and the measurements were made in leaf-on conditions. The LiDAR data densities varied between 0.28 and 1.35 points/m$^2$. The vegetation was found to be the biggest error source in the LiDAR-derived elevation model. Airborne laser scanning should be done in early spring or late autumn to reduce the effect of vegetation. It was noted from the RMSE values that DTM accuracy decreased when the slope gradient increased. The results of the off-nadir sampling angle part of the study indicate that minor differences in DEM error across the off-nadir angles may be due to slope differences. Off-nadir scanning angles should be less than 15º to minimize the errors resulting from high slope gradients. Also Hodgson et al. (2003) came to the conclusions that the mean absolute height error increased when the slope increased.

The effect of forest, penetration of pulses to the ground, and the scanning angle on the accuracy of ALS should be studied more.

### 2.4 Intensity

The term intensity has different meanings. In physics, it is the measure of the time-averaged energy flux. Also radiance is considered as intensity. In discrete return laser scanning, it is the recorded pulse echo amplitude or the peak power of the recorded echo. A technical note about intensity can be found in Katzenbeisser (2002). Intensity, reflectance, backscatter, brightness are also used side by side because scientists and engineers operating in the field of laser scanning represent different background disciplines. In this dissertation intensity is the received power as defined in the formula 2.2.

In general, the radiometric calibration of laser scanning intensity can be divided into relative and absolute calibration. In relative calibration, the measurements made applying different ranges, incidence angles, and dates are comparable for the same system. The following factors affect the received intensity: spreading loss (range), backscattering properties versus incidence angle, transmitter power changes (when pulse repetition frequency, PRF, changes), and atmosphere. In absolute calibration, the corrected value describes the target properties, and corresponding values obtained from various sensors are directly comparable to each other. In absolute calibration, the obtained and relatively corrected intensity values are linked with known backscattering coefficients or reflectance values of the reference objects.

Usually ALS data originate only from one source and from one time epoch, and consequently there has rarely been a need to compare the intensity values. However, the range to the target changes within one flight line due to scanning angle changes and due to the changes in altitude. These can be significant, especially in forest studies, where also the object height difference affects the intensity recorded. In the Swedish system TopEye these errors were already calibrated by the data provider before the laser scanning researchers became aware of the issues.

Prior to this work (Publication V), Lutz et al. (2003) constructed a model that included intensity, surface type and elevation, and scan geometry. The effect of each factor was examined. Cross-path fading of intensity can be eliminated using modeling and the remaining intensity variation correlates with range, surface elevation, and class. Luzum et al. (2004) normalized Optech ALTM 1233 intensity values by correcting the effects caused by variations in path length. This was done by dividing the observed range squared with the standard range squared. Hasegawa (2006) found in his study that intensity is inversely proportional to angle and distance, but their relation did not fit in with the theoretical model. This study involved both ground and aerial surveys (Optech ALTM 2050DC) with distance and angle experiments and adaptability of the reflection model. The intensity characteristics of the surface classes were determined. Donoghue et al. (2006) used a linear regression correction for intensity and range. The range difference in the test area was about 70 m.

More recent developments in intensity calibration are discussed in Chapter 5. Also the usage of intensity is discussed there.

## 3. Material and methods

A summary of the laser scanners/equipment, study areas, reference data, and statistical methods is presented in Table 3.1. The details of the data and methods are presented in each publication.

Table 3.1. A summary of the equipment, study areas, reference data, and statistical methods used.

| Publication | Measurement device/scanner | Study area/ target | Reference data | Statistical method |
|---|---|---|---|---|
| I | Toposys Falcon 400 m, 10 points/$m^2$ May, 2003 | Espoonlahti in Espoo, 4 km x 0.1 km | Robotic tachymeter Trimble 5602 DR200+ 4500 points, vector building map 58 roof corner points, Leica SR530 RTK | Min. 5 laser points in ref. circle, mean, median, min, max, st. dev., nearest point, 10x10$cm^2$ grid for interpolation |
| II | Faro Photon 80, 3, 5, 7, 9 m | FGI building lobby | Weighting of biomass | Two factor ANOVA, F statistics |
| III | Leica ALS50-II. 400 m, 16-17 points/$m^2$ for all points, 10-14 points/$m^2$ in the middle of swath, July 2009 | Evo in Hämeenlinna, 2000 ha | Trimble GEOX M 2005 GPS for plot centers, Plot radius 10 m, 246 field plots, tree heights, DBH, stem volumes | Multiple regression analysis |
| IV | Small angle goniometer, laser, CCD camera | Brightness targets | Spectralon reference plate | |
| V | Optech 3100, 200, 1000, 3000 m, 0.08-0.2 points/$m^2$, 0.8-1.2 points/$m^2$, 5.2-6.8 points/$m^2$, July 2005 | Sjökulla test field in Kirkkonummi, 5x40 $m^2$ | 8 portable brightness ref. targets | Regression analysis |
| VI | Airborne sensors | Sjökulla test field in Kirkkonummi | GPS, targeted benchmarks, Spectrogoniometer, permanent and portable targets | |
| Ahokas et al. (2008) | Optech 3100, 1900 m, 0.7 points/$m^2$, December 2006 ALS50-II, 2200 m, 0.5pts/$m^2$, 4750 m, 0.15points/$m^2$, April 2007 | Salo, >1000 $km^2$, road no. 52 Perniö-Salo, no. 186 Salo-Kisko, no. 1870 Kisko-Kitula, about 40 km, | Mobile VRS Leica SR530 RTK, >1400 points, 251 points, May 2007, RTK GPS +tachymeter, 87, 135, 404 points, 2003, 2007 | |

# 4. Results

## 4.1 Repeated ALS observations (Publication I)

This paper describes the height and planimetric errors of repeated high-density ALS (airborne laser scanning) strips with a more pronounced focus on building extraction. The measurements with Toposys Falcon airborne laser scanner were arranged in May 2003 in Espoo, southern Finland. A test area 5 $km^2$ in size, consisting of urban settlements and forests, was accessed for data collected from an altitude of 400 m applying a measurement density of about 10 points per square metre.

One strip 4 km long and about 100 m wide was accessed for data collected five times allowing the analysis of the repeatability of laser scanning. One strip was used as a reference and inter-strip comparisons were made. Point-wise comparison methods were also used to characterize the differences. Additionally, target models were compared to each other. Real Time Kinematic (RTK) GPS and also tachymeter measurements were used as ground reference values. The extraction of building vectors from laser scanner data was performed using interactive methods implemented in the TerraScan software. As an example, Figure 4.1 shows first pulse laser points of flight strip no. 3 and the extracted buildings.

