

ROYAL INSTITUTE OF TECHNOLOGY

Calibration of ALS Intensity Data

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Abstract

With general advancements in computer technology and development of direct geo-referencing technology, such as GPS, airborne laser scanning systems came into widespread use especially after 2002. In spite of relatively high cost of purchase, the systems proved to be cost effective, providing fast and in large volumes 3D geospatial data acquisition with unprecedented accuracy and relatively modest processing complexity. Country-wide collection of laser scanning data, mainly due to DTM derivation, is becoming an attractive possibility for mapping. Since 2009, Swedish Government has approved and financed the project of developing the New National Elevation Model (NNH) for the country of Sweden, with aspects of monitoring climate changes and other environmental impacts. The National Land Survey of Sweden, which is commissioned to carry out the project, is offering this highly accurate scanned data less expensive to secondary users, such as companies specialized in forestry applications, etc. Beside the geospatial data (X, Y, Z), laser systems additionally record the received signal intensity for each measurement. So far, intensity values were just an additional variable, not used extensively, but in recent years many efforts have been made to understand and interpret these values. The wider use of intensity data is missing due to the lack of techniques to calibrate them, so that they represent values proportional to the scattering characteristics of the target. In the scope of this thesis it was examined which properties influence intensity values and to what degree. Already proposed methods for calibration were summarized and the most suitable one was implemented based on the data from the NNH project and instruments used for it. The results proved to be good both empirically and visually, with reduced intensity variations over the same targets. The potentials of using this corrected data are presented, such as surface classification, automatic object recognition, multi-temporal analysis, and more.

Sammanfattning

Med allmänna framsteg inom datateknik och utveckling av direkta georeferering teknik, såsom GPS, kom flygburen laserskanningsystem till omfattande användning, särskilt efter 2002. Trots relativt höga kostnaden för inköp visade sig systemen att vara kostnadseffektiva, ger snabb och i stora volymer 3D geospatiala datainsamling med oöverträffad precision och relativt blygsamma bearbetningskomplexitet. Landsomfattande insamling laserskanningsdata, främst på grund av DTM härledning, håller på att bli en attraktiv möjlighet för kartläggning. Sedan 2009 har svenska regeringen godkänt och finansierat projektet av utvecklingen av den nya nationella höjdmodellen (NNH) för Sverige, med aspekter som övervakning av klimatförändringar och annan miljöpåverkan. Lantmäteri, som genomförar projektet, erbjuder detta mycket exakt skannade data billigt åt sekundära användare, till exempel företag som specialiserat sig på skogsbruk etc. Vid sidan av geospatialsdata (X, Y, Z), förvarar lasersystem dessutom intensitet av den mottagna signalen för varje mätning. Intensitetsvärden har hittills varit bara en ytterligare variabel, inte används i stor utsträckning, men på senare år många insatser genomfördes för att förstå och tolka dessa värden. En bredare användning av intensitetsdata saknas på grund av brist på tekniker för att kalibrera dem, så att de representerar värden i proportion till spridningsegenskaper av målet. Inom ramen för denna avhandling undersöktes vilka egenskaper är de, som påverkar intensitetsvärden och i vilken grad. Redan föreslagna metoder för kalibrering sammanställdes och den mest lämpliga genomfördes baserad på data från NNH projektet och instrument som används för det. Resultaten visade sig vara bra både empiriskt och visuellt, med minskad intensitetsvariation över samma mål. Möjligheterna att använda denna korrigerade data är presenterade, såsom ytaklassificering, automatiskt objektigenkänning, multi-temporal analys, med mera.

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List of Figures

Figure 1: Illustration of ALS measurement. (Wagner, 2007)......4 Figure 2: A high-speed counter measures the TOF from the start pulse to the return pulse. The time measurement is converted to a distance by using the Figure 3: Multiple discrete returns for seven pulses transmitted through a forest canopy (left) and a transect discrete return point cloud data, showing Figure 4: Phase comparison between transmitted and received CW beam. Figure 5: Scanning pattern: (a) saw toothed produced by Optech ALTM series and (b) sinusoidal pattern produced by Leica ALS scanners. Both are using Figure 6: Main components of an ALS system; Riegl LMS-Q560 as the Figure 7: LiDAR system- airborne and ground segment. (Wehr, 2008)10 Figure 8: Power transmitted, reflected, and received. (Shan and Toth, 2008) 12 Figure 11: Spread of the beam or pulse that has been emitted by the laser rangefinder and its divergence on its path to the ground object or target and on its return from the object or target. (Shan and Toth, 2008)......18 Figure 12: Multiple returns along vertical surfaces. (Shan and Toth, 2008)....19 Figure 13: Reflectivity spectrum of frost and snow. Data ASTER spectral Figure 14: Reflectivity spectrum of concrete and cement. Data ASTER Figure 15:Reflectivity spectrum of asphalt and tar. Data ASTER spectral Figure 16: Reflectivity spectrum of different wood samples. Data ASTER Figure 18: Highly reflective surface on the terrain that is not at right angles to the incident laser pulse or beam will reflect its radiation off to the side and will not return a signal to the laser rangefinder. (Shan and Toth, 2008)......25 Figure 19: Reflectivity of a diffuse target. (Shan and Tooth, 2008)......25 Figure 20: ALS results for asphalt road measured at 500m altitude. Each point is an average of several points having the same incidence angle. The error bars represent the standard deviations of the average. (Kaasalainen et al., 2009)...26 Figure 21: Comparison of intensities measured with the ones approximated by

Figure 22: Wavelength dependence of atmospheric transmission shown for
clear and hazy conditions. (Shan and Toth, 2008)28
Figure 23: Intensity image showing visible AGC effect on recorded intensities.
(Roth; Leica Geosystems, 2010)
Figure 24: Measured mean intensities over time at different reflectance
surfaces. (Larsson et al., 2007)
Figure 25: Example of a header of LAS file
Figure 26: Correlation of the average intensity values of the cells when AGC is
on and when it is off. Red dots are considered to be noise, and they were
removed from the modelling process. (Vain et al., 2010)
Figure 27: Correlation between observed and predicted intensity values using
presented equation. The root-mean-squared error between predicted and
observed intensity values is 5.65.(Vain et al., 2010)
Figure 28: AGC correction applied to beach sand laser points. Ion denotes the
intensity values when AGC is on, Ioff denotes the intensity values when AGC
is off, AGC represents the AGC values, and Model denotes the Ion values
corrected (Vain et al 2010) 39
concerced. (vuil et ui., 2010)
Figure 29: The near-infrared digital camera based reference measurement.
Figure 29: The near-infrared digital camera based reference measurement. (Vain et al., 2009)
Figure 29: The near-infrared digital camera based reference measurement. (Vain et al., 2009)
Figure 29: The near-infrared digital camera based reference measurement. (Vain et al., 2009)
Figure 29: The near-infrared digital camera based reference measurement. (Vain et al., 2009)
Figure 29: The near-infrared digital camera based reference measurement. (Vain et al., 2009)
Figure 29: The near-infrared digital camera based reference measurement. (Vain et al., 2009)
Figure 29: The near-infrared digital camera based reference measurement. (Vain et al., 2009)
Figure 29: The near-infrared digital camera based reference measurement. (Vain et al., 2009)
Figure 29: The near-infrared digital camera based reference measurement. (Vain et al., 2009)
Figure 29: The near-infrared digital camera based reference measurement. (Vain et al., 2009)
Figure 29: The near-infrared digital camera based reference measurement. (Vain et al., 2009)
Figure 29: The near-infrared digital camera based reference measurement. (Vain et al., 2009)
Figure 29: The near-infrared digital camera based reference measurement. (Vain et al., 2009)
Figure 29: The near-infrared digital camera based reference measurement. (Vain et al., 2009)

Index of Tables

Table 1: Elevation Accuracy - RMSE Values (from Optech)	14
Table 2: Specification and accuracy values for Leica IPAS10 System.	NUS4 is
the iMAR FSAS unit; DUS5 is the Litton LN-200 unit; NUS5 is a Sag	gem unit;
and CUS6 is the Honeywell MicroIRS unit	15
Table 3: Typical reflectivity of various materials at 900nm	20
Table 4: Data about processed files	46

List of Abbreviations

- AGC- Automatic Gain Control
- AGL- Above ground level
- ALS- Airborne Laser scanning
- ALSPP- ALS Post Processor
- ALTM- Airborne Laser Terrain Mapper
- BRDF- Bidirectional reflectance distribution function
- CW- Continuous wave signal
- **DEM-** Digital Elevation Model
- DTM- Digital Terrain Model
- FGI- Finnish Geodetic Institute
- FOV- Field of view
- GIS- Geographic Information System

- GPS- Global Positioning System
- IFOV- Instantaneous field of view
- IMU- Inertial measurement unit
- LAS- Log ASCII Standard
- LiDAR- Light detection and ranging
- Mpia- Multiple pulse in air
- NNH- New national elevation model
- POS- Position and orientation service
- PRF- Pulse repetition frequency (rate)
- SAR- Synthetic Aperture Radar
- SNR- Signal-to-noise ratio
- TOF- Time of flight
- TUW- Technical University Wien (Vienna)

