INVESTIGATIONS OF AIRBORNE LASER SCANNING SIGNAL INTENSITY ON GLACIAL SURFACES - UTILIZING COMPREHENSIVE LASER GEOMETRY MODELING AND ORTHOPHOTO SURFACE MODELING (A CASE STUDY: SVARTISHEIBREEN, NORWAY)

E. Lutz, Th. Geist*, J. Stötter

University of Innsbruck, Institute for Geography, Innrain 52, 6020 Innsbruck, Austria – (eric.lutz, thomas.geist, hans.stoetter) @uibk.ac.at

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ABSTRACT:

A comprehensive Geographic Information System (GIS) was developed to determine how the laser intensity of an Airborne Laser Scanning (ALS) system was affected by 1) geometry and 2) surface type. The study area contained the Svartisheibreen glacier (Svartisen, Norway) and its immediate surroundings. A model was created which contained laser intensity, surface type, surface elevation, and the scan geometry. The model utilized flight data, laser point-generated Digital Elevation Models (DEMs), and orthophotos as input. The main results include: 1) the primary cause of peripheral decreases in intensity values (i.e. *cross-path fading*) is geometry-dependent; this variation was effectively eliminated by developing Composite Laser Intensity Models (CLIMs); 2) By means of geographical and statistical analysis, the remaining primary variables influencing the signal intensity were identified as the *range*, the *surface elevation* and the *surface type*. Through this investigation it has been determined that laser intensity modelling can be effectively employed to identify surface characteristics and surface classes of glacial regions. These findings suggest that laser intensity imaging is a cost-effective alternative or addition to other optical devices such as digital cameras.

1. INTRODUCTION

1.1 Primary Objective

The primary objective is to determine how the *signal intensity* of an Airborne Laser Scanning (ALS) system is affected by 1) laser geometry and 2) surface types in a glaciated region of Svartisen, Norway. By integrating various laser intensity models (LIMs) with a comprehensive laser geometry model and a surface type model, an effective qualitative and quantitative analysis of the relevant variables is made possible, enabling relationships between surface type, laser geometry and intensity to be identified.

1.2 Purpose

The wider purpose of this study is to determine the feasibility of using intensity imagining from ALS systems to classify glacial surface types. If reflection characteristics of the primary glacial surface types are differentiable at the given wavelength (1.047 µm), then a surface classification could be conducted using laser intensity data. This would greatly increase the capabilities of ALS systems in operation over glacial regions, since the high-resolution geo-referenced infrared imagery would be a cost-effective alternative or addition to other optical devices such as digital cameras.

1.3 State-of-the-Art

1.3.1 Surface Intensity Classifications have been conducted using laser intensity modelling (e.g. Jeong-Heon Song et. al, 2002). However, the effects of laser geometry (e.g. range, angle of incidence, footprint size) have not been thoroughly examined or accounted for. Furthermore, no decisive evidence has been presented showing whether or not the signal intensity of ALS measurements can be effectively used to classify glacial surfaces.

The investigation presented here is innovative in that it a) determines laser geometry for all laser points in the study area and b) tests for correlations between geometry variables and intensity within surface classes. Hence, the reflection characteristics of the surface types can be determined and compared. Furthermore, a very effective statistical analysis is made possible using large sample sizes inherent to laser scanning.

1.3.2 General reflection characteristics of snow and ice are adequately described (e.g. Bogorodskii, 1971:44-47, Paterson, 1994:59), while only a limited number of sources describe the infrared reflection characteristics of snow and ice (e.g. Hobbs 1974, Wolfe and Zissis, 1985:3-44, 3-121 to 3-128).

Baltsavias (1999) and Wehr and Lohr (1999) have provided extensive theoretical overviews of the primary factors affecting the strength of laser signals of ALS systems. In both cases, some of the formulas have been simplified; i.e. variables have been simplified or excluded. Possible reasons include: 1) some factors, such as the diameter of the laser aperture, are several orders of magnitude smaller than other variables, such as the range, and hence are superfluous; 2) the complexity of some factor defeats the purpose of the formula, which was to concisely depict a relationship between primary variables. This may have been the case for the formulas describing the footprint size, which appears to assume that an inclined surface would posses an exposition perpendicular to the flight path (Baltsavias, 1999:203, Fig. 1a-c; Wehr and Lohr, 1999:75).