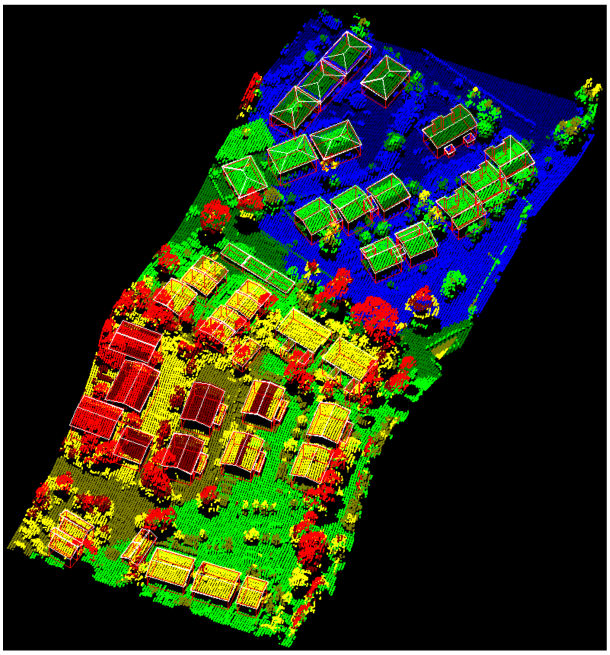

Figure 4.1. A rotated oblique view of flight strip no. 3 (first pulse) laser points and the extracted buildings.

The mean height errors for the elevation points varied between –2 cm and +1 cm and the standard deviations were mainly ±3-4 cm. In plane, the mean differences of the center points of the buildings were less than 30 cm for the first and also for the last pulse data when compared with the buildings shown on the map. The standard deviations varied between ±11-28 cm (first pulse) and ±14-18 cm (last pulse) for the extracted buildings using repeated observations. The mean errors were between 3-8 cm and standard deviations ±3-6 cm using last pulse data of repeated observations and extracted ridge information. The planimetric accuracy of an object (building) on the ground depended on

the direction of the flight. There was an along-the-track shift of about 5 cm with respect to the flight direction.
The first pulse mode observations tended to exaggerate the area and the lengths of the roofs. The first pulse data gave about 11-14% larger building roofs than the last pulse data. The roof lengths were about 21 cm longer based on the first pulse data than in reality. Correspondingly, the last pulse mode yielded underestimated results. The lengths were about 25 cm shorter than the obtained reference measurements. These systematic effects need to be accounted for, e.g. in cartographic applications. The quality assessment showed that the accuracy of the laser points is good enough for high quality ALS products beyond the elevation models.

### 4.2 Quality checking of the ALS-based elevation model

Ahokas et al. (2008) described different aspects of quality checking of the ALS-based nationwide elevation model and the main material of this study is presented here. The National Land Survey of Finland (NLS), in co-operation with the Finnish Geodetic Institute had a more than 1000 km$^2$ practical test on using ALS for the new nationwide elevation model and its quality checking in late 2006 and early 2007. The objectives of the test and study were:
a) to define the elevation quality of ALS flights from two point densities 0.5-1 and 0.1 points per square metre resulting in two flight altitudes about 2000 m and 5000 m using the Leica ALS50-II and scanning angle of ±20 degrees,
b) to compare the quality derived with two different sensors (Optech ALTM 3100 and Leica ALS50-II),
c) to define the quality of ALS derived DEM in various surface types,
d) to analyse the planimetric errors of ALS surveys, and
e) to develop and test practical methods to derive ground reference data effectively for large-area ALS collection.

As a preprocessing phase strip adjustment for the ALS data was done with the TerraMatch software at the FGI.
Reference points were measured in the following way. In addition to the RTK GPS terrain elevation measurements for various land cover types in open environment, tachymeter measurements were made in the forests. The RTK GPS have been used for the starting point measurements for tachymeter in the areas where benchmarks were not available. These ground reference point measurements were made in 2003 and 2007. Xy-reference points for planimetric accuracy estimation were measured with Leica SR530 Real Time Kinematic (RTK) GPS. To cover the ALS Salo test area with terrain elevations on hard targets mobile VRS RTK measurements were made on May 24, 2007. A GPS antenna was assembled on the roof of a van. Co-ordinates were registered every 2 seconds which corresponded to 20 to 30 m point distance depending on the speed of the car. More than 1400 points were measured during the day. According to Häkli (2004) the RMSE of VRS RTK is 2 cm in xy and 4 cm in z. Bilker and Kaartinen (2001) give RMSE accuracies 1 cm + 1-2 ppm in xy and 2 cm + 2 ppm in z in their RTK GPS report.
The comparison between the observations and reference points was made as follows. Laser points were selected so that the reference point and the compared laser point were within 0.5 m distance from each other. To increase the amount of compared points also distance less than 1 m was used for comparison. If there were one or more laser points within the predefined distance (e.g. 50 cm) from the reference point the nearest laser point was selected and the height difference between the laser point and the reference point was

calculated. In the earlier study of Ahokas et al. (2003), it was found that the interpolated height value, mean height value and the nearest laser point height value gave about the same height results in the comparison analysis.
The obtained vertical accuracy in all surface classes was better than the required 30 cm of the new 2 x 2 $m^2$ grid model. The vertical accuracy of nonambiguous planar surfaces was better than 15 cm. The obtained horizontal accuracy (StD) was 0.35 m for Optech and 0.34 m for Leica. The presented mobile VRS RTK measurement system is an effective and sufficiently accurate way to gather ground reference points from large areas using the roads within the scanned area. The standard deviation in Z was 0.11 m using 251 reference points and with a search circle radius of 1 m. Despite this, levelling and static reference point measurements have their justification where greater accuracy is required. Black asphalt roads do not reflect the laser pulses well enough back to the scanner, and thus there are holes in the distribution of laser points on this kind of surface. The elevation accuracies for the various land cover classes are indicated in Tables 4.1, 4.2, and 4.3.