Table of Contents

1	Introduction	1
	1.1 Objective.	2
	1.2 Motivation	2
	1.3 Thesis outline	<u>2</u>
2	Laser scanning systems	3
	2.1 Laser ranging	3
	2.1.1 Pulsed-type lasers	4
	2.1.2 Continuous-wave lasers	6
	2.2 Laser profiling and scanning	<u>7</u>
	2.3 System configuration	8
	2.4 Power output	<u>11</u>
	2.5 Commercial system suppliers	12
	<u>2.5.1 Optech</u>	<u>13</u>
	2.5.2 Leica Geosystems	<u>14</u>
	2.5.3 Riegl	<u>15</u>
3	Intensity measurements	17
	3.1 Beam divergence.	17
	3.2 Target cross-section	<u>18</u>
	3.3 Reflectivity	<u>19</u>
	3.4 Effects which influence intensities	20
	3.4.1 Wavelength of the laser beam	21
	3.4.2 Slant range	23
	<u>3.4.3 Incidence angle</u>	24
	3.4.4 Atmosphere.	28
	3.4.5 Automatic gain control	
	<u>3.4.6 Other influences</u>	29
4	Data	
	4.1 New National Elevation Model (NNH)	32
	<u>4.2 LAS point cloud data</u>	33
	<u>4.3 Trajectory files (TRJ)</u>	<u>34</u>
_5	Already proposed correction methods	35
	5.1 Data driven correction.	<u>36</u>
	5.2 Model driven correction.	<u>36</u>
	5.3 AGC correction.	<u>37</u>
	5.4 Atmospheric attenuation.	<u>39</u>
	5.5 Calibration.	40
6	The most suitable calibration algorithm.	
	<u>6.1 Implementation</u>	
_	<u>6.2 Evaluation of results</u>	
_7	Potential applications.	47

8 Conclusions and future work.	50
References	

1 Introduction

Country-wide collection of laser scanning data, mainly due to DTM derivation, is becoming an attractive possibility for mapping. In addition to updating the DTM, the georeferenced point cloud may be used in a multipurpose way for various other applications: updating of most important national GIS databases, city modeling, real estate deals, forest inventory, forest growth assessment, telecommunication planning, environment impact assessment, planning in civil engineering, optimization of building planning. The previous use of un-calibrated laser intensity includes estimation of planimetric shifts between ALS strips, as reported by Burman (2000), Maas (2001); segmentation of ALS data stated by Oude Elberink and Maas (2000); object classification according to Song et al. (2002), Luzum et al. (2005), Moffiet et al. (2005). The more effective use of intensity values is missing partly due to the lack of techniques to calibrate them. Understanding how the intensity values are obtained and which factors influence them, can lead to derivation of the most suitable algorithms for correcting intensities with the goal that they actually represent the reflectance of the target or a ground.

One of the factors which have to be kept in mind, are the instruments used together with principles of their data recordings and processing. It will be presented in the thesis how certain laser scanning systems deliver data already corrected for certain effects, such as range from the airplane to the ground. Some of the systems apply automatic gain adjustments of the received power- they increase the gain when dealing with low power and decrease it when the power is too high. As a consequence, gain adjustment allows more points to be recorded with more precise range determination, but also has an effect on intensity values. Understanding the quantity of the change can lead to proper correction method.

At the moment, there are two types of systems available on the market: pulsed- type and continuous-wave lasers. Laser systems can record discrete returns (e.g. the peak of amplitude of signal) or full-waveform of the pulse. Principles on which they work will be described, as well as a reason why fullwaveform digitization is not much used in ALS measurements even if it allows deriving the back-scatter cross-section of targets.

Already proposed calibration methods are summarized and some of the research studies conducted are described more detailed. As stated by Kaasalainen et al. (2009) there is a current EuroSDR (http://eurosdr.net) project aiming at feasible and cost-effective ALS radiometric calibration techniques.

Since 2009 the Swedish Government has approved and financed the project

of developing a new national elevation model for Sweden. The data is available quite cheap to secondary users with wide potential of application. Based on the instruments used for the project together with data prerequisites, the most suitable calibration algorithm was implemented and tested on the data. The results seem to be quite good, both empirically and visually. The possibilities of using calibrated data are reported.

1.1 Objective

Multiple studies showed the potential of using intensity values for a great variety of applications, such as surface classification, automatic object recognition and multi-temporal analysis, e.g. strip adjustment, forestry, and glaciology. The objective of the thesis is to understand what influences intensity values, to what degree, and to perform correction of it, with the goal that intensities actually represent values that are proportional or equal to reflectance of the scanned surface. This is done in order to use intensity values with more accuracy and understanding of their meaning. Already proposed methods for calibration are summarized, and finally, the most suitable algorithm was implemented and tested on the NNH data.

1.2 Motivation

With current NNH project, which started from 2009 and it is going to continue for at least few more years, there is a lot of spatial data available on the market. Although the primary goal is to develop country wide DEM, there is a need to use this data in the best possible way. Data is provided by National Land Survey quite cheap and quite fast after data acquisition. The secondary usage covers a very broad range of applications, from forestry applications to different kinds of scientific research studies. The usage of intensities could contribute to more accurate results and be an additional tool for e.g. classification purposes, or even an indicator for quality assessment of derived products.

1.3 Thesis outline

The overview of laser scanning systems is given in the second chapter, together with the functioning principles. Third chapter deals with intensity measurements and effects which influence them. Data and NNH project are presented in the following chapter, chapter four. Following, calibration methods are summarized and the one which was found the most adequate was implemented and tested. The results are showed in the chapter six. Possibilities of using calibrated data are presented in the following chapter.

Finally, conclusion and future work are reported in the last part.

2 Laser scanning systems

The development of topographic laser profiling and scanning systems in recent years has progressed and became one of the most important technology for geospatial data acquisition in the last millennium, according to Shan and Toth (2008). 3D data collection is explicit, fast and in large volumes, with keeping the unprecedented accuracy and relatively modest processing complexity. Systems can be installed on airborne and land-based platforms, but in the scope of the thesis, the focus will be put on airborne systems. Although laser was invented in early 1960s, the exploitation of this device began rapidly only with the introduction of direct geo-referencing technology in the mid-1990s and general advancements in computer technology, which made possible their commercial use. As the technology improved and experience was gained, airborne-based systems came to ever increasing use since 2002, despite of their quite expensive cost of purchase. Shan and Toth (2008) report that in 2007 more than 200 systems were used world-wide. LiDAR stands for Light detection and ranging. Laser scanners belong to active sensors, together with radar, with the target being illuminated by the sensor radiation and therefore independent of external illumination (the Sun). Understanding radar is necessary to understand laser systems, because similar ranging techniques are applied.

2.1 Laser ranging

All the laser measurements are based on accurate distance determination. Distance or range measurements are always based on precise measurement of time. We differentiate two methods based on laser type: pulsed-type and continuous wave lasers. The return signal can be recorded as discrete-return (only point at certain place in the pulse shape is stored, e.g. the peak of the amplitude) or the full-waveform of the signal is digitized (the whole pulse shape is stored); as shown in the Figure 1.



Figure 1: Illustration of ALS measurement. (Wagner, 2007)

Both the transmitted and received pulse shape can be digitized and recorded. Digitization of the whole pulse shape outputs a time series yielding a full-waveform characterizing a vertical structure of a target. Reduction of the amplitude peak or widening of the pulse is caused by photon spread over greater amount of time. Therefore, to determine elevation variation or a surface reflectance attributes, one has to know pulse width and amplitude. Broadening of the peak is a measure of a vertical relief of a target within the footprint. As a result we have a complexly shaped signal. In vegetated areas, the signal stores a height distribution, from signal start to end, producing 3D volumetric image of reflected laser energy. With depth through vegetation, the energy of the pulse is decreasing. With the account of this extinction, the height profile of canopy can be derived. Consequently, the stored data volume is much larger than in discrete echo recordings.

2.1.1 Pulsed-type lasers

Pulsed-type systems are based on measurements of time of flight (TOF) of a

short but intense pulse of laser radiation, which is traveling from laser ranging instrument to the object and is reflected from the object and returned back to the instrument, as shown in the Figure 2. The range from emitter to the object is derived using the following equation:

$$R = v * t/2$$

with *R* being the slant distance or range, *v* being the speed of electromagnetic radiation, which is very accurately known value and *t* the measured time interval, on which range precision or resolution is mainly dependent. Due to large distance traveled by the pulse in airborne-based systems, powerful pulse needs to be used.



Figure 2: A high-speed counter measures the TOF from the start pulse to the return pulse. The time measurement is converted to a distance by using the formula above. (Shan and Toth, 2008)

Several targets can be illuminated by a single laser pulse. The detection of them depends on the resolution of the pulse. Range resolution and consequently object detection is expressed by following equation:

$$\Delta R_{tar} = \frac{v}{2} * t_p \tag{2.1}$$

where t_p presents pulse length. The actual length of the pulse emitted by the laser is an important characteristic of any laser system, since it has a major impact on how multiple returns can be detected or differentiated. If the pulse lasts 10 ns then the pulse length will be 3 m at the speed of light (v). To achieve a 1 cm ranging resolution, the timer should be able to measure a 66 ps interval, which would require a clock rate of about 15 GHz. The limiting factor is therefore the processing speed of ranging electronics.



a: 1st = Ground b: 1st = Highest canopy, 2nd = Mid-story, Last = Ground c: 1st = Highest canopy d: 1st = Within crown, Last = Within crown e: 1st = Within crown, Last = Under-story f: 1st = Highest canopy, 2nd = Within crown, 3rd = Mid-story, Last = Ground g: 1st = Under-story

Figure 3: Multiple discrete returns for seven pulses transmitted through a forest canopy (left) and a transect discrete return point cloud data, showing data separated by return number. (Shan and Toth, 2008)

The detector outputs a time series of distinct peaks which are above the detection threshold, as shown in the Figure 3. Usually, up to four returns are detected, consequently when the area illuminated by the beam yield enough energy to exceed the detection threshold. Detection of separate returns depends on pulse width, detector sensitivity, system's SNR performance, defined detection threshold and implementation of ranging electronics.

