MENDEL UNIVERSITY IN BRNO

FACULTY OF FORESTRY AND WOOD TECHNOLOGY

DIPLOMA THESIS

Calculation of forest stand heights on the basis of airborne laser scanning on the territory of Training Forest Enterprise Křtiny

Brno 2016 **Bc. Andrea Procházková**

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Vložit zadání DP

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“*I often say that when you can measure what you are speaking about, and express it in numbers, you know something about it; but when you cannot measure it, when you cannot express it in numbers, your knowledge is of a meagre and unsatisfactory kind; it may be the beginning of knowledge, but you have scarcely in your thoughts advanced to the state of Science, whatever the matter may be*.”

William Thomson, 1st Baron Kelvin also known as Lord Kelvin, 1883

Abstract

Andrea Procházková

Calculation of forest stand heights on the basis of airborne laser scanning on the territory of Training Forest Enterprise Křtiny

This diploma thesis deals with calculation of forest stand heights on the basis of airborne laser scanning (ALS) on the territory of Training Forest Enterprise Křtiny. Point cloud data from ALS were interpolated into digital terrain model (DTM), digital surface model (DSM) and subsequently by subtraction of DTM from DSM into canopy height model (CHM). Inverted CHM was used for detection of tree tops by Inversed Watershed Segmentation; tree tops were identified as local minima. Calculated heights of forest stands were compared with height data taken from Forest Management Plan (FMP) and with data from field survey.

Key words

Airborne laser scanning, LiDAR, stand height, Training Forest Enterprise Křtiny

Abstrakt

Andrea Procházková

Výpočet porostních výšek na základě leteckého laserového skenování na území Školního lesního podniku Křtiny

Předkládaná diplomová práce se zabývá výpočtem porostních výšek na základě leteckého laserového skenování (LLS) na území Školního lesního podniku Masarykův les Křtiny. Z mračna bodů, které bylo výstupem LLS, byl vytvořen digitální model terénu (DMT) a digitální model povrchu (DMP). Po odečtení DMT od DMP byl vytvořen tzv. digitální model korun (canopy height model - CHM). Převracený rastr CHM byl použit pro detekci vrcholků stromu metodou tzv. segmentace inverzního povodí; vrcholky stromů byly určeny jako lokální minima. Vypočtené výšky z lesních porostů byly porovnány s daty z lesního hospodářského plánu (LHP) a s daty naměřenými při terénním výzkumu.

Klíčová slova

Letecké laserové skenování, LiDAR, porostní výška, ŠLP Masarykův les Křtiny

CONTENT

ABBREVIATIONS

ABA	Area-based approach
ABSA	Area-based statistical approach
ALS	Airborne laser scanning
CHM	Canopy height model
DBH	Diameter at the breast height
DGPS	Differential Global Positioning System
DMT	Digitální model terénu
DMP	Digitální model povrchu
DSM	Digital surface model
DTM	Digital terrain model
FMP	Forest management plan
FMI	Forest management institute
GNSS	Global navigation satellite system
GPS	Global positioning system
IMU	Inertial measurement units
INS	Inertial navigation system
ITD	Individual tree detection
LLS	Letecké laserové skenování
LiDAR	Light detection and ranging
NFI	National forest inventory
ŠLP	Školní lesní podnik
TFE	Training forest enterprise

1. INTRODUCTION

Since the time immemorial, men had the need to explore nature and landscape around themselves. Nowadays, geographic information systems (GIS) and remote sensing technologies support the easier way for knowledge and exploration of surroundings. Methods and technologies have been developed to such an extent that we are able to use them in various fields, forestry industry is not excluded. Management of forest resources requires cost-effective and rapid collection of the data. Therefore, GIS and remote sensing have already become fundamental tools for contemporary forest management.

Precision forestry and accelerating development of new technologies have become widely popular over the past years. Precision forestry is new direction for effective and economical forest management using modern methods, tools and technologies to obtain information about forest terrain, individual trees and whole stands. LiDAR, both aerial and terrestrial, is one of the modern and most promising technologies of precision forestry. This technology and its utilization show a huge expansion in last decades. Some countries are already using this technology in forestry practice; very great interest is given to utilization for forest inventory.

Forest inventories are very important sources of information about forest stands for successful forest management. Characteristic features within the forest such as tree species, diameter at breast height (DBH), tree height, age and other parameters need to be measured and collected. The process of stand data collection in the field can be very lengthy. Therefore, it is necessary to use new technologies that will accelerate the work. One of these technologies is currently LiDAR; laser scanning in other words. The velocity of data acquisition is one of advantages of this technology; data acquisition by geodetic measurements takes relatively long time in comparison with LiDAR technology. When LiDAR system is mounted on any moving aircraft we speak about airborne laser scanning (ALS). ALS can be used for data collection from large areas during short time and cost effectively. Thanks to these facts, ALS offers various conceivable utilizations in forest industry. The greatest attention has been given to determination of stand and single tree height on the basis of ALS. Single tree height and stand height are essential dendrometric variables which are definitely required in forest management. Height is parameter which can be easily derived from ALS data because ALS data includes elevation information.

The basic output of laser scanning is so called point cloud. Every point has its own coordinates and represents the spot from which the laser beam was reflected. Points reflected from the terrain are interpolated into digital terrain model (DTM) and points reflected from objects on the terrain are interpolated into digital surface model (DSM). These two models can be used for creation of canopy height model (CHM) which is raster representation of the tree canopy. CHM is derived by subtraction of DTM from DSM and it can be used for the detection of single tree tops and thus for the estimation of individual tree height. Tree tops are taken as local maxima in CHM and they can be obtained by several methods. One of the methods to search tree tops is inversed watershed segmentation which is based on hydrological tools. In the course of this method, CHM is inversed and tree tops correspond to local minima.

2. OBJECTIVES

The principal aim of presented thesis is calculation of forest stand heights on the basis of airborne laser scanning on the territory of Training Forest Enterprise (TFE) Křtiny and comparison of these stand heights with data from field survey and data taken from Forest Management Plan (FMP).

There are some intermediate objectives required for calculation of forest stand heights on the basis of airborne laser scanning (ALS):

- Creation of digital terrain model (DTM) and digital surface model (DSM)
- Creation of canopy height model (CHM) by subtraction of DTM from DSM
- Detection of treetops from inverted raster of CHM by Inversed Watershed Segmentation

3. AIRBORNE LASER SCANNING

Airborne laser scanning (ALS), generally Light Detection and Ranging (LiDAR), is a relatively new type of an active remote sensing technique (LILLESAND et al., 2008). Active means that it provides own sources of energy (CAMPBELL & WYNNE, 2011); it is not dependent on passive solar illumination and considering this fact, data can be collected even at night if necessary (JENSEN, 2014). LiDAR can be understood as device or technology based on application of lasers. The LiDAR technology itself is familiar since 1960´s (ZEMEK et al., 2014); first optical laser was developed in 1960 by Hughes Aircraft, Inc. (JENSEN, 2014). The utilization of LiDAR for precise determination of terrain elevations have started in the late 1970´s (LILLESAND et al., 2008). The first airborne lasers were suggested as profiling lasers (CAMPBELL & WYNNE, 2011) and these initial devices obtained elevation information exclusively under the course of an aircraft (LILLESAND et al., 2008). Though airborne laser profile systems were introduced already in the 1970s, their practical utilization has started with development of the new geo-positioning systems: global positioning systems (GPS), inertial measurement units (IMU), and inertial navigation systems (INS) (CARSON et al., 2004). By the late 1980s, these systems, which are simultaneously components of laser scanning, created the context for development of precision LiDAR scanning system that we know nowadays (CAMPBELL & WYNNE, 2011).

In the case of ALS, laser scanners are mounted on any moving airborne platform (airplane, satellites, helicopter or etc.). ALS technology is used to detect objects and to measure distances by using a laser beam (DOLANSKÝ, 2004). Laser scanning offers detailed representation of terrain and surface with high accuracy (CAMPBELL & WYNNE, 2011) and it allows precise determination of a three-dimensional (3D) structure of objects of interest (ZEMEK et al., 2014). Scanners are able to collect extremely large amount of very detailed information (LONGLEY et al., 2011). The primary output of laser scanning is a georeferenced point cloud that contains x, y and z coordinates of reflected points. The most common ultimate product of ALS interpolated from point cloud is digital elevation model (DEM) (ZEMEK et al., 2014). According to

JENSEN (2014), DEM is defined as a file or database containing elevation points over a contiguous area and this model may be subdivided into two different models (Fig. 1):

- *digital terrain model (DTM)* represents the bare surface without vegetation or any man-made constructions
- *digital surface model (DSM)* represents all features in the landscape, such as vegetation, buildings and other man-made constructions

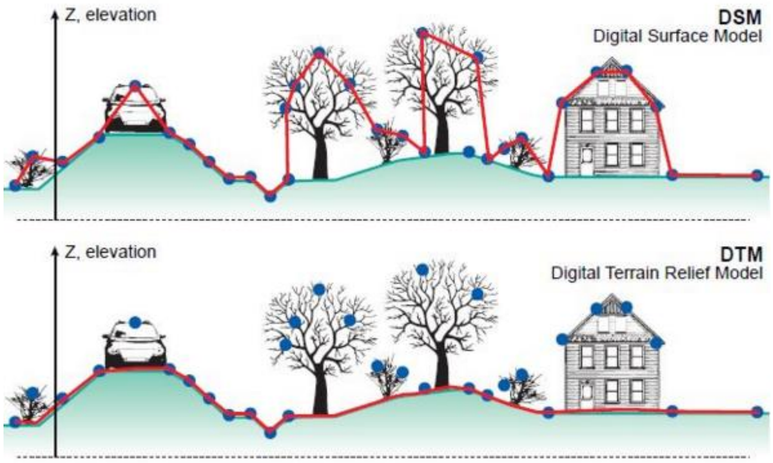

Fig. 1 *The difference between DSM and DTM*. Source: CHARIM (2016)

3.1 Description of technology

3.1.1 Laser scanning

Laser scanning, LiDAR, can be divided into airborne or aerial laser scanning (ALS), terrestrial laser scanning and mobile laser scanning (Tab. 1). When laser scanning is done by scanners installed on any moving airborne platform (airplane, satellites, helicopter or etc.), then we call this ALS. TLS system can be mounted stationary on a tripod or on some mobile ground vehicle. MLS, mobile LiDAR, is frequently taken separately from TLS and it is a modification of ALS (HOLOPAINEN, 2013).

Tab. 1 *Distribution of LiDAR*. Source: KUDA et al. (2014)

LASER SCANNING **LiDAR** (Light Detection and Ranging)		
ALS (Airborne Laser Scanning)	**TLS** (Terrestrial Laser Scanning)	
	mobile / kinetic **MLS**	static

The principle of LiDAR simply consists in measuring the distance travelled by laser beam between the source of energy and the surface. The laser beam impinges on the terrain or objects which are located at the earth's surface and it is reflected back. The location of each laser return is obtained by precise kinematic positioning using GNSS and orientation parameters achieved by IMU; GNSS provides coordinates of the laser source within coordinate system and direction of pulse is provided by IMU (Fig. 2) (SUÁREZ et al., 2005).