Table 4.1. Optech ALTM 3100, 0.7 points/$m^2$, H=1900 m. Height accuracies in (m). Search radius R<50 cm. The number of reference points was 135.

| Type | Bias | StD | RMSE | Ref. points |
|---|---|---|---|---|
| Asphalt | -0.07 | 0.08 | 0.10 | 24 |
| Diverse open land | 0.06 | 0.07 | 0.09 | 23 |
| Rock | -0.01 | 0.08 | 0.08 | 28 |
| Forest | 0.03 | 0.12 | 0.12 | 38 |
| Field | 0.11 | 0.05 | 0.11 | 13 |
| Gravel | -0.02 | 0.05 | 0.05 | 9 |

Table 4.2. ALS50-II, 0.5 points/$m^2$, H=2200 m. Height accuracy in meters (m). Search radius R<50 cm. The number of reference points was 404.

| Type | Bias | StD | RMSE | Ref. points |
|---|---|---|---|---|
| Asphalt | 0.06 | 0.04 | 0.07 | 20 |
| Diverse open land | 0.14 | 0.05 | 0.15 | 17 |
| Rock | 0.01 | 0.13 | 0.13 | 65 |
| Forest | 0.08 | 0.17 | 0.19 | 258 |
| Field | 0.10 | 0.03 | 0.11 | 16 |
| Gravel | 0.06 | 0.08 | 0.10 | 28 |

Table 4.3. ALS50-II, 0.1 points/$m^2$, flying altitude 4750 m. Height accuracy after strip adjustment is in meters (m). Search radius R<1 m. The number of reference points was 87.

| Type | Bias | StD | RMSE | Ref. points |
|---|---|---|---|---|
| Asphalt | -0.06 | 0.06 | 0.09 | 12 |
| Diverse open land | 0.01 | 0.14 | 0.12 | 5 |
| Rock | 0.00 | 0.23 | 0.22 | 10 |
| Forest | 0.02 | 0.18 | 0.18 | 53 |
| Field | -0.01 | 0.14 | 0.12 | 5 |
| Gravel | 0.04 | 0.01 | 0.04 | 2 |

The obtainable accuracy of points in Table 4.3 is also high, but the number of points hitting the ground is only 0.1 points/$m^2$ and interpolation plays a role in the quality of the DTM. The accuracy of the mobile measurements was estimated by measuring 51 static reference points with VRS-RTK GPS (Table 4.4).

Table 4.4. The accuracy of mobile VRS-RTK points. Mobile – static reference point comparison. The number of static reference points was 51.

| | |
|---|---|
| Mean difference in Z | -0.004 m |
| Standard deviation | 0.036 m |
| Max. positive difference | 0.118 m |
| Max. negative difference | -0.063 m |

It can be said that the mobile reference point measurement system yields sufficient accuracy for quality and gross error checking of ALS measurements. The obtained elevation accuracies for the various land cover classes showed that accuracy of 15 cm required by nationwide ALS for laser points can be achieved for well-defined surfaces. Also, mobile measurements can be used as reference values.

### 4.3 Laser beam transmittance (Publication II)

This paper describes the effect of biomass and scanning angle on TLS laser beam transmittance. In order to better understand the effect of the biomass and scanning angle on the penetration rate of ALS signal through the forest canopy and to obtain further support for ALS research, especially for scanning angles beyond 15º of the nadir point, we conducted an indoor experiment using small spruce trees (*Picea abies*) to represent the forest canopy. The indoor experiment enabled us to accurately measure the biomass reference values. We applied manual thinning to produce various levels of biomass and a scissor lift as the carrying platform for the laser. The weight of every tree and the total biomass of the trees after each thinning phase were measured. We removed the material evenly from the trees, starting from the newest shoots. We used a FARO laser scanner in the experiment and attached it to the scissor lift. Where the continuous, multi-wavelength amplitude-modulated beam hit multiple targets, the measurement range was not well-defined. The ALS is typically a pulse-based system, which produces multiple returns. The phase-shift-based system can be used to approximate the penetration rate of the ALS pulse-based system, since ground return does not exist where several hits are encountered. Thus, the phase-shift-based system gives a lower bound (worst case scenario) for the penetration rate than the pulse-based system does. Unfortunately, any simultaneous experimental comparison could not be organized to verify this lower bound statement about pulse-based and phase-shift-based systems. Transmittance and the biomass of each thinning phase are shown in Table 4.5.

Table 4.5. Transmittance T as a percentage of the laser beams reaching the ground from four altitudes. Minimum and maximum scanning angles in degrees.

| Biomass (kg), thinning phase | T(%), 9 m, 6°-15° | T(%), 7 m, 8°-19° | T(%), 5 m, 11°-26° | T(%), 3 m, 17°-38° |
|---|---|---|---|---|
| 24.84 (th0) | 1 | 1 | 1 | 2 |
| 19.76 (th1) | 5 | 5 | 5 | 6 |
| 13.88 (th2) | 31 | 28 | 23 | 20 |
| 8.76 (th3) | 90 | 89 | 86 | 82 |
| 5.68 (th4) | 95 | 94 | 93 | 91 |
| 0 (th5) | 100 | 100 | 100 | 100 |

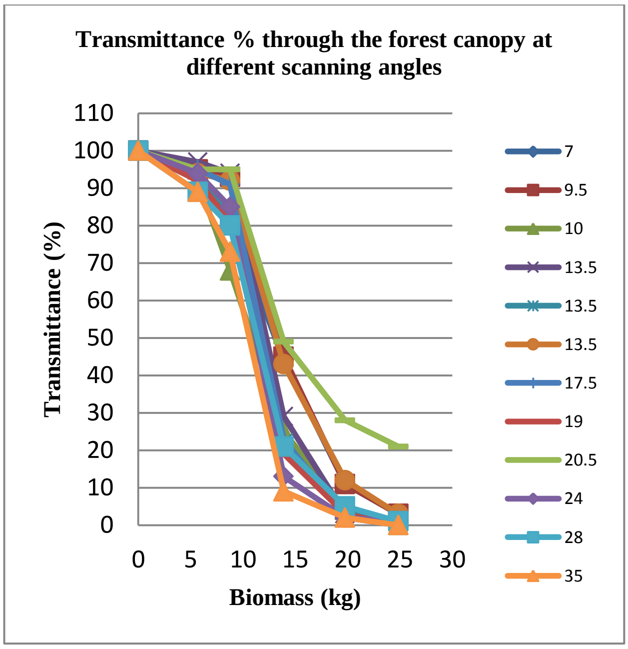


Figure 4.2. Transmittance through the forest canopy at different scanning angles (varying between 7º and 35º). We stratified the scanning angles into three groups for each height. The angle value presented is the mean value of each part.

The results show that the laser beam transmittance through a canopy formed by the crowns of small spruce trees is a non-linear function of biomass. The scanning angle has only a minor effect on the results when compared to changes in the biomass. A dense canopy causes deterioration in the transmittance of the pulses to the ground, and thereby in the accuracy of the elevation model. Scanning angles up to 38º proved feasible for elevation mapping in this indoor experiment. As a conclusion drawn from this, nationwide scanning projects of open areas should be conducted using as wide a scanning angle as possible.