2.1.2 Continuous-wave lasers

Second method refers to the lasers transmitting the continuous laser beam instead of the pulse. The phase difference between transmitted and received beam after reflection from the object is used to determine the distance from the instrument to the object; shown in the Figure 4.



Figure 4: Phase comparison between transmitted and received CW beam. (Shan and Toth, 2008)

The weakened reflected signal is then amplified and subjected to demodulation - separation of the measuring and carrier waves. Next, the reflected signal is compared with the signal of the original transmitted beam. Phase measurements are usually done using digital pulse counting technique, as reported by Shan and Toth (2008). Fractional part $\Delta\lambda$, together with the integer number of wavelengths *M* multiplied by known wavelength of the laser beam gives the total distance traveled by the beam.

$$R = (M\lambda + \Delta\lambda)/2 \tag{2.2}$$

The amplitude of the sinusoidal wave is modulated and dependent on wave's period t_m and wavelength λ_m . Ranging resolution can be improved using shorter wavelengths of the beam. For required high range resolutions, CW lasers are better option than the pulsed lasers. Achieving the same resolutions with pulsed lasers would mean the need of very short pulses (time resolution of 1ps) with sophisticated time interval counting electronics. Obviously, CW systems are used for high precision ranging applications, mainly in terrestrial applications due to the high power needed to continuously emit the radiation. CW lasers usually use two frequencies- the highest frequency determines the range resolution, while the lowest is used to solve range ambiguity. For airborne surveying, CW laser with three frequencies is required. This, together with usually not needed predefined accuracy of less than 5cm, makes CW lasers rarely used in airborne applications.

2.2 Laser profiling and scanning

A laser ranger mounted on an airborne platform could also be called laser altimeter. With the position and altitude of the airborne platform measured and determined, e.g. using a GPS/ IMU system, the corresponding range measured from that point will allow the determination of ground point elevation. Scanning mechanism- rotating mirror or a prism, enables additional profiles to be measured, mostly in cross-track direction, generating positions and elevations of a mesh of points, called LiDAR point cloud. The laser beam is deflected in vertical and horizontal direction between every laser shot by two mirrors mounted on galvanometers. Figure 5 shows examples of scanning patterns.



Figure 5: Scanning pattern: (a) saw toothed produced by Optech ALTM series and (b) sinusoidal pattern produced by Leica ALS scanners. Both are using oscillating mirror as a scanning mechanism. (Shan and Toth, 2008)

Airborne-based laser profilers are, although in a small number, still used, as reported by Shan and Toth (2008), for mapping purposes of barely changing surfaces, such as water bodies, areas covered by ice and flat land surfaces. Their operational use is mostly aimed for research studies- glacier, forest, sea surface topography, etc, due to their lower operational cost, although with a limited coverage in comparison with airborne laser scanners.

2.3 System configuration

Airborne-based laser scanners generally comprise several units (schematically shown in the Figure 6):

1. The laser, together with transmitter and receiver optics. The transmitter and receiver aperture are mounted in a way that the beams share the same optical path. The transmitter aperture is always smaller than receiver's aperture. This assures that the points on the ground illuminated by the laser radiation are always in the instantaneous field of view (IFOV) of the receiver. Beam divergence is always smaller than IFOV, so that all the laser points are always contained in the receiver's field of view (FOV). The optical signal is transformed to electric current by photodiode, whose performance depends greatly on the laser wavelength. The responsivity of photodiode should be as high as possible. The return signal is composed of reflected laser energy and noise (detectors internal noise, i.e. dark counts and external solar illumination). Narrowband optical filters will usually be placed over the photodiode in order to cut down or eliminate the effects of sunlight or other sources of

optical noise that may cause spurious signals. Sometimes, internal amplification is applied on the signal. Further, transimpedance amplifier converts photocurrent into voltage. The transimpedance amplifier should exhibit a high conversion gain and a low noise figure. The higher the SNR ratio at the output of the transimpedance amplifier the more sensitive is the receiver and the lower is the standard deviation for ranging, and the more precise is the ranging result. Receiving detector, time counter and digitizing unit are also parts of the laser unit.

2. The scanning mechanism, such as rotating mirror and angle encoder, used for scanning in cross-track direction. Optical element (rotating plane or polygon mirror) directs a stream of laser radiation at known angles, in the direction lateral or cross-track relative to the flight path, allowing the sequential measurements of the ranges and angles to successive points along this line. Profiles of the ground in cross-track, while aircraft is traveling along-track allow the elevations of the ground and its objects to be determined for a large swath of the terrain.



Figure 6: Main components of an ALS system; Riegl LMS-Q560 as the model. (Shan and Toth, 2008)

3. Electronics part, which comprises hardware for processing and control of the overall system. Normally, it is computer based, equipped with display and user interface. Commands can be given to the system to execute specific action. This unit controls the data recording system that collects and stores the measured time and waveform data from the laser rangefinder and the angular data from the scanning mechanism, together with the corresponding data from the GPS receiver and the IMU.

- 4. Positional and orientation system (POS), such as differential GPS and IMU, which is a basic for absolute positioning of the aircraft and georeferencing of the point cloud. Raw navigation data, such as GPS observations, linear and angular accelerations and angular encoder values are recorded. IMU determines roll, pitch and yaw of the laser instrument. In post-flight processing operations, accurate position, altitude and attitude of the aircraft are determined.
- 5. Software used to control and coordinate operations of the system: carry out recording, storage and preliminary processing of the measured data collected in-flight. Initial software package enables mission planning, as well as implementation of the planned flight lines by a pilot. Further, it allows setting of laser rangefinder parameters such as scan rate, pulse rate and scan angle.
- 6. Imaging device, such as digital or video camera



Figure 7: LiDAR system- airborne and ground segment. (Wehr, 2008)

Figure 7 shows all segments of airborne systems, together with the processing principles. LiDAR system and POS sample the data independently during the flight. LiDAR stores the coordinates in LiDAR's coordinate system, while POS measures GPS data including carrier phase information together with orientation data of IMU unit. POS data, stored as a function of GPS time, together with laser scanner data stored with timestamps generated from received GPS signal, can finally be synchronized and point cloud can be georeferenced. Using POS data, the position of the air-plane can be determined with very high precision, which consequently influences positional accuracy of the point cloud, reaching accuracies better than 10 cm.

2.4 Power output

The output for laser pulse is concentration of laser energy on a given area, so called radiant exposure. The output depends on the type of the laser (pulsed or CW) and the range to the target. CW lasers using phase measuring technique deploy relatively low power, varying between 10- 20 mW for distances up to 20m and 20-40 mW for ranges up to 50-70m (terrestrial based lasers). For comparison, pulsed-type lasers in airborne-based systems operating at altitudes of few kilometres, generally employ peak power level of 1-2 kW. The maximum power output of a pulse is limited by eye safety regulations. The longer the wavelength and the shorter the pulse width contributes to the more safety. Hence, 1550nm systems use higher power levels than the systems operating on 900 and 1064nm, having the same divergence and pulse width. Transmitted pulse energies are usually not provided by the instrument producers, which would be of great help when dealing with intensities.

Energy generated per pulse can be calculated using the following equation:

$$E = P_{peak} * t_p \tag{2.3}$$

with t_p being pulse duration. The average power can be calculated using:

$$P = E * F \tag{2.4}$$

with *F* being pulse repetition rate (PRF). If the pulse duration t_p is 10 ns, then the energy *E* generated per pulse is $E = P_{peak}$. $t_p = 20 \mu$ J. The average power for a PRF of 50 kHz will be $P = E F = 0.000020 \times 50,000 = 1$ W.

With longer distances, such as those required for airborne and space-borne platforms, a longer time interval will elapse between the emission and the reception of individual pulses. For a distance of 1000 m that is typical for an

airborne laser ranger, the elapsed time will be 6.7 μ s, in which case, the maximum PRF will be 1/6.7 μ s, which is 150 kHz. Thus, in general terms, a longer time interval between successive pulses will usually be required when longer distances need to be measured. However, this remark needs to be tempered by the recent introduction of the technique of having multiple laser pulses in the air simultaneously.

In early 2000s systems increased their PRF at the price of reducing the energy of the emitted pulse and, in this way, the ranging accuracy was decreased due to the less favourable SNR. Current laser systems are more powerful, so this phenomenon does not impact current state-of-the-art systems. The fact that there are multiple pulses travelling back and forth, however, requires additional processing to resolve the ambiguity (to properly pair an emitted pulse to a received one).



Figure 8: Power transmitted, reflected, and received. (Shan and Toth, 2008)

The Figure 8 is a schematic representation of the laser power distribution. The power of return signal will finally be just a small fraction of emitted power. Therefore, it needs to be amplified on the receiver and filtered from any noise before final range can be measured from elapsed time.

2.5 Commercial system suppliers

Two principal commercial suppliers of ALS systems in terms of volume are Optech International Inc. and Leica Geosystems. The third one, Riegl, also delivers complete systems, as well as laser scanning engines to a number of system suppliers and service providers in Germany and North America.

2.5.1 Optech

Canadian company Optech is manufacturing airborne-based laser systems, in series called ALTM. The first one, ALTM 1020, was introduced in 1993. Through the years, the design has stayed the same, with improvements in operational characteristics and accuracy. These systems usually employ a Class IV pulsed laser with a wavelength of 1047 nm. Towards the end of 2006, multiple pulses in air technology was introduced, which means that the system is firing a second pulse before the previous one has reached the receiver. The consequence is also higher PRF, 167 kHz in the latest ALTM Gemini model, shown in the Figure 9.