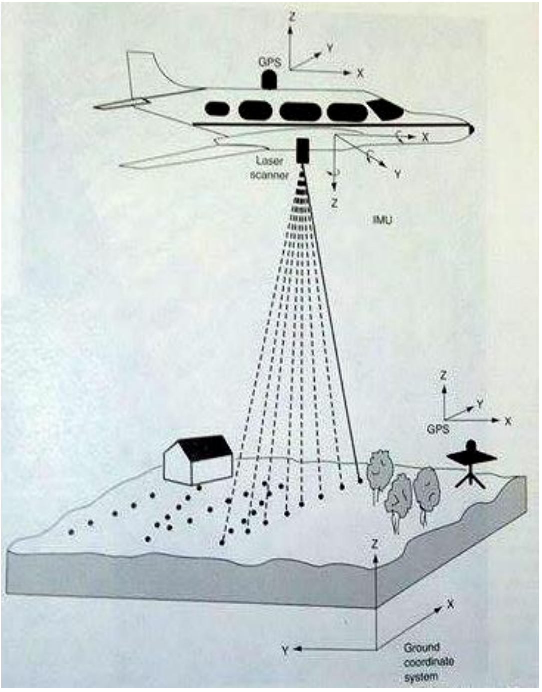

Fig. 2 *Airborne laser scanning system*. Source: LILLESAND et al. (2008)

Aerial laser scanners can be divided into Discrete Return (DR), which detect single discrete reflections, and Full-waveform scanner (FWF) (PATOČKA, 2012). FWF digitize whole waveform and DR record the time and intensity of returns (CAMPBELL & WYNNE, 2011). DR system is able to measure up to five reflections, but in practice usually measured by three or four reflections (PATOČKA, 2012). ALS systems used for forestry application are usually small-footprint, discrete-return system (MALTAMO et al., 2014), however, FWF are advantageous in creation of 3D models of vegetation (CARBOL & KLIMÁNEK, 2015).

3.1.2 Components of laser scanners

Laser scanners consist of several mapping technologies that are independent. The basic structural units are the laser unit, the scanner unit, GNSS and IMU (Fig. 3). Scanner and laser unit cooperate with each other through a control unit, which is also sometimes referred as a control unit. Inside parameters of individual components must be determined with high accuracy, therefore each of these separate units must be calibrated before the measurement. (DOLANSKÝ, 2004)

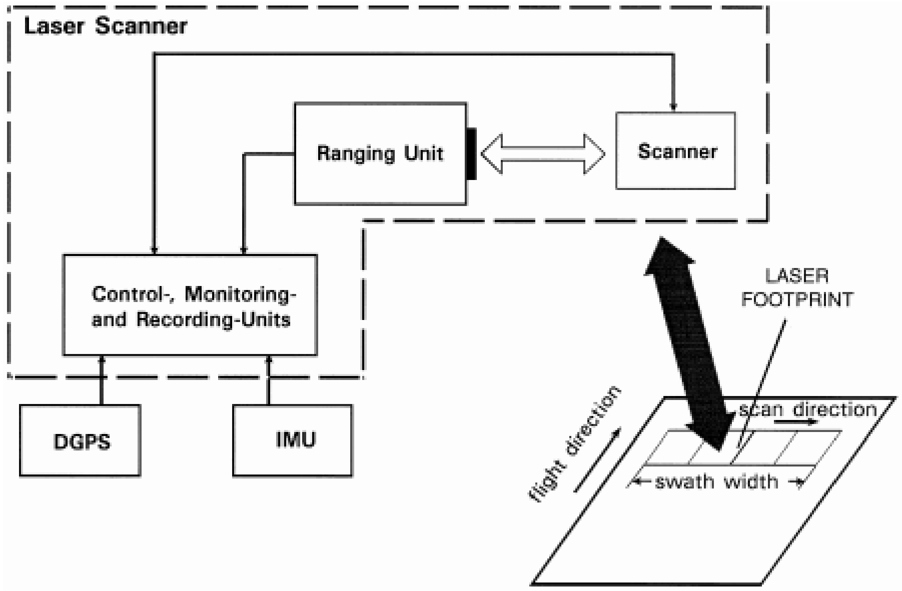

Fig. 3 *A typical ALS system*. Source: WEHR & LOHR (1999)

3.1.2.1 Laser unit

The components of the laser unit are a laser transmitter and receiver, whose optical axis is identical. The distance can be measured in two ways; by measuring the time between the emitting and returning beam or by using phase shift. Continuous-wave (CW) laser, which emits a continuous signal light energy, is based on the principle of phase shift (PATOČKA, 2012). In practice, systems with pulse width modulation are mainly used (DOLANSKÝ, 2004). The transmitter emits intermittent short light pulses and the distance is calculated from the time between sending a pulse and detection of the reflection object.

Footprint size of the laser beam depends on the flight altitude and on the divergence of the light beam (DOLANSKÝ, 2004). The beam is not projected to the surface as a point; it divides passing the forest cover and multiple reflection is measured (PATOČKA, 2012). The part of the pulse passes through the canopy into internal tree structures to the lower vegetation layers and to the ground (CAMPBELL & WYNNE, 2011).

3.1.2.2 Scanner unit

The scanning unit is designed to direct a laser (PATOČKA, 2012). According to the resulting contour laser measurement data we can distinguish between four types of scanners: scanners using rotating mirror (Fig. 4a), oscillating mirror (Fig. 4b), a fibre optic bundle (Fig. 4c) or a system of two mirrors - elliptical scanner (Fig. 4d) (PAVELKA et al., 2011). These four types are described in detail by DOLANSKÝ (2004).

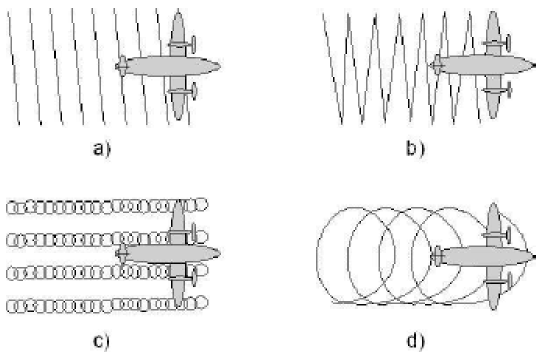

Fig. 4 *Footprint types of various scanner constructions*. Source: DOLANSKÝ (2004)

3.1.2.3 Global navigation satellite system (GNSS)

Currently, two navigation satellite systems are in operation; NAVSTAR - GPS (Navigation Signal Timing and Ranging - Global Positioning System) and the Russian GLONASS system (Global'naya Navigatsionnaya Sputnikovaya Sistema). European navigation system Galileo is presently being created.

GNSS receiver is used to determine the aircraft's position in the reference system. Method of Differential Global Positioning System (DGPS) is used. Visibility of at least four satellites is required for signal reception; at least six satellites are needed for greater accuracy (PAVELKA et al., 2011).

DGPS method is based on utilization of two GNSS receivers which record positional information at the same time. One receiver is located on the aircraft and second, terrestrial, is located on a known geodetic point with well- documented x, y and z-coordinates (JENSEN, 2014). However, if three stations are on the board, value of each bank of the aircraft can be determined (DOLANSKÝ, 2004).

3.1.2.4 Inertial measurement unit (IMU)

Inertial measurement unit (IMU) is used to record the orientation data and speed of the aircraft. Aircraft does not follow a constant speed, altitude or inclination; therefore it is necessary to record the pitch angle, bank angle and speed of aircraft (PATOČKA, 2012). This unit consists of gyroscopes and accelerometers.

System of gyroscopes can very accurately determine the tilt of a scanning system with respect to the direction of gravity. Measuring speed changes is ensured accelerometer which measures acceleration on the basis of the laws of inertia. (DOLANSKÝ, 2004)

Contemporary gyroscopes and accelerometers measure very precisely extremely small value, but under the influence of systematic errors occur gradually rise to inaccuracies (DOLANSKÝ, 2004). On-board GPS provides control of the correctness and updating the estimated position of the IMU; system in conjunction with a GPS is called GPS / IMU or generally INS (Inertial Navigation System) (PATOČKA, 2012).

3.2 Airborne laser scanning in forestry

Research on the utilization of LiDAR data in forestry sector began in the middle of 1970s with experiments using simple profiling instruments (MALTAMO et al., 2014). LiDAR technology allows the signal to penetrate through the canopy to the ground surface (VASHUM & JAYAKUMAR, 2012). Therefore first utilization of LiDAR data was for topographic purposes, mainly to derive accurate DTM (MONNET, 2012). Also nowadays, most forest applications of the LiDAR data are based on DTMs and DSMs (MALTAMO et al., 2014). DTM can be used for design and optimization of the forest road system, for planning harvesting system depending on ruggedness of terrain (MIKITA et al., 2013a) and also for protection against soil erosion (ZEMEK et al., 2014). Data transformed into DTM and DSM can be used in forestry for the formation of so called CHM (Canopy Height Model), which is digital model representing the height of canopy (CARBOL & KLIMÁNEK, 2015).

A specific strength of airborne laser scanning for forestry application is ability of creation and characterization of the 3D structure of the forest canopy (MALTAMO et al., 2014). There is possibility to use airborne laser scanning as alternative technology to field surveying and photogrammetry for collection of elevation data (JENSEN, 2014). First studied forest parameters were height (NILSSON, 1996; NÆSSET, 1997a; MAGNUSSEN & BOUDEWYN, 1998), basal area (MALTAMO et al., 2014) and stand volume (NILSSON, 1996; NÆSSET, 1997b). Height is forest stand attribute, which is directly available from ALS data (PITKÄNEN et al., 2004). Thus the greatest attention has been given to stand and single tree height; it is possible to obtain the mean height, maximum height, tree height etc. (SMREČEK, 2012).

The biggest challenge of LiDAR technology in forestry has been distinguishing between the tree species. TÖRMÄ (2000) claimed only 3D-coordinates are not enough to estimate stand tree species proportions. However, the newest researches advocate that a high degree of species-specific information may be extracted also from ALS data (MALTAMO et al., 2014). Information about tree species is usually obtained by combination of ALS data with spectral image material (VAUHKONEN et al., 2009).

Combination of terrestrial methods with ALS data or at least a combination of ALS with multi-spectral image data with high resolution appear to be the most perspective methods for determination of qualitative and quantitative tree and growth parameters (MIKITA et al., 2013a). Combination of TLS and ALS (TALS) is alternative option for more detailed tree mapping (Fig. 5). ALS cannot measure DBH directly; TALS combines accurate measurements of stem from TLS and canopy height measurement from ALS (KANKARE, 2014).

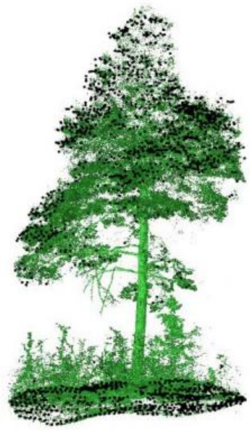

Fig. 5 *Example of combination of the TLS (green) and ALS (dark blue) point clouds*. Source: HOLOPAINEN et al. (2014)

3.1.1 Accuracy of DEM and estimated basic mensuration parameters from ALS

High quality DEM obtained from ALS with approximately 1 m spatial resolution and about 10 to 20 cm height accuracy from point cloud data is very important for forest engineers and managers (AKAY et al., 2008). DEM from the fields with low grass and from bare soil achieves a system accuracy of 15 cm (PEREIRA & JANSSEN, 1999). CIBULKA (2011) indicates that type of terrain and partially terrain slope have big influence on accuracy of DTM; the more rugged terrain, the lower the accuracy.

The results of many studies indicate that the precision across parameters vary considerably. The most assessed parameter from ALS data is height; the accuracy in estimation of this parameter from ALS data is about 1 m (LEEUWEN & NIEUWENHUIS, 2010). Most authors signify from 20 cm to 5 m underestimation of the stand height (NÆSSET, 1997a; NÆSSET & ØKLAND, 2002). Accuracy of determining the diameter ranges between 2.5 and 6.5 cm (MALTAMO et al., 2009).

MIKITA et al. (2013b) report in their study, that results confirm underestimation of heights in created DSMs. Underestimation ranged from 6.8 to 8.1 m when all the trees in the stand were taken into account; accuracy significantly improved when only trees taller than 25 m were taken into account.

CARBOL & KLIMÁNEK (2015) achieved very good results when using the obtained optimal regression relationships; standard error of the mean value up to 5% particularly for deriving heights at top stands level, 4-12% for deriving the mean heights based on the heights of all individuals within the stand, and 4-20% for deriving DBH.