## 4.4 Laser beam transmittance, Evo experiment (Publication III)

The transmittance of ALS laser pulses through the forest canopy was studied in this paper as a function of forest attributes (inventory parameters) and the scanning angle. Here transmittance is defined as the ratio between the number of pulses within a threshold of the detected elevation model versus the total number of transmitted pulses. Laser scanning using a Leica ALS50-II scanner took place on July 25, 2009, in the Evo test area in Southern Finland. The total number of field test plots was 246. Some of test plots were observed from different flight lines, and this resulted in 454 observations. Multiple regression analysis was applied to calculate the coefficient of determination ($R^2$) for the mean observation angle and for the forest attributes, such as mean height, mean diameter, basal area, and stem volume. Transmittance through the canopy to the ground as a function of stem volume is illustrated in Figure 4.3. Experience has shown that the canopy layer dominates and, in practice, determines the number of ground hits. When using scanning angles between 0º and 15º in forested areas, the scanning angle does not have a statistically significant effect on vegetation penetration nor on the number of ground hits. It appears to be feasible to increase the scanning angle in elevation modeling in boreal conditions if some degree of local shadowing is accepted in the data. Nevertheless, we do not know by how much the scanning angle can be increased.

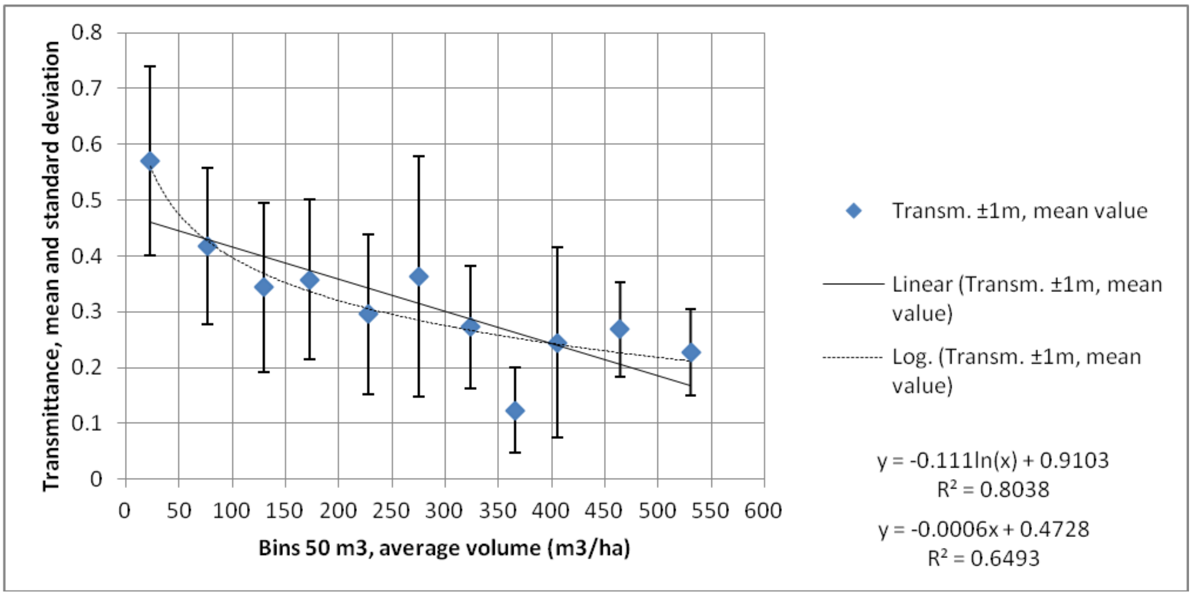


Figure 4.3. Transmittance through the canopy to the ground as a function of stem volume. Ground tolerance level ±1.0 m.

### 4.5 Surface brightness from intensity: Calibration of laser data (Publication IV)

The directional properties of eight portable brightness calibration targets (Figure 4.4) were investigated in this paper with the intention of calibrating laser scanner intensity and also to study the physics of light backscattering. Knowing the reflectance properties of brightness targets is a prerequisite for their use in accurate intensity calibration. The emphasis was on studying the phase angle. The measurements were made using a small angle goniometer. It is known that there is a strong increase in brightness toward the 0 phase angle. The measured phase curves at 1064 nm imply that the nominal (reflectance) values can be observed at about 2º-3º phase angles. Surface brightness has a clear effect on the peak amplitude and width of backscattering.

When considering airborne laser scanning, it was important to note that the variability of the recorded intensity from the brightness targets as a function of angle of incidence was small and that it is possible to use the targets as brightness references. The wavelength of 1064 nm is equivalent to that used in Optech and TopEye airborne laser scanners and thus the results are valid for these scanners. The results confirmed the usefulness of the tarps for radiometric calibration of intensity.

Figure 4.4. Targets at the Sjökulla photogrammetric test field in Kirkkonummi arranged for a digital aerial camera test to represent 5%, 10%, 20%, 25%, 30%, 45%, 50%, and 70% reflectance. Photo taken on October 4, 2004 by H. Kaartinen.

### 4.6 Calibration of the Optech intensity data (Publication V)

In this paper, the calibration of Optech ALTM 3100 laser scanner intensity data was reported using airborne experiments and known brightness targets. FGI’s permanent test field in Sjökulla includes permanent and transportable test targets for radiometric calibration, permanent ground control points for small, medium, and large-scale geometric calibration and also test bar targets for spatial analysis of analogue and digital aerial cameras. The Optech ALTM 3100 campaign was carried out during the period 12-14 July, 2005. Eight portable brightness targets with reflectance of 6.5%, 11.5%, 23%, 29%, 36%, 53.5%, 65%, and 90% were used in intensity calibration. The flying altitudes were about 200 m, 1000 m, and 3000 m.

The intensity values were corrected with respect to range, atmospheric transmittance, and attenuation using dark object addition and transmitted power (because the difference in PRF leads to different transmitter power values). After these corrections, the intensity values were directly relative to target reflectance (Figure 4.5).