In some instances, these formulas were adequate for this study, where as in others, such as for determining the footprint size, they were deemed inappropriate since they simplified the conditions affecting intensity more than necessary.

1.4 Flight Campaign Information

1.4.1 General information regarding the study area and the flight campaign is summarized in Table 1. The study area is located in the Svartisen region of Norway, and contains the Svartisheibreen glacier with its immediate surroundings, as depicted in Figure 2 with the flight paths of interest.

Study Area Characteristics	
Location (Central Point, UTM33)	4450000, 7382500
Area (Glacier + surroundings)	7,16 km^2
Elevation Range	648–1469m; ?=821m
Flight Characteristics	
*Date of Campaign**	24.09.2001
*Time of Day**	10:46 - 11:04
*Ave. Flight Elevation above Surface**	900 m
*Ave. Flight Speed**	75 m/sec
Scan Characteristics	
ALS system	Optech ALTM 1225
*Laser Pulse Frequency**	25 kHz
*Scan Frequency (# Swaths /sec)**	25 Hz
*Scan Angle**	20° - 0° - 20°
*Ave. Swath Width**	655 m
*Ave. Swath Overlap**	155 m
No. of Laser Point within Study Area	3’512’355
*Ave. Point Density**	500’000 pts/km^2
*Ave. Point Spacing**	1.5 m

Table 1: General information regarding study area and flight and scan characteristics. (*Source: TopScan GmbH, 2001)

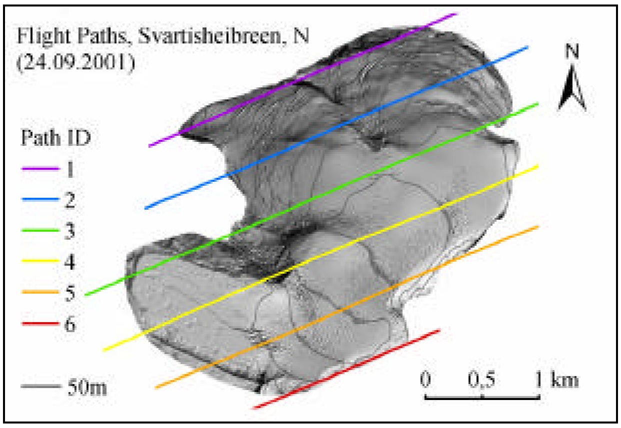

Figure 2: The study area with relevant flight paths.

1.4.2 Source Data Acquisition for this study was conducted within the bounds of the European Commission-funded project ‘Development of Operational Monitoring System for European Glacial Areas’, known as Project OMEGA. Laser point-data and flight path data were produced and supplied by the sub-contractor TopScan GmbH. Aerial photographs were supplied by the Institute of Photogrammetry and Remote Sensing, Helsinki University of Technology, and a pseudo-orthophoto by Erno Puupponen, the OMEGA project correspondent at SITO Finnish Consulting Engineers Ltd. (Espoo, Finland).

2. METHODOLOGY

2.1 Overview of Model Development

Figure 3 schematically depicts the main components of this study. Three data types (above, white) were used to develop four GIS models (middle, grey) which were then integrated into statistical and geographical data sets which were than analyzed (below). Each model component is described in the following sections, followed by a summary of the results.