In a study of SUÁREZ et al. (2005), it was confirmed that ALS underpredicted individual tree heights by 7-8% and tree height recovery model created from the linear relationship was able to predict 73% of all the heights within 1 m, 91% within 1.5 m and 96% within 2 m.

3.1.2 Basic inventory techniques based on ALS data

Forest inventory play an important role in forest management because it provides information about forest stand variables. Forest inventory based on ALS provide information about stand variables that complies with the data requirement in forest management and planning, these typical variables are mean tree height, basal area and stand volume (NÆSSET, 2007).

There are two approaches to extraction of the forest stand variables from the ALS data: area-based (ABA) and individual tree detection-based (ITD) approaches (ZEMEK et al., 2014). ABA can be found in literature also as area-based statistical approach (ABSA) (PEUHKURINEN, 2011).

The ITD approach is based on detection of individual tree top, tree heights and crown dimensions from a raster canopy height model (CHM) which is calculated by subtraction of DTM from DSM (ZEMEK et al., 2014). The process of this approach consists of sequence steps that include tree detection, feature extraction and estimation of tree attributes (MALTAMO et al., 2014). ABA is empirical method for investigating the relations between forest attributes and ALS height distributions (PEUHKURINEN, 2011). Mean tree height, mean diameter and basal area are predicted from percentiles and other distribution-related features of the laser reflected signal (ZEMEK et al., 2014). ABA methods can be divided into parametric regression methods and non-parametric nearest neighbour methods (PEUHKURINEN, 2011). ITD approach is not so often used in forestry practices as ABA approach due to the requirement for high point densities; densities between 5 to 10 points/m^2 are required for ITD, ABA approach needs less than 1 point/m^2 (ZEMEK et al., 2014).

3.1.3 Practical utilization of ALS in forest stand inventory

The traditional methods for collection of forest stand information utilize the sampling designs. Stand parameters are measured on transects, random or systematically selected plots and then these parameters can be estimated on statistical extrapolation methods. In general, usage of remote sensing data reduces number of field sampling and therefore it is more cost-effective. (WANG et al., 2004)

ALS can be used for effective and less time-consuming obtaining of essential forest inventory parameters. For practical utilization in national forest inventories (NFIs), ALS data may play different roles such as partial replacement of tree-level plot measurements or as additional data for estimation of parameters like total biomass over larger areas (MCROBERTS et al., 2010). An existing ground forest inventory may be taken as a basis for subsequent LiDAR forest inventory systems (LATIFI et al., 2015).

The first forestry inventories by using airborne laser scanning were performed in Finland already at 1999 (SMREČEK, 2012). But the first experiments with scanning lasers for forest inventory were operated already in 1991 (NÆSSET et al., 2004).

ALS is currently included as an essential component of operational forest inventories in multiple countries (MALTAMO et al., 2014); ALS-based inventories have already become common and standard practice in the Nordic countries (MALTAMO et al., 2009). But this method is also getting outside these countries; ALS/LiDAR-based forest inventories are currently operational/commercial in the United States, Canada, Spain, Switzerland, Baltic countries, New Zealand, Australia (THENKABAIL, 2016) and Latin America (PATOČKA, 2012).

Nordic countries, where the ALS data are already implemented into forest inventories, and Czech and Slovak Republics have been chosen for more detailed description of utilization of ALS data for forest inventory purposes.

3.1.3.1 Norway

Forest inventories in Norway are performed by two different geographical scales serving two distinct purposes; the NFI and forest management inventories. NFI is done in national and regional level and FMI provides data for local management of individual forest estates. (MALTAMO et al., 2014)

Norwegian National Forest Inventory (NFI) has very long tradition; it started already in 1919 and it is done in 5-year cycles. Methodology of NFI has changed over the years from line survey to permanent sample plots (GRANHUS et al., 2012). Forest management inventories already date back to 70s of the 18th century (MALTAMO et al., 2014).

The need of accurate, cheap and effective of inventory methods has driven the development of ALS-based inventory methods, which now dominates in forest inventory (Forestinventory.no, 2016). Norway was one of first countries, which started with research of potential utilization of LiDAR's data in forest inventory (CARSON et al., 2004). First studies and tests on estimation of parameters (mean height and volume of individual stands) from ALS were conducted in 1995 (NÆSSET, 1997a, b). In 1998, many different steps of ABA were described (MALTAMO et al., 2014). The result of several full scale tests was that inventories based on LiDAR have 50% less random error than the traditional methods (Forestinventory.no, 2016)

The first commercial contract for operational management inventory in Nordre Land municipality by using ALS data was awarded in 2002 by Prevista AS. After the start of this project, similar contracts were signed in other parts of Norway. Approximately around 2010, most of the forest management inventories in Norway were completed with support of data obtained from ALS. (MALTAMO et al., 2014)

3.1.3.2 Finland

National forest inventory in Finland has quite similar history as Norwegian NFI. Forest inventory based on ALS data is already in operational practice in Finland. The first research on utilization ALS data in forestry began with the ITD approach (MALTAMO et al., 2014); the main focus on single tree recognition from ALS data started in 2004 (MALTAMO, 2009), but there were also experiments of ABA (MALTAMO et al., 2014). Many studies and research projects have been done on ABA, ITD and their combination. First commercial ALS-based inventory was in 2006 and four years later, there was performed also large scale ALS-based forest inventory of private forests; all of practical inventories apply ABA approach. (MALTAMO, 2009)

At the present time, forest inventory characteristics are derived by using an ABA where low-density (~0.5 pulses/m^2) ALS data are used to generalize field-measured inventory attributes over a whole inventory area. This inventory method has succeeded in replacing traditional stand-wise field inventory. (HOLOPAINEN et al., 2014)

Arbonaut Oy is Finnish technological company with registered office in Joensuu. It is world leading company in GIS solutions for forest inventory and natural resource management. Arbonaut offers ArboLiDAR tools which are complete solution for forest inventory based on laser scanning. ArboLiDAR has been continually developed in close cooperation with forest owners and managers during more than a decade of field utilization. ArboLiDAR uses LiDAR, colour infrared imagery and GPS ground control plots. (Arbonaut, 2016)

3.1.3.3 Sweden

Swedish national laser scanning has started at 2009 by The National Land Survey (Lantmäteriet). However, utilization of data from laser scanning for forest management planning has been operational since year 2011 and Lantmäteriet had scanned 97% of all forest land in Sweden until 2015 (OLSSON, 2015).

Laser scanning data in Sweden are primarily used for creation of new national DEM. However, Swedish government have supplied funding for the production of a nationwide forest attribute map based on laser scanning data from the National Land Survey. The Swedish Forest Agency is leader of this project and Swedish University of Agricultural Sciences is project co-operator. The main aim of the project is creation of high resolution nationwide raster database with estimations of forest variables by combination of ALS data and field data from the NFI. (NILSSON et al., 2015)

The estimated stand variables are stem volume, diameter, above ground tree biomass, basal area and basal area weighted tree height. The accuracy of these estimated variables is equally good if not better than variables obtained by the traditional methods. (OLSSON, 2015)

3.1.3.4 Russian federation

Russia is large country with very extensive forested area, approximately 20% of the world’s forest resources are situated in this country. Russian forestry is characterized by small-scale properties and forest inventory is done by traditional field survey introduced 40-50 years ago (SMIRNOV, 2015). However, LiDAR based inventory has great potential in Russia; therefore Argonaut Oy is trying to penetrate to Russian forestry market.

SMIRNOV (2015) made research over 14 Russian forest companies (private forestry companies with timber harvesting activities, private forest inventory providers, state subordinate companies and forestry software developer). The study is focused on North-West Russia, the most developed Russian region in forestry. The conclusion of this study was that most of private organization generally favours deployment of LiDAR in contrast to state organizations which are against its implementation. SMIRNOV (2015) further indicates that the main obstacle for ArboLiDAR in Russian market is disapproval of this forest inventory method by officials.

3.1.3.4 Czech Republic

National forest inventory in the Czech Republic is done by government organization Forest Management Institute (FMI). FMI performs as service of the Ministry of Agriculture for forestry. Neither ABA nor ITD approaches are used in Czech forest inventory. Czech forests are richer on the species composition in comparison with Scandinavian forests which means that the allometric models have to be tailored to multiple species (ZEMEK et al., 2014).

Nevertheless, the ALS data are already studied for utilization in NFI of the Czech Republic. FMI uses Digital Terrain Model of the Czech Republic of fourth generation (4G DMR) for creating of normalized digital surface model (nDSM). 4G DMR was created from ALS data scanned between 2009 and 2013 by State Administration of Land Surveying and Cadastre. It is just question of time when ALS data will be used for inventory practices in Czech Republic.

3.1.3.5 Slovak Republic

National Forest Centre (NFC) is responsible for National Forest Inventory, monitoring and mapping of Slovak forests. NFC is forestry agency established by the SR Ministry of Agriculture. At present, the NFC investigates the utilization of software „reFLex“ (Remote Forest Explorer) in the common practice in detection of the status and development of forest ecosystems.

Software application „reFLex“ is designed for contactless monitoring of forest but also non-forest ecosystems directly from remote sensing data. One of the options of this application is also a package of tools for ALS data processing. Main functions of this application include detecting and deriving some dendrometric parameters (number of trees, height of trees, timber volume, crown projection and coverage of trees in the forest). (SAČKOV, 2015)

4. FOREST MENSURATION - TREE and STAND HEIGHT

In Central Europe, the concept of forest mensuration is synonymous with dendrometry and stand measurements (LAAR & AKÇA, 2007). ZACH et al. (1994) define dendrometry as discipline about measurable variables of trees and forest stands, the interrelationship of these variables, methods of measurement and required tools.

Utilization of dendrometric methods and variables is very important for the forest management from production, economic and technical point of view.

Basic dendrometric variables are subject of measurements in forest (Tab. 2). These variables can be related either to individual trees, their parts or whole forest stands. Variables can have qualitative or quantitative character. Qualitative variables are immeasurable and we are able to describe them verbally, e.g. tree species. Quantitative variables are measurable e.g. the height or the diameter of the tree.

International dendrometric symbology was approved in 1959 at a conference IUFRO in Oxford (ZACH et al., 1994).

Tab. 2 *Summary of basic dendrometric variables.*

Variable	Abbreviation	Unit
Age	t	[year]
Diameter	d	[cm]
Circuit	o	[m]
Breast-height circular base	g	[m^3]
Height	h	[m]
Volume	v	[m^3]

In dendrometry, as already mentioned above, there are variables which are measured for individual trees and also variables which express the features of the stand. Therefore, height needs to be divided into single tree height and stand height. Both are essential dendrometric variables. We need to measure the height of trees to determine the volume of individual trees as well as for other purposes (KORF et al., 1972).

4.1 Tree height

According to LAAR & AKÇA (2007), we can define total tree height the distance between the top and base of the tree, measured along a perpendicular, dropped from the top (Fig. 6).

ZACH et al. (1994) phrase height of tree as the distance between two parallel planes perpendicular to the axis of the strain; lower one goes through the base of strain and upper passes top of the tree. However, thus defined height of tree is very difficult for determination during practical measurements and therefore vertical height is measured. ZACH et al. (1994) define vertical height as distance of two horizontal planes; lower plane passes through the base of stem and upper plane passes through the treetop.

Total height may be equal to the total length of the stem if tree has single and straight stem. Height of leaning trees is vertical distance from the stem base to the uppermost point of the tree.

Measurement of broadleaf tree height can be more complicated, due to their crowns. Therefore it is better to perform these measurements in state without leafs; it means at spring or at autumn (KORF et al., 1972).