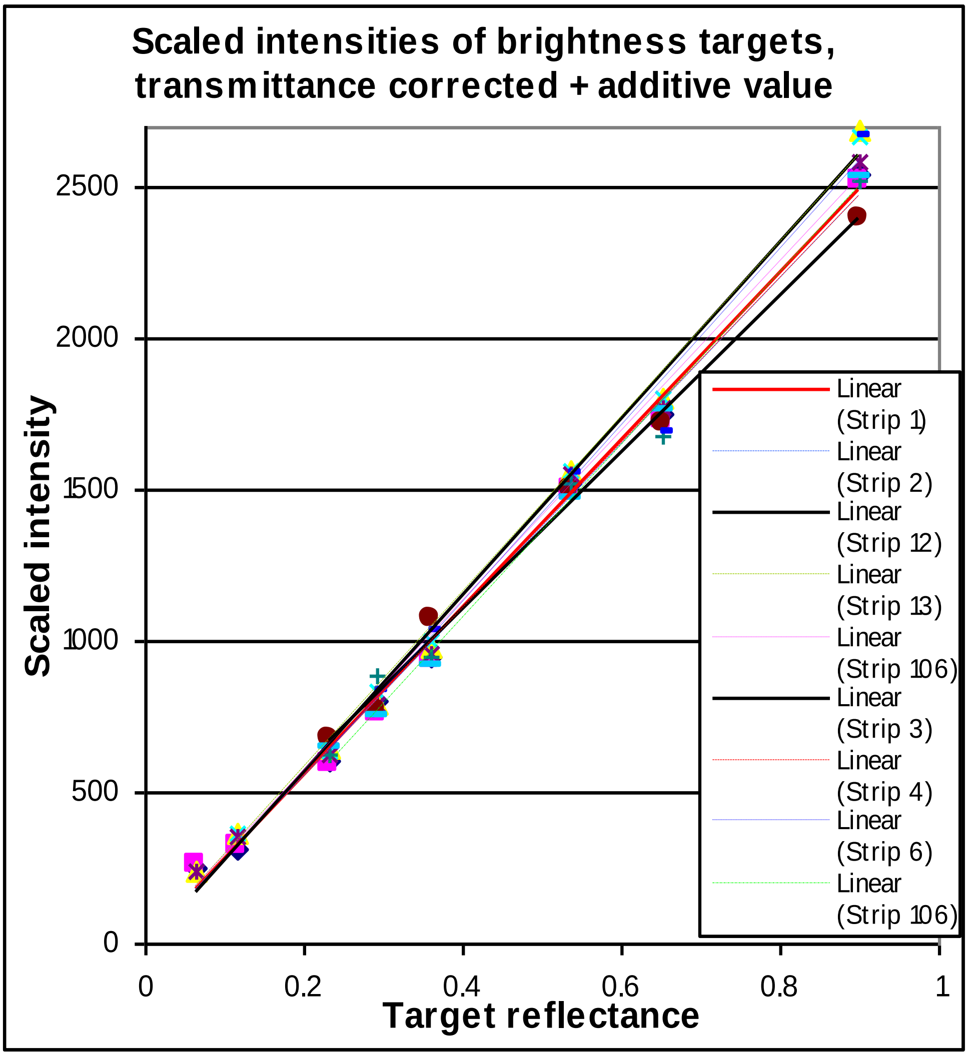


Figure 4.5. Intensity values corrected for atmospheric transmittance and additive values from regression lines. The corrected intensity values from H=200 m Strips 1 and 2, H=1000 m Strips 12, 13, 106, and H=3000 m Strips 3, 4, 6, 106 coincide very well.

The flight altitudes of 200 m and 1000 m were suitable for intensity calibration using artificial test targets due to the practical aspects of calibration (the size of the calibrator). Signals with reflectances of less or equal of 10% could not be obtained (neither recorded due to insufficient signal-to-noise ratio nor reduced in the pre-processing phase) when flying at 3000 m altitude.

This was the first time when the entire calibration process was carried out starting from the principles of radar equation. Absolute calibration was possible using the external reference targets with known attributes.

When conducting nationwide laser scanning, the relative calibration of intensity can be done according to the principle presented in Publication V

$$I_{corrected} = I_{raw} \cdot \frac{R_j^2}{R_{ref}^2} \cdot \frac{1}{\cos\alpha} \cdot \frac{1}{T^2} \cdot \frac{E_{Tref}}{E_{Tj}} \qquad (4.1)$$

The absolute calibration of the intensity can be done according to the formula

$$\rho_{abs,cor} = \frac{I_{corrected}}{I_{cor,calib.target}} \cdot \rho_{calib.target} \tag{4.2}$$

Where $I_{raw}$ is the original intensity value, $R_j$ is the slant distance (flight line j), $R_{ref}$ is the reference distance, α is the angle of incidence, $T$ is the total atmospheric transmittance, $E_{Tref}$ is the transmitted reference pulse energy, $E_{Tj}$ is the transmitted pulse energy along flight line j, $I_{cor,calib.target}$ is the corrected intensity value of the calibration reference target, and $\rho_{calib.target}$ is the reflectance of the calibration reference target. $\rho_{abs,cor}$ is the reflectance of the target.

### 4.7 Sjökulla test field (Publication VI)

This paper describes the Sjökulla test field, its construction, and its spectral properties. The Finnish Geodetic Institute established this permanent test field in 1994 for geometric, radiometric, and spatial resolution calibration purposes. High resolution satellite and aerial imaging systems as well as laser scanners have been tested there. Permanent resolution and reflectance targets made of gravel are among the characteristics of this test field (Figure 4.6).

Figure 4.6. The Sjökulla test field before the renovation of areas 2) and 3). 1) Permanent dense spatial resolution target, 2) Permanent grey scale, 3) Permanent large reflectance areas, 4) Sparse resolution bar target, 5) Permanent circular targets, 6) Portable Siemens star, 7) Portable grey scale/brightness target.

The test field has provided facilities for airborne laser scanning testing since 2000 (e.g., Ahokas 2001) and there is room for additional equipment to better serve the ALS community in this subject area. The geometrical test field with targeted benchmarks can be used also for testing the geometrical accuracy of airborne laser scanning. The circular white targets with black background are 0.3 m and 0.4 m in diameter. They are made of painted plywood.

Although manufacturers conduct their own laboratory calibration and field testing, field testing and calibration of the entire airborne digital sensor system after installation has to be done annually by the user and the Sjökulla test field is very useful for this purpose.

## 5. Discussion

### 5.1 Accuracy assessment of nationwide laser scanning

In Finland, the height accuracy specifications of laser points and of the national 2 x 2 $m^2$ grid DEM were set to 15 cm and 30 cm and these accuracy limits can be achieved. Publication I also confirms that the planimetric accuracy of ALS is suitable for various applications. It is driven by the IMU characteristics and flying altitude. Thus, the results of Publication I can be transferred to other flying altitudes.

The accuracy assessment of nationwide laser scanning needs improved tools. Using VRS GPS for this purpose is one possibility. In the study by Kaartinen et al. (2012), it was found that 1-2 cm accuracy (std) in elevation can be reached up to a range of 35 m with the best MLS (mobile laser scanning) systems, and that planimetric accuracy in good GNSS conditions is 2-4 cm. Since the GNSS solution causes the biggest error in MLS and therefore the accuracy assessments of Ahokas et al. (2008) (VRS GPS) and Kaartinen et al. (2012) are also comparable, it seems that mobile laser scanning is an effective technique also for application in nationwide laser scanning. Mobile laser scanning can create an accurate point cloud usable in both planimetric and elevation accuracy assessments. Currently, FGI is developing a national test field for ALS using also MLS.