Figure 9: Optech ALTM Gemini

The scan rate goes up to 70 kHz for current models. With improved technology, maximum flying heights have risen to 3500 and 4500m, for ALTM 3100 and Gemini. As scanning mechanism, oscillating plane mirrors are used, with a FOV, which can be set to 50°. The quoted rangefinder range resolution is \pm 1cm. With better scanning and geo-referencing performances, positional and elevation accuracies have risen as well, with latter one still dependent on flying height and PRF. The elevation accuracy will vary with the flying height and the PRF over the range +/- 5 to 35 cm, as represented in the Table 1.

Laser Repetition Rate (kHz)	500 m Altitude (cm)	1000 m Altitude (cm)	2000 m Altitude (cm)	3000 m Altitude (cm)	4000 m Altitude (cm)
33	<5	<10	<15	<20	<25
50	<5	<10	<15	<20	N/A
70	<5	<10	<15	N/A	N/A
100	~10	~10	~15	NT / A	NI / A

Table 1: Elevation Accuracy – RMSE Values (from Optech)

2.5.2 Leica Geosystems

Leica's airborne-based laser system series is named ALS series. In the 2003 model ALS50 was introduced. In 2006 the improved ALS50-II was introduced (shown in the Figure 10), featuring multiple pulses in air technology (Mpia).



Figure 10: ALS50-II Leica Geosystems

Systems emit laser radiation with wavelength of 1064 nm and could be operated at maximum of 6km. Maximum PRF goes up to 200 kHz and scan rate to 90 Hz. Specified accuracies can be found in the Table 2.

Table 2: Specification and accuracy values for Leica IPAS10 System. NUS4 is the iMAR FSAS unit; DUS5 is the Litton LN-200 unit; NUS5 is a Sagem unit; and CUS6 is the Honeywell MicroIRS unit.

		NUS4	DUS5	NUS5	CUS6
Absolute	Position	0.05–0.3 m	0.05–0.3 m	0.05–0.3 m	0.05–0.3 m
accuracy after	Velocity	0.005m/s	0.005m/s	0.005m/s	0.005m/s
postprocessing	Roll and pitch	0.008°	0.005°	0.005°	0.0025°
(RMS)	Heading	0.015°	0.008°	0.008°	0.005°
Relative	Angular random	< 0.05	< 0.01	< 0.01	< 0.01
accuracy	noise	deg/sqrt (h)	deg/sqrt (h)	deg/sqrt (h)	deg/sqrt (h)
	Drift	<0.5 deg/h	<0.1 deg/h	<0.1 deg/h	<0.01 deg/h
IMU	High performance	200 Hz	200 Hz	256 Hz	200 Hz
	gyros	FOG	FOG	Dry-tuned	Ring laser
				gyro	gyro
GPS receiver	Internal in IPAS10 control unit	IPAS10 12-channel dual frequency receiver (L1/L2) low iit data, DGPS ready		(L1/L2) low noi	se, 20 Hz raw

The latest ALS70 model, which was recently introduced to the market, is offering a higher performance employing its "Point Density Multiplier" technology. Two streams of laser pulses are simultaneously generated using a single laser rangefinder and scanning mechanism in combination with a beam splitter and a multiple pulse operating regime. The initial announcement states a maximum effective pulse rate of 500 kHz at flying height of 1000 m AGL and a 200 Hz scan rate using the dual stream of laser pulses.

2.5.3 Riegl

The Austrian company Riegl has for many years been producing different kinds of laser measuring instruments. In recent years, it has produced a range of terrestrial-based laser systems; in 2005 Riegl was on the second place in sales of terrestrial systems, after Leica. The company entered field of ALS in 2003. They developed laser scanning engines which they were selling to other system suppliers, who then integrated POS and software to complete system. Riegl's own system was first introduced in 2006, in so called LMS series. Two types of systems can be differentiated: ones for lower operating height used for applications such as corridor mapping and power line surveys (flying height up to 450m for targets with 80% of reflectivity) and the ones for higher altitudes and large-area surveys (height up to 1500m for targets with 80% of reflectivity). The latter systems can record full-waveform intensity of the reflected signal. The laser is Class I pulsed-type emitting in NIR wavelength of 900 or 1550 nm with PRF up to 200kHz. Model LMS-Q680i was announced in

2010, and features a maximum PRF of 400 kHz using RIEGL's multiple pulse technology (with 3 pulses in the air simultaneously) together with a maximum scan rate of 200 Hz over a 60 degree FOV. New V-Line series has been introduced in the autumn of 2010, with two models, VQ-480 and VQ-580. Maximum PRF goes up to 300 kHz and scan rate to 100 Hz. The maximum operating altitude for both of these scanner engines is circa 1000m. The VQ-480 scanner is intended for lower-altitude applications, while the VQ-580 is designed to measure on snow and ice.

3 Intensity measurements

The terms signal intensity, reflectance intensity and pulse reflectance are often used for the value of return amplitude or energy of returned pulse. To study this intensity value, a power equation for radar will be used:

$$P_r = \left(\frac{P_t D_r^2}{R^4 \beta_t^2 \Omega}\right) \rho A_s \tag{3.1}$$

where P_r and P_t are the received and transmitted powers, respectively, D_r is the receiver aperture size, R is the range, β_t is beam divergence, Ω corresponds to the bidirectional properties of scattering, ρ is the reflectivity of the target surface and A_s is the receiving area of the scatterer.

The amplitude of the received signal depends on the wavelength and energy of the transmitted pulse, the distance to the target, the target reflectance, the transmission of the atmosphere, the area of the receiver aperture, the throughput efficiency of the receiver, the sensitivity of the detector, and, in the case of analog detection, the amplification gain applied to the detector output. Also, it is influenced by background radiation, the size, reflectance, slope and roughness of the illuminated surface. Generation of these intensity values is usually not well specified by the instrument manufacturers and the intensities need to be corrected in order to represent a value proportional to the reflectance of the scanned surface. There is no insight given into the pulse detection algorithm. The intensity may correspond to e.g. the peak of amplitude or the integral of return signal over pulse width.

Most ALS systems operate with beam divergence 0.3-0.8 mrad on the flying heights up to 3500m, giving relatively small footprint and good spatial resolution. Variations in scan geometry, due to changes in topography of the scanned surface, lead to heterogeneous scanning pattern, which means gaps in certain parts as well as overlapping footprints in other parts. Consequently, the recorded intensities have to be corrected for the influences of terrain topography and flying altitude. The need for calibrated intensity values is largest in areas with high elevation differences, such as mountainous areas, where raw intensity values can hardly be used.

3.1 Beam divergence

According to the predefined angular spread of the beam, the beam will illuminate certain circular or elliptical area, with the surface of the area depending on the range to the object; shown in the Figure 11. The greater the range to the object, the greater the surface which will be illuminated. The

return signal will therefore be the mixture of reflections occurring in the illuminated area. The irregularity of the surface in shape or elevation, shall also contribute to the area illuminated by the beam. The typical values of beam divergence are between 0.3 to 2 mrad.



Figure 11: Spread of the beam or pulse that has been emitted by the laser rangefinder and its divergence on its path to the ground object or target and on its return from the object or target. (Shan and Toth, 2008)

3.2 Target cross-section

The measure which contains all target characteristics is target cross-section and is expresses by the following equation:

$$\sigma = \left(\frac{4\pi}{\Omega}\right) \rho A_s \tag{3.2}$$

with scattering solid angle of the target Ω , the target reflectance ρ and the target area A_s . The back-scatter cross-section is a measure of the electromagnetic energy intercepted and radiated by object, according to Wagner et al. (2006). As long as the whole cross-section of illuminating beam hits the surface, the measured range and intensities will be within tolerated accuracy. The problem arises when the beam hits an edge (shown in the Figure 12) or passes through semi-transparent material, especially when distance between objects is less than pulse length (range resolution).



Figure 12: Multiple returns along vertical surfaces. (Shan and Toth, 2008)

Since in full-waveform systems the whole back-scattered signal is digitized, it allows individual detection algorithms to be applied, determining amplitude, pulse width and received energy. Target cross-section σ can be determined free of assumptions. As the equation shows, cross-section σ is a function of the wavelength, the size, the directivity of the back-scattered signal and the reflectivity of the target. Surface composition and its roughness, together with laser beam wavelength influence the value of target cross-section.

3.3 Reflectivity

Reflectivity is defined as a ratio of scattered radiation from the ground or object over incidence radiation on the same surface. Reflectivity of certain targets depends greatly on the wavelength of the laser. Reflectances of different surfaces are measured using reference targets, obtained *in situ* or through laboratory measurements. An example of different surface reflectivities is shown in the Table 3.

Material	Reflectivity (%)
Lumber (pine, clean, dry)	94
Snow	80-90
White masonry	85
Limestone, clay	Up to 75
Deciduous trees	Тур. 60
Coniferous trees	Тур. 30
Carbonate sand (dry)	57
Carbonate sand (wet)	41
Beach sand; bare areas in desert	Тур. 50
Rough wood pallet (clean)	25
Concrete, smooth	24
Asphalt with pebbles	17
Lava	8
Black neoprene (synthetic rubber)	5

Table 3: Typical reflectivity of various materials at 900nm

If the strength of the reflected signals that are received by the ranger is very weak, the range over which the required measurements can be made will be reduced since no detectable return signal will reach the receiver. Highly reflective surfaces can saturate the detector, while pulses from low reflectance surfaces may occasionally be too weak to be recorded. In order to convert recorded intensities to reflectance, we should have measurements to reference targets. Knowing reflectivity of calibrated surfaces and having their intensity values, one can calculate reflectivity of other targets within scene using measured intensity values by applying linear regression.