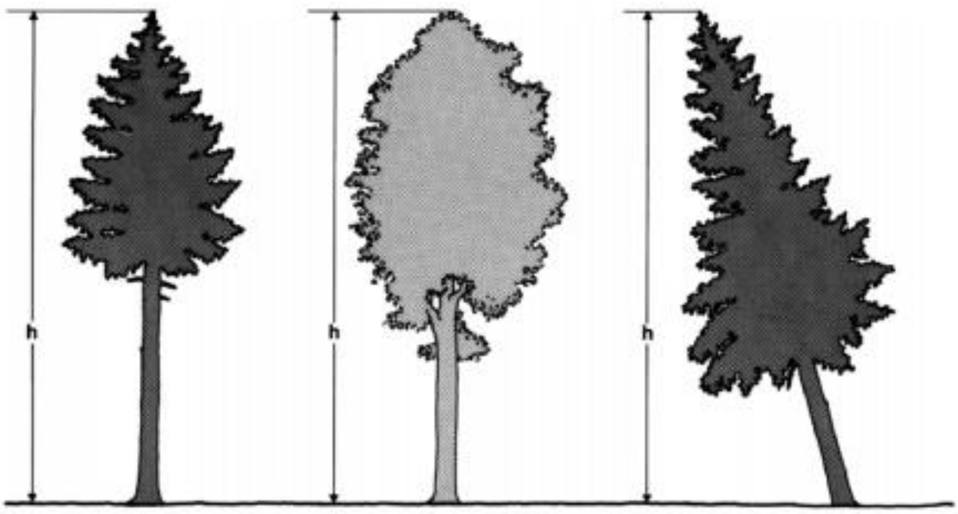

Fig. 6 *Defining tree height*. Source: LAAR & AKÇA (2007)

4.1.1 Tools and principles of measuring tree height

The telescopic poles can be used for measuring the height of low trees (up to 15m). Height measurement of taller trees is done by hypsometers. Hypsometers can be based on trigonometric principle or geometric principle (LAAR & AKÇA, 2007); similarity either right angle triangles or general triangles (KORF et al., 1972).

Other devices not primarily intended to measure the heights could also be used; geodetic instruments, field-map or smartphones using the appropriate application. However, there is also possibility to calculate tree height on the basis of airborne laser scanning, what is subject of this thesis.

4.1.1.1 Hypsometers according to the trigonometric principle

These hypsometers are based on similarity of right angle triangles. They measure the vertical angles between the baseline and the top and base of the tree from the eye level (Fig. 7). This group includes for example those hypsometers: Blume–Leiss hypsometer, Haga hypsometer, Suunto clinometer and electronic hypsometer Haglöf Vertex IV. (LAAR & AKÇA, 2007)

The tree height is then calculated from equation: $h = e \times (\tan\alpha 1 \ - \tan\alpha 2)$

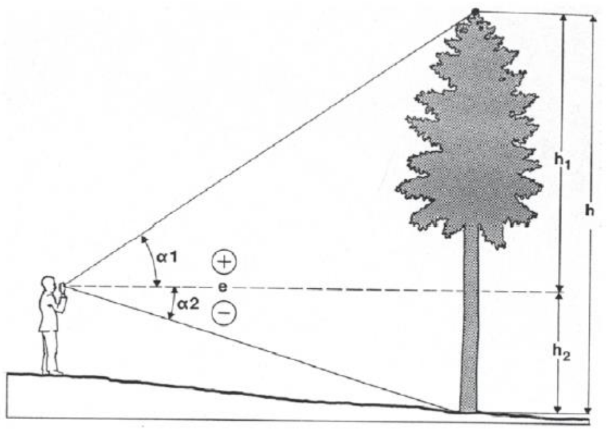

Fig. 7 *Measurement of height according to the trigonometric principle*. Source: LAAR & AKÇA (2007)

4.1.1.2 Hypsometers according to the geometrical principle

These hypsometers are based on similarity of general triangles. The *Christen hypsometer* is the most common hypsometer based on geometrical principles. This hypsometer is composed of folding blade in the form of ruler; blade has fixed lenght (usually 30 cm) and it is equipped with a nonlinear scale. Another component is a pole with a fixed length of 4 m. (ZACH et al., 1994)

During the measurement of height, the pole is held against the tree. Measurement is carried out from position where the top of the pole, the top of the tree and the base of the tree are visible. The triangles ABC with Abc and ABD with Abd are similar and the height of the tree is read at point *d* (Fig. 8). (LAAR & AKÇA, 2007)

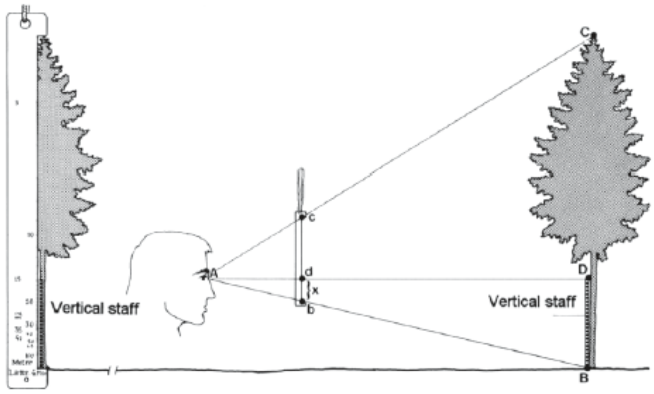

Fig. 8 *Measurement of tree height by Christen hypsometer*. Source: LAAR & AKÇA (2007)

The height of the tree is calculated from the the equation: $BC = BD \times \frac{bc}{Ab}$,

where BD = 4 m and bc = 0.3m, after putting these values into equation: $BC = h = \frac{1.2}{bc}$.

4.2 Stand height

Stand is a territory that consists of a number of trees which are relatively homogeneous or have a familiar set of characteristics. The height of trees within the stand is a basic value that is sorely needed in forestry and especially forest management. Stand height is required for determination of the site index of a stand, calculation of the stand volume and for to prediction of the future growth from stand characteristics (LAAR & AKÇA, 2007). It therefore follows that stand height is important to calculate the volume of wood in stand and thus for forest inventory. However, stand height has its significance in the even-aged stands; greater age difference means lower definition of height maturity of stand (KORF et al., 1972).

Mean height of the stand is site quality predictor. The best characterization of mean stand height is arithmetic mean. However, the arithmetic mean is not widely used in practice, because height of every tree in stand is required. Field measurement of heights from all trees within the stand is very expensive and time consuming. This method can be used in small stands, where the measurement of every tree´s height is possible. Then all the heights from stand are summarized and divided by the total number of trees to determine the mean height. Alternative used for arithmetic mean height is mean height of the average tree. Average trees are trees with mean diameter at the breast height (DBH).

Some procedures of measurement the stand parameters select the biggest trees for processing of stand height estimation. The reason is to avoid the influence of thinning and mortality to the stand height. Tallest trees are in main layer, which has biologically better importance in evaluation of site productivity than other layers. The biggest trees can be defined variously and accordingly we distinguish dominant height, top height and predominant height.

Dominant height is mean height of the dominant trees within forest stand. This height is useful in uneven-aged stands. Stand dominant height has importance in forestry because this height reflects the site productive capacity of the species on particular sites (WEST, 2009).

Top height is mean height of 100 or 10% trees with largest DBH within the stand. This height is useful in uneven-aged stands. The estimated top height of the stand is less sensitive to thinning. Top height is useful for growth predictions. (LAAR & AKÇA, 2007)

Predominant height is the average height of particular amount per unit area of tallest trees within the stand. Predominant height is harder to determine than top height; trees with largest diameter are easier for identification from field survey than tallest trees. (WEST, 2009)

5. MATERIALS AND METHODS

5.1 Study area

Full name of the area is Training Forest Enterprise Masaryk forest Křtiny. This area of interest is located in the South Moravian Region, north and northeast from Brno city (Fig. 9). The territory belongs to Brno-countryside and Blansko districts. TFE Křtiny was founded in 1923 and it is special-purpose facility of Mendel University in Brno. TFE and Faculty of Forestry and Wood Technology of MENDELU constitute the educational and research unit. TFE Křtiny is continuous forest complex punctuated by agricultural land and urban area of several municipalities; the terrain is considerably disaggregated by deep valleys of Svitava River and Křtiny brook (LESOPROJEKT BRNO, 2013).

Fig. 9 *Location of TFE Křtiny.*

Forest coverage of the area is fairly high. Forest lands cover an area of 10 265 ha. The altitude of forests stands ranges from 210 to 575 m a.s.l.. The most dominant forest stands are mixed stands with 46% of coniferous species and 54% of deciduous trees. 116 forest types in 4 forest vegetation zones are mapped within the TFE. Average annual temperature of 7.5 ° C and average annual rainfall of only 610 mm are limiting factors for this area. Spruce, pine, larch, beech and oak are the main tree species of the territory. (Školní lesní podnik Masarykův les Křtiny, 2008)

TFE Křtiny is divided into three forest districts; Habrůvka, Vranov and Bílovice. Field measurements were carried out on sampling plots within the area of the biggest forest district which is Habrůvka.

5.2 Used data

Three types of data were required for the processing of this diploma thesis; data from airborne laser scanning, Forest Management Plan and data measured in the field.

LiDAR data were crucial; they were needed for creation of DTM, DSM and the subsequent creation of CHM. Data from field survey and from Forest Management Plan were used for comparison with mean heights calculated on the basis of airborne LiDAR data.

5.2.1 Data from ALS

Airborne laser scanning data were crucial for the processing of this thesis. Data were being scanned between 17th and 18th of September 2014 according to prepared flight plans. They used aircraft Cessna 206 Turbo stationair OK-EKT and scanner Leica ALS70-CM (SN 7209); GNSS apparatus SPAN3.911/CUS6-"uIRS" was part of the laser scanner. Data were taken in the coordinate system ETRS-89 (UTM 33N) and ellipsoidal heights (GRS-80). Average density of points taken by scanner was 7.8 point/m^2. (BEDNÁŘ & LECÁK, 2014)

Data were received in the LAS file format which is typical format for storing airborne laser scanning data. The LAS file contains point cloud data records from ALS. These data were already received georeferenced to WGS84 coordinate system and classified into ground points and first return points; terrain is differentiated from other objects on the surface.

5.2.2 Data from Forest Management Plan

Forest Management Plan was elaborated by company LESPROJEKT BRNO, a.s. and it is valid from year 2013 to 2022. It has been prepared according to the Forest Act no. 289/1995 Coll. and regulations of the Ministry of Agriculture which follow this law. Through this plan, stands were selected according to the representation of tree species.

Three main tree species for stands were chosen; oak, beech and spruce. Mean heights of stands, where the representation of one of these species was higher than 60%, were used for this work.

5.2.2.1 Forest Management Plans of the TFE

Forest management plans (FMP) are the tools for forest owners which support management of the forest stands. FMP are usually elaborated for ten years.

All legal entities were required to obtain forest management plans by government decree no. 35/1944 Coll., regardless of the size of forest area. Forest management plans of Training Forest Enterprise Masaryk forest Křtiny from 1951, 1963 and 1973 were processed under this regulation. Professor of forest management at Mendel University, Bohumil Doležal, was involved in the processing of these plans where he was verifying his theoretical knowledge. Forest management plan from 1983 was done under the act no. 96/1977 Coll., Czech national council act about the management and state administration of the forest management governmental and decree no. 13/1978 Coll., Decree of the Forest and Water Management Ministry of the Czech Socialist Republic on the categorization of forest, forest management practices and forest management planning (valid until December 31, 1995). Principles of prof. Doležal and prof. Jaroslav Beneš were also used for processing this FMP. Close to nature management was applied in management plans from the years 1993 and 2003. (MATĚJÍK, M. et al., 2009)

5.2.3 Data from field survey

Field survey was done on the territory of Training Forest Enterprise Křtiny in Habrůvka forest district. Collecting field data took place during the year 2015 and measurements were performed on 50 circular plots; every plot got its number from 4001 to 4050. Radius of each circle was 12.62 m, which means that every plot with this radius corresponds to area of 500 m^2. Equally large plots are used for National Forest Inventory in the Czech Republic. The centres of plots were measured by precise global navigation satellite system (GNSS) apparatus named Topcon Hiper Pro. Exact coordinates were given to each centre point of the plots by this apparatus.