### 5.2. Increasing scanning angle in nationwide laser scanning

Next I proceed to examine the circumstances from the point of view of nationwide laser scanning with enlarged scanning angles and calibrated intensity values.

The accuracy requirements of nationwide laser scanning in Finland as regards elevation accuracy (15 cm) make it possible to increase the scanning angle. Widening the scanning angle from the present ±20º to ±36º will result in a swath width that is double compared to the one with a ±20º scanning angle. Also, the simulations of Goulden and Hopkinson (2010) showed that the remaining height error (5 cm constant GPS error excluded) at 2000 m AGL flying altitude will be less than 10 cm with a scanning angle of 25º. Another method of increasing the swath width is to fly above 2500 m but this is not advisable. Dark objects (reflectance less than 10%) do not reflect laser pulses back to the sensor well enough from altitudes higher than about 2500 m. Holes in the laser data sets appear over asphalted streets and dark roofs. Low point density on the ground makes also the classification process more labor-intensive. The suggested flying altitude for nationwide laser scanning is, thus, between 2000 m and 2500 m as it has been to date. The results in this dissertation are based on the data of the commercial airborne laser scanner systems that present the technology of today and the statements are true in this context. In the future, ALS systems may be designed so that they can be used in higher altitudes than today. When the laser output power is limited it is recommendable to use wider scanning angles instead of higher flying altitudes to increase the swath width. This can be concluded from the fact that the degradation of the slant range accuracy follows $\sigma_{R \sim R}{}^2$ ($\sigma_R$ is the slant range R standard deviation) for pulse-based systems (Wehr 2009).

The forests in Northern Finland are sparse and there are open areas such as mires and fell areas. In Southern Finland shadowed areas inevitable increase as a result, but the 20% strip overlap compensates for this situation. The scanner technology enables FOV values of 50º to 75º and so ALS service providers can increase their FOV values for nationwide ALS if the NLS specifications allow. Airborne imaging could be combined with ALS if the ALS scanning angle were larger, e.g., the Leica ADS80 has a FOV of 64º cross-track. Simultaneous aerial imaging provides visual data for checking the classification result of laser points.

Nowadays, with ALS data being subcontracted from companies with national specifications, this results in costs of 15-50 cents per hectare depending on the size of the contract. In Sweden, the value of the contract was 28 cents/ha with the contract covering the whole of Sweden. Even though the elevation model accuracy under Finnish conditions allows increasing the scanning angle, the accuracy of other applications would most probably deteriorate. For example, the same data are sometimes used for forest inventory. When using area-based features in the forest attribute estimation, it can be expected that the accuracy of inventory results will deteriorate when there are scanning angle differences within the data. The area-based feature approach uses attributes such as, canopy density percentiles, which change with changing scanning angles. Also, change detection capabilities and other application potentials may deteriorate when the scanning angle is made larger. These are matters deserving more research.

### 5.3. ALS intensity calibration

Intensity is an essential feature of ALS data. Nationwide laser scanning in Finland also includes intensity values, but their further processing is lacking. The future use of intensity values is, thus, possible if needed one day. Intensity provides backscattering information on the surface reflecting the laser pulses. The degree of intensity is influenced by the distance to the target, the angle of incidence, the reflectance of the target, the atmosphere, the transmitted pulse energy, the receiver noise and changes in sensitivity, the laser speckle, the wavelength, the pulse width, and the surface geometry of the target. In the literature, the articles dealing with intensity can be divided into three main categories; namely, geometry, classification, and calibration.

Intensity values provide additional visual information about the **geometry** of laser points. Even though the geometry does not in itself need intensity calibration, calibrated intensity values may help in identifying the objects. Intensity values have been used to determine shifts in planimetry between ALS flight strips (Burman 2000 and Maas 2001). Maas (2002) explained a combination of height and reflectance data matching for measuring height and planimetric discrepancies in ALS data. Georeferenced intensity values are useful on flat areas where planimetric shifts can be revealed between adjacent flight strips. The intensity values of a 25 kHz laser scanner were used as an aid in co-registering laser data with hyperspectral data (Mundt et al. 2006).

In the **classification** application, intensity is used separately or as an additional channel/parameter in the process. The following articles deal with cases where intensity correction was not applied. In their study, Song et al. (2002) assess the possibility of land cover classification using LiDAR intensity data. A Riegl scanner with 900 nm laser was used in the separation of four land cover classes (asphalt, grass, roofs, and trees). The intensity values for asphalt vs. grass and asphalt vs. trees classes were separable, but the separability of asphalt vs. roof and grass vs. trees was very low. Non-normalized and noisy intensity data hampered this study. Farid et al. (2006) used small footprint LiDAR data to differentiate between young, mature and old cottonwood trees in Arizona, United States. The instrument used was an Optech ALTM 1233 and the data was preprocessed onto a two-band image, one band containing a high accuracy canopy altitude model and the other band a near-infrared intensity image. An algorithm for maximum likelihood was used in the supervised classification of the cottonwood age categories. The overall classification accuracy was 78%. It was concluded that the merging of high spatial resolution multispectral data and LiDAR data could improve classification results. In Lovell et al. (2003), tree gap and cover information was derived from intensity values using them as additional predictors. Intensities were used to separate the data to obtain vegetation and ground classes by assuming that the instrument intensity response was linear. The ratio of reflectance of vegetation to ground is one parameter in the gap probability calculation. The sources of error in the results were the possible nonlinearity or range dependence in the intensity calibration. Jonas (2002) dealt with some applications using the intensity values of ALS. It was found that the accuracy of ALS data could be improved using common features in the overlapping laser strips. Also, the intensity values could be used for classification of laser points because the height information is not always sufficient to delineate features. In the study by Morsdorf et al. (2010) height and intensity data were used to discriminate between three different vegetation strata in a multi-layered forest in the Mediterranean region. Kim et al. (2009), Brandberg (2007), and Ørka et al. (2007) used intensity values in tree species classification. Ground surface classification with the aid of intensity values has been used by Brennan and Webster (2006) and Yoon et al. (2008).

Tree species classification using ALS intensity data can be found also in Holmgren and Persson (2004). They reported high degrees of accuracy for tree species partly the outcome of using correctly range-calibrated ALS intensity data (TopEye).
Since the release of Publications IV and V, the usage of intensity and its **calibration** have been studied in some articles. Coren et al. (2006) generated pseudo-reflectance surface maps by carrying out a radiometric calibration of the Optech ALTM 3033 laser scanner amplitude (intensity) data. The authors' intention was to determine the backscattering of the laser footprint on the ground. The slope and reflective properties of the surface were not taken into account. These pseudo-reflectance maps have been used to classify targets.