3.4 Effects which influence intensities

As stated by Boyd and Hill (2007) the effects that influence intensities can be divided into system and target variables, both exhibiting co-dependency. In the systems variables we can include: emitter-target distance, incidence angle, atmospheric attenuation, beam divergence, laser footprint size and signal processing. Target reflectivity, roughness of the surface, bidirectional scattering properties and size of target fall into the later group, the target

variables. Target properties within forest are mainly a function of leaf area and inclination, tree density and specie.

3.4.1 Wavelength of the laser beam

Some of the factors which are dependent on the laser wavelength are detector sensitivity, atmospheric transmission and target reflectance. The reflectivity properties of the diffusive targets come greatly from remote sensing field. The difference with laser scanning field is that incidence radiation comes from the Sun. Now-days there are many research studies concerned with the reflectivity properties of some materials depending on the wavelength. Boyd and Hill (2007) report about reflectivity values of different materials through endeavours spectroscopy found of and can be here http://pubs.usgs.gov/of/2003/ofr-03-395/ofr-03-395.html Reflectivity of . snow and frost (Figure 13), concrete and cement (Figure 14), asphalt and tar (Figure 15) and wood (Figure 16) are given as an example, in respect with different wavelengths.



Figure 13: Reflectivity spectrum of frost and snow. Data ASTER spectral library. (Larsson et al., 2010)



Figure 14: Reflectivity spectrum of concrete and cement. Data ASTER spectral library. (Larsson et al., 2010)



Figure 15:Reflectivity spectrum of asphalt and tar. Data ASTER spectral library. (Larsson et al., 2010)



Figure 16: Reflectivity spectrum of different wood samples. Data ASTER spectral library. (Larsson et al., 2010)

3.4.2 Slant range

The ability of the laser system to receive a returned signal, depends greatly on the reflectivity of the target in accordance with the range (shown in the Figure 17). Some systems report maximum operating distance according to the target reflectivity. For example, Riegl company states for their LMS-Z210i pulsed-type laser operating on maximum distance of 350m for natural targets having reflectivity larger than 50%. For target with reflectivity of >10% this operating distance decreases to 150m. Leica Geosystems provides in their literature for certain instruments, the effect of reflectivity on the precision with which some surface can be modeled. As an example, the HDS4500 terrestrial-based scanner, which uses CW ranging method, have reported precision of < 1.6 mm for dark gray surfaces with 20% reflectivity, while for the white surfaces with reflectivity of 100% this precision increases to 1.0 mm, tested on the range of 10 m. For longer range of 25 m for respective surface this values become < 4.4 mm, respective < 1.8 mm.

As reported by Ahokas et al. (2005) for Optech ALTM 3100 instrument, targets whose reflectivity is 10% could not be recorded at flying height of 3000m due to insufficient SNR ratio. Intensity values measured within 10 meters in distance are saturated and are therefore not useful for reflectance calculations.



Figure 17: ILRIS terrestrial-based system. (Larsson et al., 2007)

The recorded intensity is proportional to R^2 for homogenous targets filling the full footprint, to R^3 for linear objects (e.g. wire) and to R^4 for individual large scatterers according to Ahokas et al. (2006). As stated by Korpela (2008), range on power of n is inversely proportional to intensity, however, the optimal value of *n* varied from 2.3 to 2.5 for surfaces consisting of shrubs, lichens, grass or gravel.

One of the factors which need to be taken into account is relative height differences of the scanned area. The normalization of the intensity by considering the object distance in a typical urban area yields only small modifications below 5%. The correction is needed if range variability between sensor and targets, is more than about 3 to 5 percent of the mean range. Performing range-based normalization on data acquired with a laser sensor that supports gain adjustments should not be attempted, because the effects of range are already embedded in the recorded intensities. The range to target R is considered the most important factor to be accounted for with intensity data from vegetation surfaces.

3.4.3 Incidence angle

The incidence angle is defined as the angle which the laser beam forms with the ground, or more precise with the surface normal. For flat surfaces, the incidence angle equals the scan angle. The effects of incidence angle has been studied in photonics and optics, but the results have limited application in remote sensing of natural targets, according to Kaasalainen et al. (2009). For highly reflective surfaces, which are on the slope, most of the radiation will go to the side and not directly to the laser scanner, as shown in the Figure 18.



Figure 18: Highly reflective surface on the terrain that is not at right angles to the incident laser pulse or beam will reflect its radiation off to the side and will not return a signal to the laser rangefinder. (Shan and Toth, 2008)

When dealing with forest canopy, the laser pulse emitted at nadir will be able to penetrate the canopy and reach the ground below it. With increasing the incidence (scanning) angle, the ability of pulse to penetrate canopy and reach and reflect from ground will decrease. More research is needed in order to completely understand scattering of laser radiation. In airborne laser scanning in general and in the scope of the thesis, it is assumed that scattering follows Lambertian (cosine) law. The studies conducted by Kaasalainen et al. (2009) showed that using Lambertian correction is practical and valid for angles up to $\pm 20^{\circ}$. For greater angles, the data accuracy is very limited to estimate the performance of any correction method.



Figure 19: Reflectivity of a diffuse target. (Shan and Tooth, 2008)

Hard surfaces, such as rocks, buildings or tree trunks, which have diffusive reflectance properties, are usually idealized as if the scattering takes place in hemispherical pattern, with maximum radiation in direction perpendicular to the target surface, and reflectivity diminishing rapidly with smaller angles (Figure 19). This assumption is called Lambertian law, and is expressed by a cosine function. Instruments measure only a fraction of reflectance scattered into direction of illumination (0° between emitter and receiver). The Lambertian law expresses how reflectance *R* is a proportional to incidence angle α , with k_L being a constant:

$$R = k_L \cos(\alpha) \tag{3.3}$$

Scattering behaviour of natural targets is not Lambertian and the equation presents a simplified mathematical law. Figure 20 and 21 are representing results achieved during experiments compared with predicted intensities using the cosine law.



Figure 20: ALS results for asphalt road measured at 500m altitude. Each point is an average of several points having the same incidence angle. The error bars represent the standard deviations of the average. (Kaasalainen et al., 2009)



Figure 21: Comparison of intensities measured with the ones approximated by Lambertian law, respective to reflectivity. (Larsson et al., 2007)

The error of approximating that reflectivity follows cosine law is reported to be smaller than error range in data points.

3.4.4 Atmosphere

The atmospheric transmission of the beam will depend on the density of aerosols in the air and clouds. Visibility is one of factors when performing measurements, where good visibility is a prerequisite for the ALSM missions, with cloud-free path between airplane and target. Haze due to aerosols and water vapor can significantly reduce the beam transmission (Figure 22).



Figure 22: Wavelength dependence of atmospheric transmission shown for clear and hazy conditions. (Shan and Toth, 2008)

The incident beam will on its way from instrument to the target be subjected to scattering due to dust and water droplets in the air. It will be furthermore be affected by scintillation effects of the atmosphere through which the beam is traveling. This effect is double: on the way from the instrument to target, and on its way back from target to the instrument.

3.4.5 Automatic gain control

In order to improve a response rate from transmitted signal (increase the number of received points) some instruments apply dynamic reduction or amplification of return energy. The goal is to fit the received energy in the range of the receiver. If the received power is over receiver's maximum level, the AGC will reduce the gain to fit it within receiver's limits. In contrary, if the power is lower than predefined minimum, the AGC will increase the gain. The main instrument used in the NNH project, Leica ALS50-II uses this Automatic Gain Control (AGC). AGC is useful for getting returns even from low-reflectance surface. Although, the intensities obtained will be dependent on

the surrounding environment- which means that there can be variations within one surface type. For example, an asphalt road will have different intensities obtained before and after the laser pulse goes across e.g. water surface. Since the water has low reflectivity, this will raise AGC level, which means that returns will be amplified for certain amount. After the laser pulse in a cross-track line will reach the asphalt again, this return values will still be affected by higher AGC gain, and therefore, the intensities of asphalt road will be higher. Overall intensity data will follow AGC applied gain, and consequently it will not be proportional to the reflectivity properties. An example of scanned area with obvious AGC influence on intensities is shown in the Figure 23.



Figure 23: Intensity image showing visible AGC effect on recorded intensities. (Roth; Leica Geosystems, 2010)

The AGC is working in an 8 bit scale, which means that it records values from 0 to 255.

3.4.6 Other influences

When talking about intensity values back-scattered from roughed water surface, the influence of wind speed is reported by Bufton et al. (1983). From nadir view, water absorbs 98% of the radiation, again depending on wavelength. For near-infrared wavelengths, the beam penetrates only in the

magnitude of couple of centimeters. In NIR band water content of the material can modify the IR reflectance.

The strong sunlight back-scattered from highly reflective surface may saturate the detector, producing less accurate or invalid reading. However, usually systems are not affected by other reflections.

Target properties, such as dust, dirt and moisture influence the reflectivity of the object. Dust and mud on the target will decrease the distance for pulse detection due to the low reflectance of mud at 1541nm, as stated by Larsson et al. (2007). Laser scanning instrument itself also influences intensities. Larsson et al. (2007) reports how range measurements and intensities are influenced by internal temperature of instrument (shown in Figure 24). Intensity values are different if instrument is warmed up, ca after 1hour of being turned on. It takes ca 1h in order that the instrument becomes steady for range measurements when scanning same static scene. Even the intensities are affected by the internal temperature of ILRIS instrument.