On each plot, height of every tree with diameter at breast-height greater than 7 cm was measured. Heights were measured by laser hypsometer Haglöf Vertex IV, transponder (active electronic reflector) was used for measurement also. Transponder was placed on tree at breast height, which was also set up in the options of hypsometer. Subsequently, it is necessary to walk away from the tree to a minimal distance (minimal distance should be equivalent to the estimated height of the tree) and to the point from which the top and the base of the tree are visible. First the distance to the tree was measured by hypsometer aimed at the transponder, then it used the inclinometer to determine the angle to the base of the tree and the angle to the top of the tree and finally the height of a tree is calculated on the basis of trigonometric functions. Tree heights were measured by principles based on the methodology of outdoor data collection for the National Forest Inventory in the years 2001 – 2004. Examples of incorrect and correct measurements are shown in Fig. 10.

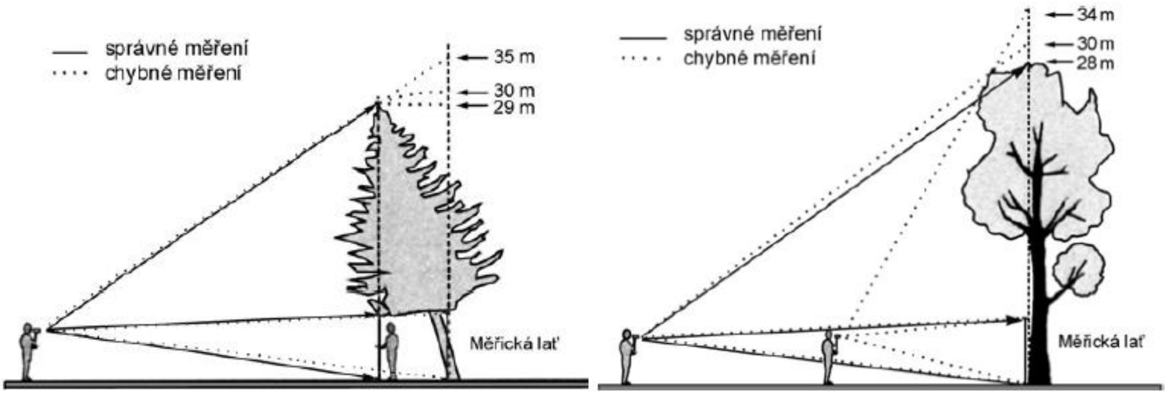

Fig. 10 *Height measurement of inclined trees (left) and height measurement of deciduous trees - observance of a reasonable distances (right).* Source: ÚHÚL (2003)

5.3 Used software

There are various software packages that allow to work with LiDAR data; for example LASTools, TreeVaW, TerraScan or SAGA GIS. However, ESRI ArcGIS Desktop is sufficient and well-arranged program for the purpose of this thesis.

5.3.2 ESRI ArcGIS Desktop 10.2

ArcGIS includes three basic applications, which are interconnected; ArcCatalog, ArcMap, and ArcToolbox. This application allows creating, editing and analysing maps and also provides complete functionality for creating map output (KLIMÁNEK, M. et al., 2008). This software also enables to work with data from airborne laser scanning, which are in LAS format.

One of the main applications of ArcGIS for Desktop is ArcMap which was used for processing all data. However, another application was used for 3D view of data; the name of this application is ArcScene.

5.4 Data processing

The first step in procedure was calculation of tree heights on the entire territory of TFE Křtiny. These heights were calculated by so called Inversed Watershed Segmentation method from CHM, which was obtained from subtraction of DTM from DSM. Calculated heights were then compared with heights from Forest Management Plan and also from field survey.

5.4.1 Calculation of tree heights on the basis of ALS data

5.4.1.1 Creation of canopy height model

The work started by loading all the required data into the software. Although ArcGIS enables users to work with data in LAS format, direct opening of these data is not possible in this software. In order to import this format, there is need to use geoprocessing tool called *Create Las Dataset*, which is found in ArcToolbox. When LAS Dataset is created, the work with point cloud data is possible.

After creation of the LAS Dataset, points were interpolated into DTM and DSM. These digital models were created by using the tool *LAS Dataset to Raster*. Although both models were made by the same way, it was necessary to change the settings before using tool *LAS Dataset to Raster*. There was need to open *Layer properties* of our LASDataset and change the properties in the tab *Filter*. These changes are important in order to control what points will be processed. It indicates that definition of point filter must be done for both models separately. During the creation of DTM, ground returns were chosen as filter; only the points, which were generated as ground points, could be used to form digital terrain model. In the second case, first returns were chosen as filter for creation of DSM.

CHM was derived by subtraction of DTM from DSM (Fig. 11). This process was easily executed by using tool *Raster Calculator* from toolset *Map Algebra*.

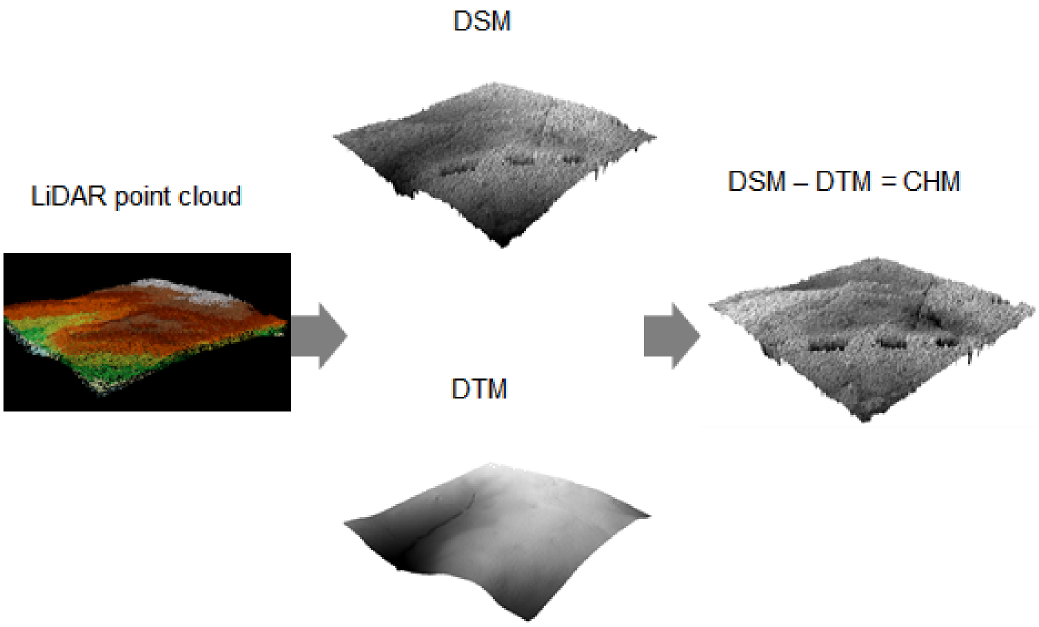

Fig. 11 *A representative procedure of creation of CHM from LiDAR point cloud*.

5.4.1.2 Inversed Watershed Segmentation

Method of Inversed Watershed Segmentation was used for detection of tree tops. This method is based on hydrological tools. Classical watershed segmentation is based on the fact that local minima are endorheic depression. Tree tops were identified as these local minima from inverted CHM.

Tool *Focal statistic* was used before CHM was inverted. This tool calculates for every cell location a statistic of values with a specified neighbourhood around cell (ESRI, 2016). This tool was used for elimination of multiple tree tops and branches. Circle was chosen as shape of neighbourhood. Map was chosen as unit. Height and width got value 1. Maximum was selected as statistic type; it calculates the maximum (largest value) of the cells in the neighbourhood (ESRI, 2016).

Canopy height model was inverted by the tool *Negate*, which multiplies the raster by -1; the sign of the cell values of the input raster changed cell-by-cell (Fig. 12).

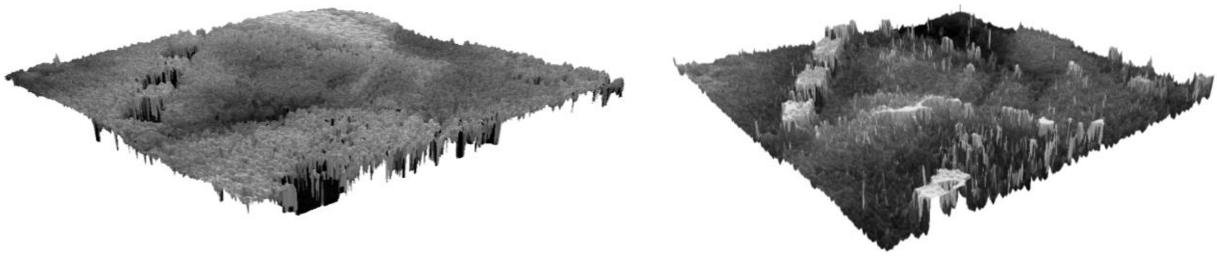

Fig. 12 *Illustration of CHM (left) and inverted CHM (right).*

After the creation of inverted CHM, two hydrological tools were used. First we used *Flow direction* tool which creates a raster of flow direction from each cell to its steepest downslope neighbouring cell (ESRI, 2016). Second used hydrological tool was *Flow length* in which downstream was chosen as direction of measurement. In this case, tool calculates the downstream distance along the flow path for each cell (ESRI, 2016).

The resulting raster had to be reclassified by using the instrument *Reclassify*. This tool reclassifies or changes the values in a raster (ESRI, 2016). Values which had zero value got new value, number 1. All other values were reclassified as NoData. Cells with new value 1 represented tree tops. The tool *Raster to polygon* was used to conversion of reclassified raster to polygon. Then tool *Feature to point* was used to create points generated from the representative locations of input polygons which represented tree tops. In the end, the tool *Extract multi values to points* was used for an assignment of heights from CHM to the points which were identified as tree tops.

5.4.1.3 Comparison with data from field survey

Exact coordinates of each centre point of the plots were measured by precise global navigation satellite system (GNSS) apparatus. In ArcMap, circle buffer zone of 12.62 m was created around every of these centre points by the tool *Buffer*. Subsequently, the tool *Clip* was used. The *Clip* tool extracts input features that overlay the clip features (ESRI, 2016). Layer with points which represented single trees was selected as input feature and layer with plots obtained by using *Buffer* tool was chosen as clip feature.

The mean heights of the plots were calculated as arithmetic mean of heights obtained from field survey. These mean heights were compared with the mean height of trees from ALS. Comparison was done for each plot by subtraction of mean heights calculated on the basis of ALS data from mean heights obtained by field measurements.

5.4.1.2 Comparison with data from Forest Management Plan

The layer with single trees obtained from ALS and layer of FMP were used for the comparison. Stands in FMP were selected according to the representation of tree species. Three main tree species for stands were chosen; oak, beech and spruce. Further condition was that representation of these species within the stands was higher than 60%. Three new layers were created on the basis of these selected stands; spruce stands, oak stands and beech stands with the representation of main species higher than 60%. The maps of the stands within the area of TFE Křtiny are available in annexes.

Mean heights were calculated for every stand from trees detected from ALS data which fall to a particular stand. These mean heights of the stands were compared with mean heights of the stands from FMP. The comparison was done by subtraction of stand mean height calculated on basis of ALS from mean stand heights from FMP. This process of comparison was executed separately for spruce, oak and beech stands.