Methods of intensity calibration have been also presented by Wagner et al. (2006), Höfle and Pfeifer (2007), Höfle et al. (2007), Kaasalainen et al. (2008, 2009a,b,c, 2011). Korpela (2008), Korpela et al. (2008, 2009, 2010a,b), Kukko et al. (2008), Jutzi and Gross (2009), Vain et al. (2009, 2010), Gatziolis (2011), and Hyyppä (2011).

Wagner et al. (2006) used the Gaussian decomposition technique for processing and calibrating complete waveform data produced by a RIEGL LMS-Q560 airborne laser scanner. Range, amplitude, and pulse width were used in the calibration equation to produce a cross-section of the backscatter. Höfle and Pfeifer (2007) used two methods for correcting intensity data. Data-driven correction uses homogeneous areas to estimate parameters for the global correction function that accounts for all range-dependent effects. Model-driven correction uses the physical principles of radar systems and corrects each intensity self-sufficiently. Höfle et al. (2007) used ALS point clouds as well as intensity values for glacier surface segmentation in the Austrian Alps. The correction procedure accounted for spherical loss, and topographical and atmospheric effects. The intensities were normalized to a range of 1 km and a Lambertian scattering on the surface was assumed. Kukko et al. (2008) investigated the effect of the angle of incidence on laser scanner intensity. They found that the decrease in target brightness is significant mostly at angles of incidence >30º. The effect is stronger for bright targets. Korpela (2008) used the distance normalized intensity values for mapping ground surface lichens. Normalization improved the accuracy of the classification. Korpela et al. (2008) studied the potential for combined use of airborne LiDAR and digital imagery in the classification and measurement of common seedling stand vegetation. Range-normalized intensity was a strong explanatory variable. In the research of Korpela et al. (2009), the distance normalization factor was $R^{2.5}$ which was a compromise between the power of 2 for large areas and the power of 3 for linear scatterers. Without intensity correction, the internal standard deviation of classes was 10-15% greater than after distance normalization. In the two studies by Korpela et al. (2010a,b) Optech ALTM 3100 and Leica ALS50-II sensors were used and range normalization and the effects of automatic gain control (AGC) were examined. Good classification results were obtained also without AGC correction Korpela et al. (2010b). Jutzi and Gross (2009) normalized the intensity data based on the method using range and surface angle of incidence. Also, the atmospheric attenuation was estimated. Kaasalainen et al. (2009c) studied the topographic (angle of incidence) and distance effects in laser scanner intensity correction. The cosine correction worked reasonable well for most surfaces. The ALS scanning angles went up to 22°. Radiometric calibration with reference targets was studied in Kaasalainen et al. (2009a,b). Hyyppä (2011) presented a summary of intensity calibration of laser scanning and of the conclusions presented in the EuroSDR (European Spatial Data Research) project "Radiometric Calibration of ALS Intensity". Overlapping strips and the corresponding intensity values have been found to be useful for minimizing data variation, and the constants of the intensity correction formula can be determined (Gatziolis 2011).

The calibration of the ALS intensity values was not the primary objective in the field of ALS research when the work on this thesis was launched. Even though intensity values have been utilized to some degree, the radiometric calibration of intensity is still in its pre-utility phase. Not even the spreading loss (distance) effect has been corrected. The TopEye system performs automatic range correction for the intensity data provided to the customer, but other systems do not. Thus, there was a need to develop radiometric calibration methods for ALS intensity data.

Intensity calibration at the NLS does not exist at the moment. A nationwide calibrated ALS intensity data set could be used for land cover classification. It could provide information on the reflectance properties of targets and possible time series in the form of updates augmenting our historical knowledge of the environment. Analysis of multi-temporal intensity data could become a reality. The usefulness of intensity data could be improved if the dynamics offered by the scale of 12 bit recording could be exploited to its maximum (0-4095). Instead only 0-150 counts of sensor units are offered in some campaigns (Kaasalainen et al. 2011).

Targets with known backscattering data are needed for carrying out absolute intensity calibration. Reference data can be collected on the ground using near infra-red cameras (Vain et al. 2009). Asphalt surface has proved to be a stable target when conducting experiments. Digital photography is a useful method especially when dealing with targets whose surface reflectance properties are non-homogeneous (gravel/sand). Digital photography is also a good alternative as it is not always possible to use tarps for intensity calibration nor is it always possible to take samples of natural targets for conducting laboratory measurements. The Fuji IS PRO camera with an 850 nm infra-red filter is a feasible choice, but other filters can be used according to the wave length of the laser scanner. The change in power when using a flash is about 2%. Reference measurements should be carried out simultaneously with laser scanning since the reflectance properties of natural targets tend to change depending on humidity and other environmental factors.

In order to carry out intensity calibration in practice, some recommendations based on the present research work done can be given about the data provided to the customer. Laser points can be joined with flight strips by means of time stamps, and thus the trajectory data should be available. Meta data should include information about the transmitted pulse energy. If there are changes in the intensity values due to control actions, this should be mentioned. A prime example of this is the AGC on/off situation. Vain et al. (2010) studied AGC calibration and they found that rapid AGC changes are difficult to correct. A project area can be re-scanned at a later point in time and this causes non-homogeneity in the data. The same information should be provided to the customer also in this case and the system changes need to be informed about. Atmospheric data collected during the flights are also useful for intensity calibration. The standard models offered by MODTRAN are feasible alternatives if nothing else is available. An example of AGC variation is shown in Figure 5.1.

Reference data can be collected on the ground using a calibrated digital camera with an infra-red filter. The procedure is to photograph a homogenous and stable reference target and then to measure its coordinates to locate the reference target within the ALS data. A reflectometer or laboratory equipment are useful in carrying out absolute calibration.