Figure 24: Measured mean intensities over time at different reflectance surfaces. (Larsson et al., 2007)

Hopkinson (2007) assumes that in both the wide beam and high altitude datasets, the reduced maximum distribution height is largely a function of increased pulse footprint area and reduced pulse energy concentration. The values are strongly dependent on range as well as on PRF. Variation in PRF changes the transmitted values, which also have an influence on intensity.

The discrete return representation of vegetation is greatly instrument dependent. The detection of a ground through the canopy depends on spatial and angular distribution of gaps through the canopy, incidence angle, divergence and wavelength of the beam, range to target (by which the footprint on the ground is defined), sampling density, reflectivity of the ground, etc. Canopy attribute measurements (such as height of crown, depth and underlying stories) will therefore not be the same when measured with different instrument and one should take special care when in use for change detection purposes. Here, the full-waveform systems are much better solution, but on the other hand they also have their limitations.

4 Data

The thesis is current with the project of developing new national height model of Sweden. The data is accessible as LAS files together with metadata and trajectory files. The LAS files follow ASPRS specification LAS version 1.2. approved by ASPRS Board 09/02/2008.

4.1 New National Elevation Model (NNH)

The National Land Survey of Sweden (Lantmäteriet) was commissioned by the Swedish Government, to produce the new national elevation model, with recommendations from Climate and Vulnerability Commission. Since 2009, National Land Survey is carrying out airborne laser scanning (LiDAR) in accordance with a plan embracing the requirements connected to climate change and other environmental issues. The aim is to produce a new Digital Elevation Model (DEM) in which the standard error is better than 0.5 m for grid points in a 2 m grid.

The plan of the project is as follows:

- Production planning is ongoing during the duration of the project
- Start of production was July 2009
- Production time is 7 years, of which the first 4 years will focus on laser scanning.
- Data is available to customers approx. 6 months after the scanning of the area

During the first four years of the project, the focus is on data acquisition (scanning). During that time, new elevation data will be available for almost all of Sweden in the form of geo-referenced and auto-classified laser point clouds. A 2 metre grid, calculated from laser points classified as ground points, will also be produced. Edited products will be produced in accordance with user demands during the later part of the project. The scanning work is planned so that south of Sweden will be done during non-growing season, i.e. when deciduous trees do not have leaves and crops are short or absent, while north of Sweden will be scanned during early spring and late autumn, while north of Sweden will be scanned during summer.

The instruments used in the project are mainly Leica's ALS50- II and ALS60, together with sometimes used Optech ALTM Gemini. Instruments operate on wavelength of 1064 nm and are pulsed-type lasers.

Prerequisites for the project planning and scanning are quite strict, with e.g. visibility during the flight has to be excellent, flying height 2300m, strip overlap should be 20%, footprint 0.5-1m, density of the points 0.5-1 point per m2, scan angle up to $\pm 20^{\circ}$, etc.

The data, provided as a courtesy of National Land Survey of Sweden, includes all data from POS and GPS observations together with raw scanning data. Raw data was necessary for AGC correction, because the current LAS files do not have AGC values stored as an attribute for each point.

4.2 LAS point cloud data

Data delivered by National Land Survey follows ASPRS specifications version 1.2., with point data format 1. LAS is a binary file format, consisting of a header and point records. Header of a LAS file is shown in the Figure 25.

LA	S File Information	
	Total Points Loaded: Source ID Count :	12022697
	LAS Header	
	File Source ID: GUID: LAS Version: System ID: Generating Software: Flight Date Julian: Year:	0 0000000-0000-0000-0000-0000000 1.2 <empty> TerraScan 0 0</empty>
	Header Size: Point Data Offset: VLR Count:	227 229 0
	Point Data Format: Point Data Record Length: Number of Point Records: Points Br Paturn	Format 1 28 12022697
	Return 1: Return 2: Return 3: Return 4: Return 5:	9851640 1978259 187692 5106 0
	X,Y,Z Scale Factors:	0.0100, 0.0100, 0.0100
	Clipboard	OK I

Figure 25: Example of a header of LAS file

Point data records store information about position, intensity of the signal for the point, point classification and timestamp. A sample is provided below:

```
% Compiled module: PROV2.
```

```
% Compiled module: READLAS_RECORDS.
```

Point	records:						
{	4630164	-499964	8088	36	9	2	4
0	1	488388.40}					
{	4630347	-499976	8091	49	9	2	4
0	1	488388.40}					
{	4630531	-499987	8081	48	9	2	4
0	1	488388.40}					
{	4632147	-499987	7876	109	73	2	3
0	1	488388.41}					
{	4631960	-499975	7878	143	73	2	4
0	1	488388.41}					
{	4631776	-499963	7884	209	73	2	4
0	1	488388.41}					

4.3 Trajectory files (TRJ)

The trajectories recorded by Leica systems are in .sol format, but since data processing is done in Terrascan software, de facto standard is TRJ file. Data in the files is stored in binary format, following Terrasolid's specification.

Trajectory positions have stored data about position, orientation of the airplane at certain timestamp, quality of these data and timestamp. A sample is provided below:

```
% Compiled module: READTRJ RECORDS.
Position records:
         488361.00 581450.26 6708141.8
{

      2342.2355
      -176.09778
      -0.021269270
      -0.58296301

      8
      42
      1
      0}

      {
      488361.01
      581450.25
      6708142.1

                                                                                                              5

      2342.2286
      -176.09591
      -0.013548403
      -0.58267420

      8
      42
      10
      1
      0}

      {
      488361.01
      581450.25
      6708142.5

                                                                                                               5

      2342.2217
      -176.09373
      -0.016650230
      -0.58050772

      8
      42
      10
      1
      0}

      {
      488361.02
      581450.25
      6708142.8

                                                                                                               5
2342.2148 -176.09153 -0.028716249 -0.57615785
8 42 10 1 0}
{ 488361.02 581450.24 6708143.1
                                                                                                               5
2342.2079 -176.08964 -0.036761108 -0.57336207
                                                                                                               5
8 42 10 1 0}
{ 488361.03 581450.24 6708143.4
2342.2009 -176.08778 -0.030277504 -0.57399781
8 42 10 1 0}
                                                                                                               5
```

5 Already proposed correction methods

The first attempts to calibrate laser intensity and back-scatter cross section includes Luzum et al. (2004), Kaasalainen et al. (2005), Coren and Sterzai (2006), Ahokas et al. (2006), Donoghue et al. (2006), Wagner et al. (2006) and Höfle and Pfeiffer (2007). Luzum et al. (2004) assumed a signal loss related to squared distance. In Donoghue et al. (2006) a linear correction approach for intensity was found adequate. In Kaasalainen et al. (2005), the intensity was proposed to be calibrated by a known reference target. Coren and Sterzai (2006) suggested a method taking into account laser spreading loss, incidence angle and air attenuation. An asphalt road was used as homogeneous reflecting area. In Ahokas et al. (2006), a more general correction method was proposed, i.e. intensity values needs to be corrected with respect to range, incidence angle (both BRDF and range correction), atmospheric transmittance, attenuation using dark object addition and transmitted power (because difference in PRF will lead to different transmitter power values). According to Hyyppä and Wagner (2007) calibration of intensity has close links to back-scattering coefficient recorded by SAR and microwave systems, radiometric calibration of optical satellite imagery and calibration of digital aerial images.

For segmentation and classification purposes it would in general be sufficient to perform a relative correction of the ALS amplitude and waveform measurements. Relative correction methods such as proposed by Coren and Sterzai (2006), Ahokas et al. (2006) and Höfle and Pfeifer (2007) aim at reducing echo amplitude variations by correcting the measurements relative to some reference, e.g. relative to a reference range R_{ref} . Gatziolis (2009) states that in order to ensure accurate range-based intensity normalization there should be no significant changes in atmospheric transmittance between scanning swaths, nor combining of laser intensity data recorded by using different instruments, or the same instrument operating at different scanning frequencies. Violation of one or more of these requirements will lead to unidimensional class intensity signatures that are less compact compared to those obtained when requirements are met and, hence, likely to be manifested by lower overall classification accuracy.

However, it is much more desirable to convert the echo amplitude and waveform measurements into physical parameters describing the backscatter properties of the scatterers in a quantitative way. The reason for that is to compare measurements from different sensors and/or flight strips, extract geophysical parameters from the back-scatter measurements using models, carry out multi-temporal studies over large areas, and build up a database of back-scatter measurements for different types of land cover and incidence angles. Wagner et al. (2006) reports that amplitude and waveform measurements from different sensors, acquisition campaigns and flight strips are not directly comparable. The cross section σ and the back-scattering coefficient γ , which is defined as the cross section normalized with the cross-section of the beam hitting the target, are the preferred quantities for describing the scattering properties. Hence, either σ or γ should be used in the calibration.

Two approaches for correction are stated by Höfle and Pfeifer (2007): data driven and model driven approach. Both have different requirements for input data. Results from both methods show noticeable reduction of intensity variation, up to $1\3.5$ of original variation.

5.1 Data driven correction

Data driven approach uses predefined homogeneous area in order to empirically derive the parameters for global correction function using leastsquare adjustment, which accounts for all range- dependent influences. The method is suitable when there exist data from multiple flying altitudes over certain area, not the whole dataset (parameters can be derived from a sample and applied to the whole set). Once the parameters are obtained, they can be applied to different missions with the same system settings and similar atmospheric conditions. For the estimation of parameters, only measurements to extended targets are taken into account (just a single return is considered), so the area illuminated by pulse can be calculated. As well, the target has to have uniform reflectance (points on the borders of two materials cannot be used).