6. RESULTS

6.1 Comparison with data from field survey

Field survey was performed on 50 circular plots within Habrůvka forest district; every plot got its own number from 4001 to 4050. Radius of each circle was 12.62 m, which means that every plot with this radius corresponds to area of 500 m^2. Together on all plots, 1,305 trees were targeted by the field survey. Representation of trees over the plots is described in Tab. 3. Spruce is the most represented tree species on survey plots; slightly over 75% of all trees are spruces. Predominance of deciduous trees was just on seven plots. Beech is the most prevailing deciduous tree species on the plots.

Tab. 3 *Representation of tree species on plots*.

	Number	**%**
Spruce	986	75.56
Larch	56	4.29
Pine	22	1.69
Beech	218	16.70
Others	23	1.76
Total	**1,305**	**100**

Number of trees measured in the field survey was higher than the number of trees calculated from ALS data; 901 trees were detected from ALS data, which means the difference of 404 trees in comparison with ALS data. Smaller number of detected trees from ALS may be caused because although the stem fell in the plot area, the top of tree can be outside of the plot border; such trees could be then excluded from calculations. Detailed summary of values from all the plots is available in annexes.

The biggest difference in numbers of trees was on the plot 4018; 62 trees were measured on the field survey, but 28 only were detected from ALS data. After reviewing data on trees within this plot, it was found that plot was composed of the spruces with the exception of three trees and 16 trees were smaller than 20 m. Another big difference was recorded on the plot 4027 where 50 trees were measured by field survey but only less than half was detected from ALS data. On this plot, there was also observed relatively large amount of trees lower than 20 m, it was 12 trees. Together on all plots, there were measured 150 trees below 20 m by field survey. Conversely, the lowest difference was detected on plots 4002 and 4016 where the amount of trees detected from ALS data was the same as observed trees on field survey. Even on these plots slight amount of smaller trees than 20 m was detected. Both these plots are mostly occupied by beech. Situation was reversed on one plot; the amount of tree detected from point cloud was higher than amount of trees observed on field measurements. However, this difference was just 3 trees.

The result from comparison of the mean heights from field measurement with mean height calculated on basis of ALS was not fully satisfactory (Tab. 4). Mean deviation was negative. Root-mean-square error (RMSE) was 2.8 m in case that all plots were included in the process of comparison. On the basis of this result, there was research on causes of greatest deviations.

Tab. 4 *Comparison of measured mean heights with mean heights calculated on ALS basis.*

Number of plots	**50**
Minimum	-7.5923
Maximum	5.8692
Mean	-1.020484
Standard Deviation	2.610969
RMSE	2.803309957

Fig. 13 shows relatively normal distribution of deviations. The most of error values range between -0.9 and 1.4; 22 of deviations were within this interval.

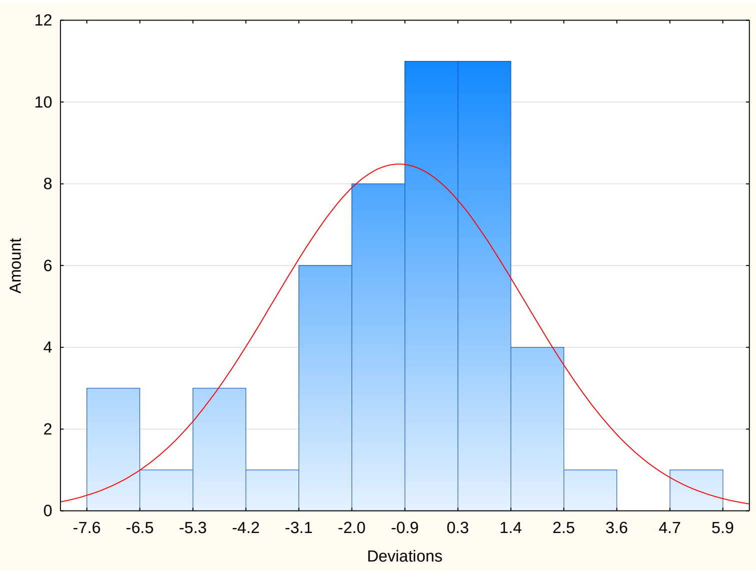

Fig. 13 *Frequency histogram of deviations (survey plots)*

The greatest difference, where mean height from ALS was higher than mean height from field measurement, was found on plot 4014. The difference was approximately 7.6 m; mean height from field survey was about 28.6 m and 20.98 m from ALS. Only deciduous trees (beech and hornbeam) were observed on this plot and 16 trees were lower than 20 m. Other such cases were found for example on plots 4003 and 4015; both these plots were also composed of the vast majority of deciduous trees. The biggest amount of trees smaller than 20 m were found on the plot 4003; 27/45 measured trees were below 20 m height.

The greatest difference of opposite case (when mean height from field measurement was higher than mean height from ALS) was detected on the plot 4008; difference was 5.9 m. This plot is specific by the lowest amount of observed trees, just 7 trees were measured on field and 10 trees were detected from ALS data. For this reason, the plot was not used for following evaluation of the results.

F-test, a test of the difference of two variances, was used for statistical evaluation of the detected heights of trees. The test has not excluded the null hypothesis of compliance for variances of mean heights from ALS and from field survey (Tab. 5). It derives from the fact that P-value is higher than 0.05.

Tab. 5 *F-test of two variances (ALS vs. field survey)*

	ALS	*Field survey*
Average value	31.384184	30.2147
Dispersion	14.82017884	19.80871841
Observation	51	51
Difference	50	50
F	0.748164446	
P(F<=f) (1)	0.154128785	
F krit (1)	0.625197145	

6.1.1 Results after elimination of plots with high difference in amount of detected trees

Number of trees measured in the field survey was higher than the number of trees calculated from ALS data; 901 trees were detected from ALS data, which means the difference of 404 trees in comparison with ALS data. The results were slightly better after elimination of 14 plots, where the difference in amount of trees was higher than 10 trees, nevertheless RMSE was still pretty high (Tab. 6).

Tab. 6 *Comparison of measured mean heights with mean heights calculated on ALS basis after elimination of plots with high difference in amount of detected trees*

Number of plots	**36**
Minimum	-7.5923
Maximum	3.3506
Mean	-0.610544
Standard Deviation	2.310772
RMSE	2.39006929

6.1.1 Results after elimination of plots with trees in understorey

Some plots were specific due to the presence of trees in understorey. After elimination of plots with more than 5 trees in understory, the results were slightly better than after elimination of plots with high difference in amount of trees (Tab. 7).

Tab. 7 *Comparison of measured mean heights with mean heights calculated on ALS basis after elimination of plots with trees in understorey*

Number of plots	**41**
Minimum	-6.6354
Maximum	3.3506
Mean	-0,73372
Standard Deviation	2.190879
RMSE	2.310475239

6.1.2 Results after elimination of plots with predominance of deciduous trees

The best results were obtained after elimination of plots with predominance of deciduous trees (Tab. 8). The RMSE was just a little bit over 2 m. Maximal deviation was the same as in two previous cases, which means that the changes were just in negative numbers.

Tab. 8 *Comparison of measured mean heights with mean heights calculated on ALS basis after elimination of plots with predominance of deciduous trees*

Number of plots	**42**
Minimum	-6.149
Maximum	3.3506
Mean	-0.60699
Standard Deviation	1.962725
RMSE	2.054440626

6.2 Comparison with data from Forest Management Plan

Stands in FMP were selected according to the representation of tree species. Three main tree species for stands were chosen: oak, beech and spruce. Representation of the main tree species within the stands was determined higher than 60%. There was found 139 oak stands, 274 beech stands and 151 spruce stands with representation of the main tree species within the stands higher than 60%. Oak stands cover an area of 403.5 ha, beech stands cover 920.6 ha and 356.8 ha are covered by spruce stands.

Mean heights of stands calculated on basis of ALS were subtracted from the mean heights taken from the FMP. Positive differences mean that mean heights of stands calculated on basis of ALS are lower than mean heights from the FMP. Negative differences mean the opposite situation. Maximum and minimum deviations, systematic error (Mean), standard error (Standard Deviation) and Root Mean Square Error (RMSE) were computed for all stands.

F-test was done for all stands (Tab. 9). In all three cases, the P-value was lower than 0.05, which indicates statistically significant difference between the ALS and FMP. The lowest P-value was in case of beech stands.

Tab. 9 *F-test of two variances (ALS vs. FMP)*

	Oak stands		**Beech stands**		**Spruce stands**	
	ALS	**FMP**	**ALS**	**FMP**	**ALS**	**FMP**
Average value	19.76218561	21.03597	25.27482482	28.23722628	30.63237	30.25166
Dispersion	14.56867197	10.16536	41.40262752	8.452675062	11.97607	7.109581
Observation	139	139	274	274	151	151
Difference	138	138	273	273	150	150
F	1.433167852		4.898168593		0.593649	
P(F<=f) (1)	0.017672176		3.35179E-36		0.000762	
F krit (1)	1.324461087		1.220730348		0.763794	

6.2.1 Oak stands

It was found that there are 139 oak stands on the territory of TFE Křtiny and it covers 403.5 ha area. At these stands oak representation is over 60%. RMSE from all these stands is more than 4.3 m, but that is not satisfactory result. The maximal difference is over 24 m and minimal is almost 6.5 m (Tab. 10).

Tab. 10 *Comparison of mean heights from FMP with mean heights calculated on ALS basis (all oak stands)*

Number of stands	**139**
Minimum	-6.4911
Maximum	24.2187
Mean	1.273786
Standard Deviation	4.198351
RMSE	4.387331979

The histogram is significantly leftward (Fig. 14). The most of values are between -1.4 and 1.2; 57 values is within this interval. This histogram also show that there are visible extreme positive values.

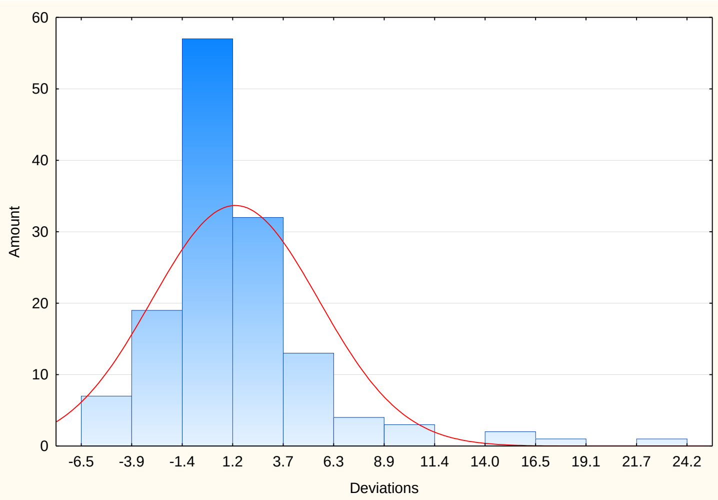

Fig. 14 *Frequency histogram of deviations (oak stands)*

After the check of problematic stands, the stands with maximal positive differences were found as sparse. Elimination of these stands from process of comparison decreased the RMSE below 2 m (Tab. 11).

Tab. 11 *Comparison of mean heights from FMP with mean heights calculated on ALS basis (after elimination of sparse oak stands)*

Number of stands	**112**
Minimum	-6.4911
Maximum	2.9861
Mean	-0.260807
Standard Deviation	1.97487
RMSE	1.99201702

6.2.2 Beech stands

Within the territory of TFE Křtiny, there are 274 of beech stands where beech is over 60%. These stands cover an area of 920,6 ha. RMSE from all beech stands is very high, more than 7 m (Tab. 12) The maximal deviation is over 27 m and minimal is below -8 m.

Tab. 12 *Comparison of mean heights from FMP with mean heights calculated on ALS basis (all beech stands)*

Number of stands	**274**
Minimum	-8.2205
Maximum	27.5537
Mean	2.962401
Standard Deviation	6.445449
RMSE	7.093633

The histogram is leftward same as in case of oak stands (Fig. 15). The most of values are between –2.3 and 0.7; 71 values is within this interval.