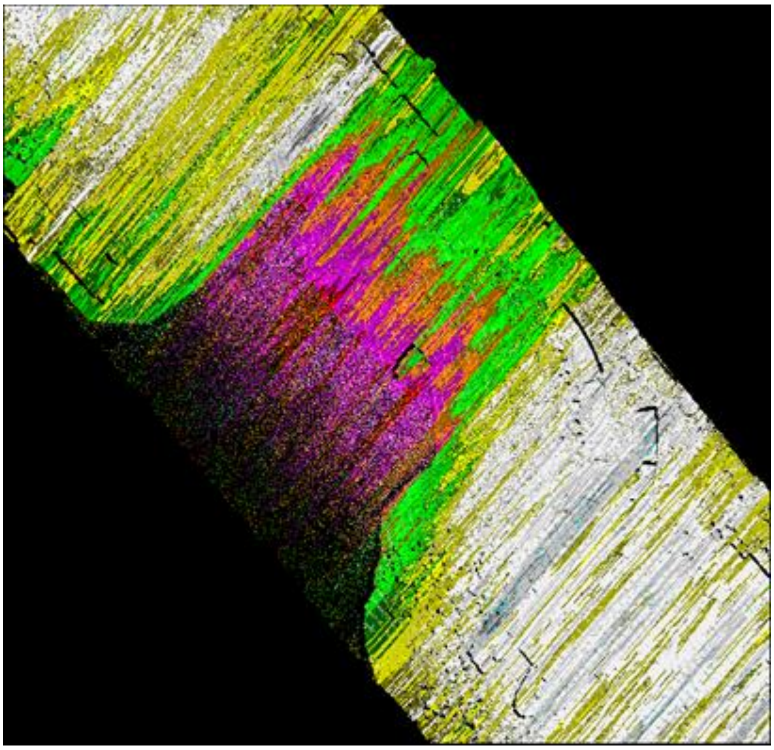

Figure 5.1. The image shows Leica ALS50II AGC’s value changes in Kivenlahti Espoo caused by the water area in the middle of the image. The flying altitude was about 500 m and the swath width was about 360 m.

## 6. Summary and conclusions

The basic hypothesis in this study was threefold: i.e., that (i) airborne laser scanning is a technique accurate enough to be used for current nationwide elevation modeling, (ii) calibration of intensity can be done, and (iii) the transmittance of laser pulses to the ground surface is affected by the forest biomass.

In the course of the work on this dissertation work, the accuracy of the first nationwide laser scanning tests was analyzed, the effect of scanning angle on laser pulse transmittance for boreal forest elevation modeling was tackled, and an intensity calibration method using portable brightness targets was developed based on the FGI's test field concept.

The main results obtained were as follows:

- Publication I: The quality assessment showed that the accuracy of the laser points from repeated observations is sufficient for high quality ALS products.
- Publication II: The scanning angle has only a minor effect on the elevation model's results when compared to changes in biomass. Biomass was the foremost factor affecting the transmittance of laser pulses to the ground. Dense canopies cause deterioration in the transmittance of pulses to the ground and thereby also reduced elevation model accuracy.
- Publication III: The canopy layer dominates and, in practice, determines the number of ground hits. When using scanning angles between 0º and 15º in forested areas, the scanning angle does not have a statistically significant effect on the penetration of vegetation nor on the number of ground hits. It appears to be feasible to increase the scanning angle in elevation modeling in boreal conditions if some degree of local shadowing can be accepted in the data.
- Publication IV: When considering airborne laser scanning, the variability of the recorded intensity from the brightness targets as a function of the angle of incidence was minor and it was found that the targets can be used as brightness references. The wavelength of 1064 nm is equivalent to that used in the Optech and TopEye airborne laser scanners, and thus the results are valid for these scanners. The results confirmed the usefulness of the tarps used as targets for radiometric calibration of intensity.
- Publication V: The calibration process for intensity values was examined. The intensity values were corrected with respect to range, atmospheric transmittance, attenuation using dark object addition, and transmitted power. Following these corrections, the intensity values were found to be directly related to target reflectance. The absolute calibration can be done using external reference targets with known attributes.
- Publication VI: The testing and calibration of airborne digital sensors needs to be carried out and the Sjökulla test field was found suitable for this purpose.
- Ahokas et al. (2008): The obtained elevation accuracies for land cover classes showed that the nationwide ALS requirement of an accuracy of 15 cm for laser points can be achieved for well-defined surfaces. In addition, mobile laser scanning can be used as a reference source.

The results obtained confirmed the hypothesis.

The ALS is a powerful tool for measuring the coordinates and intensities of objects. Without it the accurate creation of the new Finnish national 2 x 2 $m^2$ grid DEM would not have been possible. Many fields of applications benefit from the nationwide ALS data and the 2 x 2 $m^2$ grid DEM as is demonstrated in Chapter 1.1. The accuracy assessments of the nationwide ALS have revealed that the geometric accuracy of the ALS is sufficient to fulfil the accuracy requirements of the present form of the Finnish nationwide 2 x 2 $m^2$ grid DEM. Considering that the ALS technology is sufficiently evolved, a 1m grid DEM could be produced at least for some parts of Finland as presumably higher density (>0.5 points/$m^2$) of laser point coverage on the ground will be used when next updating the nationwide ALS.

The scanning angle is one of the parameters affecting the productivity of ALS surveys. Scanning angles up to 38º have proved to be feasible for elevation mapping following indoor experimentation. The transmittance experiment in the Evo test area showed that the scanning angle does not have a statistically significant impact on the penetrability of the boreal forest in the study when using scanning angles from 0º to 15º. It appears to be feasible to increase the scanning angle if some degree of local shadowing is accepted in the elevation model data. This opens up new possibilities for nationwide collecting of laser scanning data and the simultaneous collecting of scanning and imaging data. The other advantage is that there will be economical savings in the ALS process as production costs are reduced. It is, therefore, somewhat astonishing that the number of studies looking into the optimization of ALS flight parameters for multi-use national laser scanning is so small. In the field of forestry, proper research into the effects of the scanning angle is lacking. When using area-based features, increasing the scanning angle is expected to lead to significant loss of accuracy, and consequently the optimization of the scanning angle depends on the application.

The arc of development in the testing radiometry applied to airborne sensors can be seen in the facilities at the Sjökulla test field. The gravel grey scale was used for testing the radiometry of analogue images using microdensitometers. The designing of portable test targets in 1995 made it possible to test image quality in different parts of the survey area (Kuittinen et al. 1996). Additionally, there was a need to test radiometry using the portable grey scale later referred to as brightness targets. A set of these was designed in 2000 (Ahokas et al. 2000). The portable brightness targets enable the calibration of ALS intensity measurements as does the use of Spectralon reference panels in laboratory conditions. The characteristics of the targets should be verified at the same wavelength for both ALS and in the laboratory. Laser scanner intensity information could enable better classification of laser points and help in the separation of tree species and different surface types. Painted portable tarps are sufficient for calibration reference purposes for determining laser intensity. Methods for relative and absolute calibration for ALS intensity exist already as is indicated in Publication V and Chapter 5, but their implementation is currently lacking in practice. An intensity correction method should be used as a pre-processing part of airborne laser data processing. As a result, the usability of intensity values may increase in practical applications. Since different laser scanners are used in nationwide laser scanning, the use of intensity is hampered in present practices.

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