5.2 Model driven correction

The second approach, model driven, is based on correcting each point in the point cloud with account of the physical principles of laser systems. In radar remote sensing the calibration is performed based on the radar equation which gives the received power as a function of sensor parameters, measurement geometry and the scattering properties of the target. LiDAR applies same physical principles as microwave radar, but on shorter wavelength. For the LiDAR case, the radar equation can be derived:

$$P_{r} = \left(\frac{P_{t}D_{r}^{2}}{4\pi R^{4}\beta_{t}^{2}}\right)\eta_{sys}\eta_{atm}\sigma$$
(5.1)

with system η_{sys} and atmospheric transmission factor η_{atm} . It is assumed following: the receiver field of view matches the beam divergence; emitter and detector have the same distance to the target; the reflectors are extended Lambertian reflectors; the surface slope can be estimated from neighbouring points; the atmospheric conditions are known (and constant); the transmitted laser power P_t is assumed to be constant (or changes in time or due to different scanner settings are known); and the receiver maps incoming power linear to the recorded intensity values.

The intensity measurements depend on the instrument used, and this should be taken into account when performing calibration algorithms. The Finnish Geodetic Institute (FGI) reports that for TopEye MK-II instrument, R² correction is already done; for ALTM 3100 R² correction is needed; while Leica's ALS-50II instrument need to specially be taken into consideration because Automatic Gain Control changes the levels of intensity, and therefore the effect of AGC needs to be inverted to reflectance properties.

EuroSDR has from 2008 approved and funded a project, in cooperation of Finnish Geodetic Institute (FGI) and Technical University Wien (TUW), to develop feasible and cost- effective approaches for radiometric calibration of ALS intensity data. FGI focused their work on discrete echo recordings, while TUW did experiments concerning full-waveform intensity calibration. The calibration concept which they developed, is based on external *in situ* reference targets, such as portable brightness tarps, commercially or naturally available sand and gravel and laboratory/field calibration (sports fields, tennis courts, golf courses, sand roads, natural beaches etc.) was also studied.

5.3 AGC correction

Understanding the principles of AGC gain is of great importance, because these data cannot be used in any kind of study without first removing the AGC effect. The correction method developed by FGI and reported by Vain et al. (2009) is based on the data over calibrated targets with AGC turned on and off. The diagram correlating these two sets is shown in the Figure 26.



Figure 26: Correlation of the average intensity values of the cells when AGC is on and when it is off. Red dots are considered to be noise, and they were removed from the modelling process. (Vain et al., 2010)

The relationship is found to be linear, and following correction equation is reported:

$$I_{off} = a_1 + a_2 * I_{on} + a_3 * I_{on} * AGC$$
(5.2)

where a_1 , a_2 , and a_3 are the constants determined by least squares fitting, a_1 being -8.093883, a_2 2.5250588, and a_3 -0.0155656. Relationship between observed and predicted intensities are presented in the following figures, Figure 27 and Figure 28.



Figure 27: Correlation between observed and predicted intensity values using presented equation. The root-mean-squared error between predicted and observed intensity values is 5.65.(Vain et al., 2010)



Figure 28: AGC correction applied to beach sand laser points. I_{on} denotes the intensity values when AGC is on, I_{off} denotes the intensity values when AGC is off, AGC represents the AGC values, and Model denotes the I_{on} values corrected. (Vain et al., 2010)

5.4 Atmospheric attenuation

Generally, information about atmospheric conditions, such as Rayleigh and aerosol scattering transmittance, during a flight campaign are not available.

However, visibility can sometimes be obtained from airport, as well as weather data. Visibility can be used as a parameter to model atmospheric effect, with , e.g. radiative transfer model Modtran, as stated by Höfle and Pfeifer (2007). As output, total atmospheric transmittance can be estimated. Höfle and Pfeifer (2007) suggest that atmospheric attenuation coefficient *a* (in dB/km) can be extracted from data by selecting ranges and topographically corrected intensities of a homogeneous area using the following equation:

$$a = 5000 \log_{10} \left(\frac{I_1 R_1^2 \cos \alpha_2 f_{sys1}}{I_2 R_2^2 \cos \alpha_1 f_{sys2}} \right) \frac{1}{R_2 - R_1}$$
(5.3)

Gross (2008) states that atmospheric attenuation can be calculated using the formula:

$$T^2(R) = e^{-2\alpha R} \tag{5.4}$$

5.5 Calibration

Because current ALS instruments do not monitor sensors functions crucial for the radiometric calibration of the measurements (e.g. laser pulse energy), their calibration has yet to rely solely on external reference targets. Figure 29 is showing some samples used as reference targets in an experiment conducted by FGI.



Figure 29: The near-infrared digital camera based reference measurement. (Vain et al., 2009)

Since it is not always possible to use commercially available tarps, Vain et al. (2009) reports an attempt of using certain natural targets, relatively stable surfaces such as asphalt road, football field and harbour asphalt. In contrary, concrete acted quite unstable. An example of deriving reflectance properties of parking lot asphalt using different reference targets is shown in the Figure 30.



Figure 30: Back-scattered reflectance values for parking lot asphalt, using different reference targets. (Vain et al., 2009)

6 The most suitable calibration algorithm

The most suitable algorithm for calibration was chosen depending on the data provided. Data driven method was not possible to implement due to the lack of data from various flying heights. The Finnish Geodetic Institute (FGI) has developed a practical calibration approach based on pre-calibrated *in situ* reference targets. Their studies showed that intensity values needed to be corrected for: range, incidence angle, atmospheric transmittance and transmitted power. The correction is shown by the following equation:

$$I_{corrected} = I_{original} \frac{R_i^2}{R_{ref}^2} \frac{1}{\cos(\alpha)} \frac{1}{T^2} \frac{E_{Tref}}{E_{Tj}}$$
(6.1)

with $I_{original}$ being recorded, raw intensity value, R_i is slant range from airplane to the point, R_{ref} is chosen reference range, α is incidence angle at which the point is recorded, T is the total atmospheric extinction, E_{Tref} is pulse energy value chosen as referent and E_{Tj} is pulse energy in the current flight line. The scanning and correction principles are represented by the Figure 31, while full calibration process is included in the Figure 32.



Figure 31: Schematic principles of scanning and corresponding corrections. (Kaasalainen et al., 2007)

Several assumptions were made: the surface has Lambertian scattering

properties; emitted laser power is stable during flight, among others.

For Leica's ALS50-II instrument AGC effect has to be taken into account because it changes the levels of intensity. Therefore, and primarily, the effect of AGC needs to be inverted to intensity. Correction is described in previous chapter, and follows the equation:

$$I_{off} = a_1 + a_2 * I_{on} + a_3 * I_{on} * AGC$$
(6.2)

with constants $a_1 = -8.093883$, $a_2 = 2.5250588$, and $a_3 = -0.0155656$.



Figure 32: Calibration method proposed by the FGI. (Kaasalainen et al., 2007)

6.1 Implementation

The algorithm implementation was done in Interface Definition Language (IDL), which is a language platform for ENVI software.

As mentioned before, in order to get reflecting properties of targets, it is first necessary to remove the effect of gain adjustment or AGC.

In order to calculate the range and incidence angle it was necessary to determine airplane position at the time the point was recorded. This was done using timestamps. Trajectory file (.TRJ) was imported, together with points from point cloud stored in LAS file. Range between point and airplane position can be calculated using following equation:

$$R = \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2 + (z_1 - z_2)^2}$$
(6.3)

The user has to input standard reference range R_{ref} for the algorithm and test data, which was set to 2300m according to NNH project. The scaled intensity values with selected reference height are, therefore, calculated. Pulses with different incidence angles should be corrected to account for the change of

reflectivity as a function of incidence angle (the effect not known well enough). Scan angle, which is stored as an attribute for each point, was used for the correction.

From FGI it is proposed that the effect of the atmospheric attenuation should be corrected using atmospheric modeling software, e.g. Modtran. The software is not free. As an input to the software, one has to give: laser wavelength, flying altitude, weather conditions and visibility. Atmospheric extinction $(1/T^2)$ can be modelled. For the thesis scope, it was difficult to obtain software Modtran, together with data about weather conditions and visibility on the flying dates. Therefore, atmospheric attenuation effect was not corrected, because of the lack of weather and visibility parameters on the dates of the flight measurements. Still, the prerequisites for the measurements are quite strict, so it is assumed that the visibility during the flight was good. In conversation with experts from FOI, I have come to the fact that the factor which has the most effect on the scanned data might be the visibility. If aerial imagery would have been provided, then it would have maybe been possible to derive visibility. Second option would be to calculate atmospheric attenuation coefficient a, but in order to do so, data from two different flying heights to same target (obviously simultaneously) is needed.

One of the reported corrections is the one for different pulse energies. The higher PRF, the lower the pulse energy is. The transmitted power will be assumed to be changed when PRF is changed. Pulse energy is usually unknown in practice and not reported by instrument manufacturers. Leica Geosystems store for their ALS50-II series, this average power output in mission log files. This correction was not implemented, due to the lack of information about the pulse energies from producer's side. Since the same sensor is used (Leica ALS50-II) on the same flying height, we assume the laser power output for each laser shot in one measurement was the same.

For the absolute calibration of the intensity we need calibration targets, the reflectance of which is known. Alternative would be using natural targets, such as asphalt road and others.