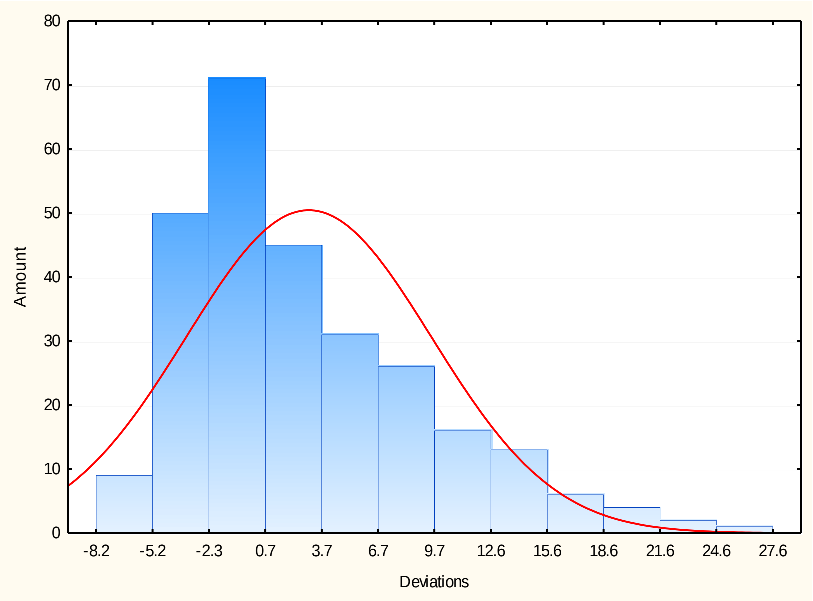

Fig. 15 *Frequency histogram of deviations (beech stands)*

There are 6 stands where the difference exceeds 20 m and 41 stands where the difference goes beyond 10 m. The review of these stands revealed that there are opened plains within stands, so these stands are significantly sparse. Even stands where deviation was about 3 m were found as sparse. The results have improved after the elimination of such sparse stands (Tab. 13).

Tab. 13 *Comparison of mean heights from FMP with mean heights calculated on ALS basis (after elimination of sparse beech stands*)

Number of plots	**160**
Minimum	-8.2205
Maximum	2.7519
Mean	-1.45862
Standard Deviation	2.240726
RMSE	2.673656

But there were still noticeable minimal negative deviations. The first sight on the stands with these deviations did not show any visible problems. After closer inspection of these stands, it was found that some trees calculated from ALS were over 40 m height and these trees subsequently raised the value of mean heights of stands and thus deviation from mean heights from FMP.

6.2.3 Spruce stands

On the territory of TFE Křtiny, there are 151 of spruce stands where spruce is represented by more than 60%. Spruce stands cover an area of 356.8 ha. RMSE from all spruce stands is 2.8 m. Maximal deviation is 12.1 m and it is not so high as in cases of oak and beech stands (Tab. 14).

Tab. 14 *Comparison of mean heights from FMP with mean heights calculated on ALS basis (all spruce stands)*

Number of stands	**151**
Minimum	-5.6825
Maximum	12.089
Mean	-0.38071
Standard Deviation	2.739103
RMSE	2.765434

Fig. 16 shows that again the histogram is leftwarded. The most of values are between 0.2 and -2.7; 81 values ranged within this interval.

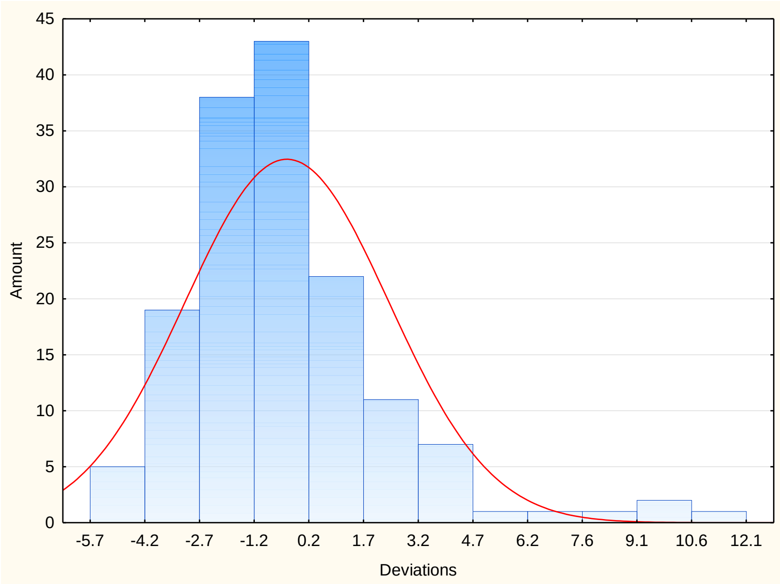

Fig. 16 *Frequency histogram of deviations (spruce stands)*

As in the cases of oak and beech stands, there were also found some sparse stands which caused worse results. However, spruce stands were not found so sparse and only few stands were eliminated. After this elimination, RMSE was just slightly over 2 m (Tab. 15). The minimal deviation stayed the same and maximal decreased to 2.95 m. Mean deviation was negative.

Tab. 15 *Comparison of mean heights from FMP with mean heights calculated on ALS basis (after elimination of sparse spruce stands)*

Number of stands	**137**
Minimum	-5.6825
Maximum	2.9509
Mean	-1.01713
Standard Deviation	1.726941
RMSE	2.004214

7. DISCUSSION

Discussion is divided into three parts. First the detection of individual trees from ALS data needs to be discussed. The reason is that the accuracy of individual tree detection and subsequent estimation of tree heights have big influence on the results from comparison with field measurement data and data taken from FMP. Then comparisons of ALS data with data from field survey and with data from Forest Management Plan are discussed.

7.1 Discussion on individual tree detection from ALS

The individual trees needed to be detected for obtaining heights of trees. Top of trees were determined by Inversed Watershed Segmentation from inversed CHM. CHM is raster representation of the tree canopy and contains information about the height of individual trees; each cell value represents the height difference between the top of the canopy and the terrain. This model was derived by subtraction of DTM from DSM which were created from laser point cloud.

Individual tree detection requires high density of points (optimum is somewhere between 5 and 10 points/m^2). Lower density increases the probability of omitted tree tops (ZEMEK et al., 2014). The average density of ALS point cloud used for this thesis was 7.8 points/m^2 which means that density of the points from ALS was in the optimum for utilization of these data. However, it still could have some negligible influence on decreased amount of detected trees and higher density of points would probably cause slightly better results.

The accuracy of created models from point cloud depends on the density of point cloud, on the structure and composition of the forest stand but it is also affected by the timing of laser scanning. The deciduous trees have higher permeability for laser beam out of the growing season than during the growing season. Out of the growing season the deciduous trees are more permeable than coniferous and conversely. Data were scanned between 17th and 18th of September 2014 and according to HÁJKOVÁ (2012), leaves of oak and beech within the altitudes of TFE start to fall at the beginning of November. It means that laser scanning took place at a time when deciduous trees still had leaves and thus the laser beams penetrated to the lower layers harder.

The spatial resolution of DTM, DSM and subsequently CHM has high influence on accuracy of tree detection (ZEMEK et al., 2014) and also the algorithm has a considerable effect on the result of tree detection, this result is usually affected by the parameterization of the method (VAUHKONEN, 2010). This leads to further inaccuracies during the procedure of calculation of single tree heights, stand heights and comparison with other height data from field survey and FMP.

The tree tops can be defined as local maxima of CHM (or local minima in case of inverse CHM). The detection of local maxima as tree tops has some problems, not all trees are always detected or local maxima do not correspond to the tree tops. This leads to further inaccuracies during the procedure of calculation of single tree heights, stand heights and comparison with other height data from field survey and FMP. One of the issues in the tree detection is the absence of a maximum because the laser beam did not hit the true top of the tree. According to PITKÄNEN et al. (2004), this problem for example occurs in the moment when top of smaller a tree is adjacent to the branches of taller tree. The top of smaller tree has no local maximum in CHM and only the taller tree is detected. VAUHKONEN (2010) noted that trees that were smaller (their height was 40–60% less relative to the dominant height) were most probably missed. Acceptance of possible trees from pixels that were approximately local maxima could be one solution of this problem (PITKÄNEN et al., 2004). On the other hand, the identification of objects which are not trees as trees can occur together with omission errors (VAUHKONEN, 2010). This problem was clearly visible in results from comparison of calculated mean height with stand height from FMP and it is discussed below.

Fig. 17 shows the various situations how the laser beams can hit the canopy and what are the subsequent mistakes of tree detection and calculation of the heights. In the case A, the laser beam hits the true top of the tree and the real height of this tree can be calculated. Case B shows the situation when the laser beam hits the small tree. However, this tree is ignored in the process of individual tree detection. Situation C is the most common, laser beam does not hit the tree top and the local maximum is not equal to the true top of this tree. In the case D, two tops are detected because one of the hits is intercepted at a lower height. Situation E shows that trees can be assigned a larger height if they are situated on some little hill or mound (which was omitted in the DTM). In the last situation, some tree can be totally ignored in case of sparse stands.

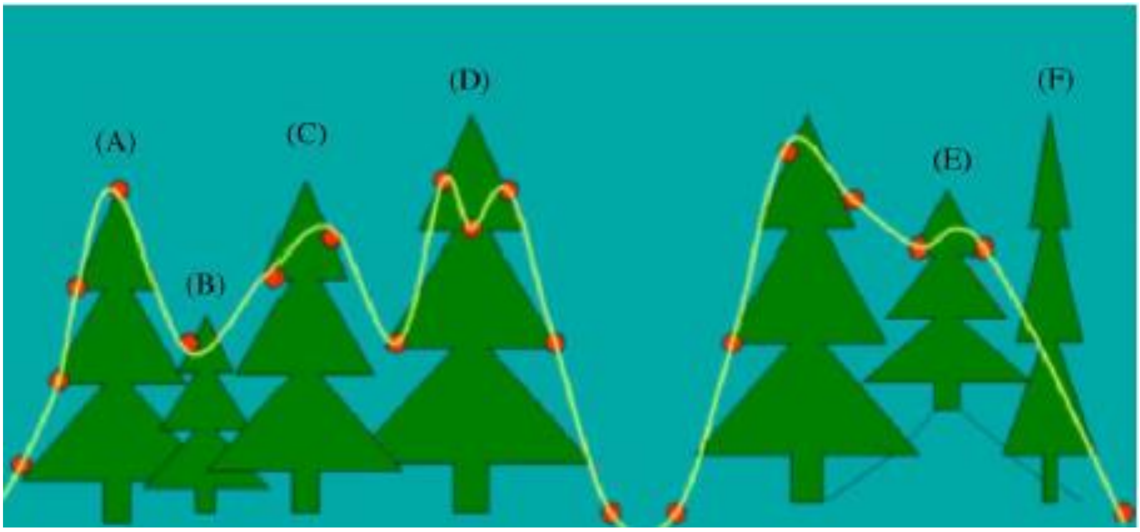

Fig. 17 *Likely scenario in use of ALS in forest survey*. Source: SUÁREZ (2005)

The errors caused by miss the tree top and by point density can be partly eliminated by the utilization of the tool *Focal statistics*.

7.2 Discussion on results from comparison ALS data with data from field survey

Number of trees measured in the field survey was much higher than the number of trees calculated from ALS data. 1,305 trees were targeted by terrestrial survey and 901 trees were detected from ALS data, which means the difference of 404 trees. This very high difference in amount of trees can be mainly affected by trees which were not identified from ALS data. Problems with identification of individual trees from ALS data are discussed in previous section of discussion. This difference could be also caused because some measured trees could have tops outside the plot borders and thus they were excluded from the calculations. Also trees in understorey play a role in this difference. Trees in understorey might not be scanned at all or they could be inhibited by interpolations or filtrations. This can also affect accuracy. The most of trees in understorey were found on the plots with predominance of deciduous trees.

The field measurements of trees can be subjective, the human factor plays a big role. Heights measured by different people in same time can vary even there are methods and rules for measurement of these heights. KOČTAŘ (2011) also highlighted this problem; in his thesis some trees compared with DSM were overestimated and some underestimated. MIKITA et al. (2013b) indicate that tops of trees targeted by hypsometers cannot always positionally correspond to the highest points of the interpolated surface and thus errors of tens of meters can appear. Therefore, the question arises whether height is more accurate if obtained from ground-based measurement or from calculation on basis of ALS data.

When all plots came into comparison, the great errors were observed and the research on causes of these errors was required. This research included the gradual elimination of the plots that have some specific features (Tab. 16).

Tab. 16 *Comparison of measured mean heights with mean heights calculated on ALS basis (different types of plot elimination)*

	All plots	**Elimination of plots with high difference in amount of detected trees**	**Elimination of plots with trees in understorey**	**Elimination of plots with predominance of deciduous trees**
Number of plots	**50**	**36**	**41**	**42**
Minimum	-7.5923	-7.5923	-6.6354	-6.149
Maximum	5.8692	3.3506	3.3506	3.3506
Mean	-1.020484	-0.6105	-0,73372	-0.607
Standard Deviation	2.610969	2.31077	2.19088	1.96273
RMSE	2.803309957	2.39007	2.31048	2.05444

Mean heights from ALS data were subtracted from mean heights measured on the field survey; positive numbers mean that mean heights from field survey were higher than from ALS data and negative numbers mean opposite. The mean errors are all negative (Tab. 16), which disagrees with most authors (NÆSSET, 1997a; NÆSSET & ØKLAND, 2002) who signify from 20 cm to 5 m underestimation of the stand height from ALS data. Explanation for this result may be the underestimation of tree heights in field measurements. Results have improved with eliminations of the plots with specific features.

The best total results were obtained after elimination of plots with predominance of deciduous trees. It means that species composition play very great role in the accuracy of results. There are two reasons why the deciduous trees could strongly affect the results. First reason is that field measurement of the height of deciduous tree is more complicated than measurement of coniferous trees. For deciduous trees, it is crucial to measure the height from distance equal or greater than the estimated height of the tree; the shorter the distance is, the greater errors in height measurement occur (ÚHÚL, 2003). The second reason is that detection of the tops of deciduous trees from ALS more is more problematic than in the case of coniferous; deciduous trees has very ofter multiple crowns of irregular shapes (VAUHKONEN, 2010).

7.3 Discussion on results from comparison ALS data with data from Forest Management Plan

The first problem for comparison of stand heights from ALS data with stand heights from Forest Management Plan is already difference in definition of stand height. Stand height can be understood as arithmetic mean of all trees within the stand or mean height of the average trees (average trees are trees with mean DBH), then there are also used dominant height, top height and predominant height. Stand heights from ALS were calculated as arithmetic mean of all heights within stands, but this is not used in common practice of determination stand heights during the creation of FMPs. Stand heights in used FMP are mean heights of the average trees which are used as alternative for arithmetic mean height in characterization of forest stands.

The detection of average trees from DBHs within stands and subsequent mean heights calculation of these average trees could be one solution of this problem. However, KANKARE (2014) noted that DBH cannot be measured directly from ALS as heights and modelling is needed. Calculation of DBH is available by regression models. Its accuracy is mostly dependent on suitability of DBH models and the Czech Republic does not have such models yet (MIKITA et al., 2013a). Utilization of top height, dominant height or predominant height in creation of FMPs would be second solution, because as VAUHKONEN et al. (2009) noted, detected trees from ALS are highly representative of the dominant tree layer. Biggest and tallest trees in main layer have biologically better importance in evaluation of site productivity. Furthermore, the problem of unidentified trees in understorey from ALS data would disappear.

At the first sight on results, very high maximal deviations were noticeable. These maximal deviations were highly over 20 m in the case of oak and beech stands. Spruce stands did not show so high maximal deviation as oak and beech stands, however still the maximal deviation was higher than 10 m. So high deviations signify that mean height from ALS were very small in comparison with the stand heights from ALS. The reason of so high deviations was found after the reviewing of the problematic stands. Stands, where these deviations appeared, were very sparse (Fig. 18). Points identified as trees by inversed watershed segmentation were found also in open areas; on places where no trees apear in real. The heights of these wrongly identified trees were very low, which consequently decreased the mean height of stands. Spruce stands did not include so high maximal deviations as oak and beech stands. The reason is that spruce stands were not found sparse to such extent as oak and beech stands. Results were much better after the elimination of sparse stands. However, just elimination of such stands is not solution of the problem. One of the solutions of such issue could be cutting the CHM in required height; this method is explained in TRČKA (2015). Required height would be determined as borderline (for example 1 m) and anything lower than this value would not be identified as tree.

Fig. 18 *Illustration of incorrect detection of tree tops within the sparse oak stands*.

Mean heights of stands calculated from ALS data were subtracted from stand heights taken from FMP; positive numbers in deviations denote that mean heights from ALS were lower than stand heights from FMP and negative numbers mean opposite. The mean deviations of stands (after elimination of all sparse stands) were again negative values as in case of comparison of ALS mean height and mean heights from field survey. Once more this disagree with the general statement that heights from ALS are mostly underestimated. There are some possible reasons why the results do not agree with literature. The stand heights from FMP could be underestimated; again it may be affected by human factor. Second reason could be the presence of trees exceeding the main layer. These trees could not be taken into account in the process of creating FMP. The occurrence of these trees in calculation of the mean heights from ALS could increase the value of these mean heights. Another probable reason could be different timing of data acquisition. FMP is from the year 2012 and ALS was performed in 2014, which logically means that trees were higher during of ALS. Thus stand heights from FMP must be smaller than heights from ALS.

Despite some visible problems and resulting errors, ALS is a very promising and perspective technology for utilization in forest inventory. Compared to traditional forest inventory methods, ALS provide the precise determination of tree position and shows the spatial variability of vegetation heights.

8. SUMMARY

In the beginning of this thesis, the technology of ALS, its utilization in forestry sector (mainly focused on forest stand inventory) and basics of forest mensuration were described. The height, which was examined attribute in this thesis, is directly available from ALS data. Utilization of ALS data for estimation of tree and stand parameters have been studied and tested in many countries. Forest inventories based on ALS have already become common and standard practice in the Nordic countries, the United States, Canada and other countries. LiDAR generally is very promising technology and it is only a matter of time, when it will be used as common forestry practise worldwide. For example in the Czech and Slovak Republic, implementation of ALS in forest inventory is already tested.

The principal aim of presented thesis was calculation of forest stand heights on the basis of airborne laser scanning on the territory of TFE Křtiny. Point cloud data from ALS were interpolated into DTM, DSM and subsequently by subtraction of DTM from DSM into CHM of entire area of TFE. Inverted CHM was used for detection of tree tops by Inversed Watershed Segmentation; tree tops were identified as local minima. Calculated mean heights were compared with heights measured on sample plots and with height data taken from FMP of TFE.

When comparing ALS with field survey, fewer trees were detected from ALS data than by field survey. It was apparently caused by tree species composition and by vertical spatial structure. The results did not agree with most authors, even after elimination of plots with trees in understorey and plots with predominance of deciduous trees. Literature signifies from 20 cm to 5 m underestimation of the stand height from ALS data; however heights from ALS were higher than heights measured on field. Explanation for this result may be the underestimation of tree heights in field measurements, presence of trees in understorey and deciduous trees.

Fundamental problem of comparison of ALS data with FMP was the utilization of mean height of the average trees in FMP. Few solutions of this issue were suggested. Another problem was the presence of sparse stands. These stands, especially in the case of beech and oak stands, increased maximal deviations to more than 20 m. The elimination of these stands showed the better results, but again the problem of overestimated values from ALS was observed. The best results were obtained in spruce stands, which mean that species composition has big influence in accuracy of ALS.

Laser scanning has very big potential in forestry sector. However, the individual tree detection has still some problems and there are many factors that affect the accuracy. The subsequent development of technology and methods for utilization in forestry sector in conditions of Central Europe is required.

9. ZÁVĚR

Na začátku této diplomové práce byla popsána technologie LLS a její využití v lesnictví, zejména pro potřeby inventarizace lesa. Také byly popsány základy dendrometrie, důraz byl kladen na stromovou a porostní výšku. Laserové skenování má velký potenciál pro využití v lesnictví. Zkoumanou dendrometrickou veličinou v této práci byla výška. Výška je taková veličina, která je přímo dostupná z dat LLS. Vyžití dat z LLS pro odvození stromových a porostních veličin již bylo studováno a testováno v mnoha zemích. Lesní inventarizace využívající data z LLS se již staly běžnou praxí v Nordických zemích, Spojených státech, Kanadě a dalších zemích. LiDAR obecně je velmi perspektivní technologie a je jen otázkou času, kdy ji v lesnické praxi začnou využívat i další země. Například v České a Slovenské republice je již testováno využití dat z LLS v inventarizaci lesů.

Hlavním cílem předkládané diplomové práce byl výpočet porostních výšek na základě leteckého laserového skenování na území Školního lesního podniku Křtiny. Z mračna bodů, které bylo výstupem LLS, byl vytvořen DMT, DMP a následně, po odečtení DMT od DMP, byl vytvořen tzv. digitální model korun (CHM). Převracený rastr CHM byl použit pro detekci vrcholků stromu metodou tzv. segmentace inverzního povodí; vrcholky stromů byly určeny jako lokální minima. Výšky stromů identifikovaných v CHM byly následně porovnány s daty naměřenými při terénním výzkumu a s porostními výškami získanými z LHP.

Při porovnání LLS a pozemním měření, z dat LLS bylo identifikováno mnohem méně stromů, než bylo změřeno v terénu. Toto bylo zřejmě způsobeno druhovou skladbou a vertikální prostorovou skladbou. Výsledky z porovnání nesouhlasily s mnoha autory a to ani po odstranění výzkumných ploch, na kterých se nacházelo velké množství stromů v podúrovni a také na kterých byla převaha listnatých stromů. V literatuře se uvádí, že LLS data jsou o 20 cm až 5 m podhodnocená, avšak výšky vypočítané z LLS byly vyšší nežli ty naměřené v terénu. Vysvětlení této situace může být výrazné podhodnocení výšek při pozemním měření nebo přítomnost stromů v podúrovni a také přítomnost listnatých druhů dřevin.

Použití porostní výšky ze středního kmene u LHP a použití střední výšky (aritmetického průměru) u LLS bylo základním problémem při porovnávání LLS a LHP. Dalším problémem byl výskyt velmi prořídlých porostů. Tyto porosty, zejména v případě buku a dubu, zvyšovaly maximální odchylky na víc jak 20 m. Odstranění těchto porostů přineslo lepší výsledky. Avšak stejně jako při porovnávání s pozemním měřením, i zde byl problém s nadhodnocenými hodnotami z LLS. Nejlepší výsledky byly dosaženy u smrkových porostů, což naznačuje, že druhová skladba má velký vliv na přesnost LLS.

Letecké skenování má velký potenciál pro využití v lesnictví. Nicméně, individuální detekce stromů má stále své problémy a přesnost je ovlivněna mnoha činiteli. Je nezbytný budoucí vývoj jak technologie, tak i metod pro využití v lesnictví v podmínkách střední Evropy.

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Annex No. 2 *Map of field survey plots within the area of TFE Křtiny*

Annex No. 3 *Map of stands within the area of TFE Křtiny*

Annex No. 4 *Table of comparison between mean heights from ALS and field survey (FS: field survey, C: coniferous, D: deciduous)*