6.2 Evaluation of results

The visual inspection of corrected intensities compared with original intensities showed quite good results, with the reduction of obvious scanning stripes and more homogeneous intensities within the same surface types. Results are shown in the following figures, Figure 33 and 34.



Figure 33: Prints of the screen of the intensities in a point cloud: original (left) and the same, corrected file (right). The file corresponds to File 1 in the Table 4. LAS file provided by operator (file is not georeferenced)



Figure 34: Intensity images from LAS file, generated with ALS Post Processing software. The file is georeferenced, but with less number of point returns. The file corresponds to File 3 in the Table 4.

Normalizing data on a standard range will lead to significant spreading or narrowing of standard deviations. The primary objective of intensity correction is to reduce variations of scan geometry and atmosphere. The standard deviation shows the degree of variation. Therefore, for evaluation of correction results the coefficient of variation (C_v) of intensities before and after correction is chosen as a measure of quality as stated by Höfle and Pfeifer (2007). Coefficient of variation is defined as a ratio of standard deviation and the mean of a dataset. The data for some corrections is reported in the Table 4. It has to be noted that file under number three, was corrected using trajectory file with shorter time interval (Δt) between sequential positions, therefore, ranges are more precisely determined.

File	No. of points	C _v uncorrected	C _v uncorrected	Processing time
1	368316	0.513	0.512	1 min
2	4304505	0.766	0.767	8min
3	344485	0.660	0.644	20min
4	1000000	1.108	1.132	2min

Table 4: Data about processed files

7 Potential applications

Intensity values can be used as an independent factor or as an additional value in many applications. The intensity value has already been used as an additional variable in surface classification and object detection, as reported by Höfle and Pfeifer (2007), especially in forestry and glaciology. Since a pulse is range- resolved (several returns from single pulse can be obtained), with different surfaces having different reflectance (vegetation relative to underlying ground), it is easier to differentiate surface types and features and improve the value of ALSM mapping. Low intensities returned from power lines due to the small reflective area, have been used to differentiate first pulses from power lines and from vegetation. For segmentation and classification purposes it would generally be sufficient to perform a relative correction of the ALS amplitude and waveform measurements. Calibrated intensity could give added value for laser scanning campaigns, for example in making object recognition and classifying easier and more reliable for automatic tools, such as automatic target recognition, and consequently more reliable generation of the DEMs. Surface classification would be easier and more reliable using reflectance values, with good spectral separability given in NIR domain. Using elevation, together with intensities can lead to discrimination of objects. Homogeneity of area could also help in the classification process. The best separability between classes can be determined using mean intensities and standard deviations, by determining largest distances in feature space. Limiting a data to a subset of last pulses with predefined minimum and maximum intensities, could contribute to e.g. automatic road extraction or similar. According to Kaasalainen (2007), intensity calibration procedure has applications in, e.g., the utilization and processing of the data from full-waveform LiDARs (which have recently become common) into calibrated back-scatter cross-sections. This would offer a possibility of classifying the data based on the shape of the returned laser pulse and the cross-section amplitude, and thus facilitate the development of more accurate digital terrain models and more effective classification of targets. Hofle and Pfeifer (2007) state that intensity could be used to improve classification results. Boyd and Hill (2007) reports various usage of intensities, such as the identification and mapping of age of lava flows from active volcanoes, glacial and archaeological (paleochannels) features. This could be specially useful in high mountainous glaciated areas where optical imagery has its problems (shadows, lack of texture).

Toth (2007) reports using calibrated intensity values for strip adjustment.

Although any obvious anomaly in ranges would likely cancel out in overlapping strips, an error caused by differences in surface material would easily lead to biases in the data and create strip degradation or deformation. While early LiDAR strip adjustment techniques were based on using only range data, current systems typically provide multiple return and intensity signal capabilities that can improve the LiDAR point cloud accuracy and support various strip adjustments processes. For example, the intensity-based range compensation became a standard on modern systems, resulting in improved vertical accuracy for several surface types. In addition, multiple returns or waveforms could offer the potential for direct measurement of surface discontinuities, such as if the footprint happens to include the upper and lower edges of a vertical wall and, thus, improve strip adjustments by providing both vertical and horizontal control.

Moffiet et al. (2005) give an overview of methods connecting intensities with vegetation and forest analysis and points out that for deriving reflectance, back-scatter cross-section has to be considered. Furthermore, intensity statistics can be used for deriving closure, spacing and type of foliage within tree crowns. The calibration technique will also enhance the methods of monitoring and mapping of forests (e.g. tree growth), construction, and agriculture. Gatziolis (2009) reports extension to applications that use intensity-derived metrics relative to vegetation height quantiles. In forestry, intensities have been used in determining forest biomass and volume, basal area and tree density of certain forests, as well as tree species predictor.

Calibrated intensity values could also contribute in multi-temporal analysis, although here it is necessary to have absolutely calibrated intensity data. To compare data recorded on different epochs with different environmental conditions, it is necessary to use comparable variable, free from influences of ALS system, weather and scan geometry, on the data. Storing timestamps for points allow developing laser emitter position and consequently scan geometry, as well as time dependent changes of surface properties due to e.g. water content. There are also prospects for environmental change detection and monitoring, such as snow melt or snow/glacier albedo variation, hydrological processes and climate change.

According to Harding (2007) calibrated intensity images could be used for creating monochromatic, single-band reflectance images at certain laser wavelength. When converting point cloud to a 2D surface, it is necessary to take into account interpolating technique and output cell size, in order to use intensity values optimally. Since the typical surfaces acquired in a geological/geophysical survey are generally irregular, these results imply that

the intensity data can be easily used in order to evaluate the reflectance of the material at the considered wavelength, e.g. for pattern recognition purposes. Intensity density function, introduced by Clode et al. (2005) helps to overcome noise in intensity set. Ahokas et al. (2006) state the use of intensities for matching laser scanning data with aerial imagery. Intensity data fused with multi-spectral images can indicate vegetation when calculating NDVI (but one has to be careful with man-made objects such as roofs). Intensity images can surpass ortophotos when distinguishing surface features.

8 Conclusions and future work

In the thesis the principles of laser systems and intensity recordings were examined. The effects which influence these values were reported. Based on the data from the NNH project, the most suitable calibration algorithm was chosen. The implementation of algorithm was done in IDL software. The data was corrected for the influences of AGC, range was corrected with respect to reference range of 2300m, together with correction for scan angle. In the calibration algorithm implemented, scan angle was used in correction, but instead of it, incidence angle should be used (it is necessary to calculate surface normal from neighbouring points). Visual inspection shows good results, such as reduction of obvious lines of scanning and homogeneity of same surface types. Empirical results, indicated by coefficient of variation, which should have decreased after applying correction algorithm are mostly good, although some show slight increase. This could be the effect of the airplane positions, with using position at nearest timestamp (the positions were not interpolated between two sequential timestamps, with time interval ∆t of 0.25s).

Some of the effects could not be corrected, such as atmospheric attenuation of the signal, due to lack of weather parameters and to the cost of necessary software (Modtran). As well, there were no digital images delivered, which could be helpful in deriving visibility of the conducted measurement and atmospheric conditions during the flight. The second effect which was not corrected was effect of different pulse energies due to the lack of energy data from instrument manufacturers. Namely, it is assumed that the pulse energy is the same within one scan. Instrument producers should provide more information on the system functioning (output power, pulse detection) and algorithms already applied on the data.

Even though full-waveform digitization proved to be much better when dealing with target reflectivity, because they allow deriving back-scattering properties of the target, there always exist a trade off between best results and possible technology, meaning that full- waveform exhibit more processing complexity and cost. Although, Riegl company has reported that they deliver a terrestrial-based system, which is already performing all the necessary corrections and deliver corrected intensities.

The corrected data was not calibrated due to the lack of data to reference targets.

There are still many challenges for radiometric calibration: detectors are not

optimized for intensity (e.g., nonlinear amplifiers/reducers, automatic gain control,...) and available sensor information is very limited (on, e.g., pulse energy).

Current LAS files do not store attributes about AGC applied gain. The space for this variable is already assigned to each point (the field User Data according to LAS Specification). In current files, this value is 0. Flight operators should work on generating and delivering this value, which is quite simple procedure, shown in the Figure 35.

Output File Options	
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C LAS Ver 1.0 GPS Seconds	of Week
C Adjusted Stan	dard GPS Time
Note: LAS 1.3 will be generated automatically	
when waveform processing is selected.	
Standard LAS File (LDRYYMMDD_HHMMSS_0.LAS)	ut GeoTIFF Images
▼ LAS File with time stamp (LDRYYMMDD_HHMMSS_1.LAS)	Size (m) 1
Enerquest LAS file (YYMMDD_HHMMSSAll.las) Ent	er 0 for "AUTO"
Limit LAS file size to 0 (million points)	
Curtaut AGC in Elight Line ID field	
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ASCII File Options Include	Return
I 1st Return (HHMMSS_1.dat) Num	iber
2nd Return (HHMMSS_2.dat) Last Return (HHMMSS_L.dat)	
3rd Return (HHMMSS_3.dat) All Returns (HHMMSS_A.dat)	
4th Return (HHMMSS_4.dat)	
5th Return (HHMMSS_5.dat) 1 Positive Scan First Returns (HHMM	SS_p.dat)
First of Multi(HHMMSS_f.dat) Regative Scan First Returns (HHM	vISS_n.dat)
☐ Single Return Only (HHMMSS_s.dat)	
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	ale dila dessa ia
NUTE. You may select multiple output file options. The file hame format for ea shown in parenthesis	ch file type is

Figure 35: In order to include values of AGC applied gain for each point, it is necessary to include this option in ALSPP

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