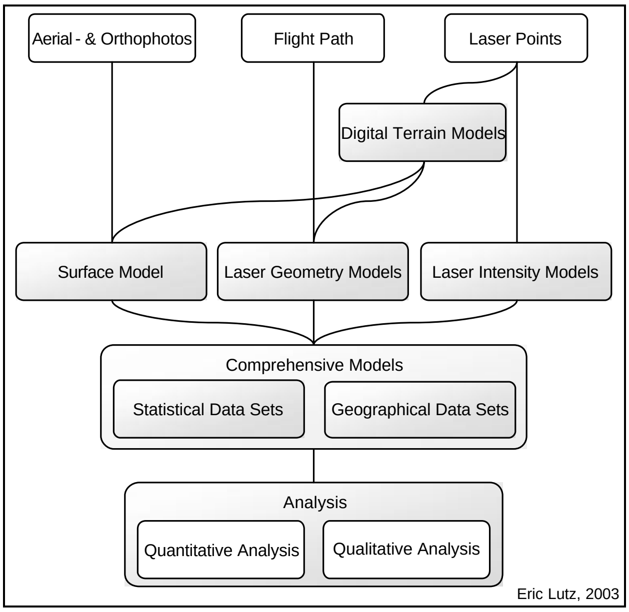

Figure 3. Model overview

2.2 Model Components

2.2.1 Digital elevation models (DEMs) with 1m resolution were generated from the laser point data using SCOP++ and ArcMap 8.2. DTMs, including slope, exposition and shaded relief data sets, were generated from a source DEM. These data sets served as inputs for 1) the geometry modelling, and 2) the geometric interpretation of surface features as part of the surface modelling component.

2.2.2. Surface modelling was conducted using ArcMap 8.2 and included the following classes: 1) temporary snow, 2) firn and ice, 3) water (pro-glacial lake), 4) bedrock and debris. Additional surfaces classes were mapped, including crevasses within temporary snow (ca. 600), transition zones between snow, ice and rock, and icebergs in the pro-glacial lake. These classes served as *buffer areas*; i.e. these surfaces were excluded from the four main classes to ensure that the primary geometrical and intensity characteristics of the main classes could be identified.

A minimal map accuracy of ca. +/-2m was achieved by developing a technique that utilized both aerial photography and DTMs. Orthophotos, which were generated from traditional black and white aerial photos and digital colour aerial photos, were used to classify surfaces on grounds of *optical* interpretation criteria. DTMs were used to classify surface features based on *geometric* interpretation criteria. For example, snow-ice boundaries were identified using optical criteria, while the mid-line of marginal crevasses was identified using geometric characteristics. The high quality of the orthophotos is qualitatively made evident in Figure 4. Figure 5 depicts the surface classification.

Figure 4: 3D-modeling reveals the high accuracy of the orthophotos; in the foreground, orthophoto crevasses lie directly *within* the DEM-generated crevasses.

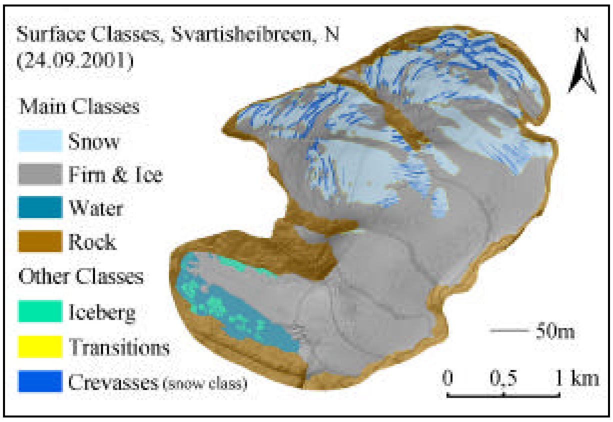

Figure 5: Surface Classification.

2.2.3 Geometry modelling was developed using ArcInfo Workstation 8.2. It consists of a self-contained set of AML scripts which, for all cell locations within a given scan swath, generates the elementary laser characteristics: range *R*, angle of incidence f , and footprint size *A*. The model requires two geo-data inputs: 1) aircraft position and orientation data, and 2) a DEM generated from laser point data.

The fundamental challenge of creating a geometry model lies in creating a model that connects the relevant aircraft position and orientation data with the laser points on the surface. Conventional laser point data contains no attribute that can serve as such a link (e.g. time of point measurement).

Hence, a raster-based model was developed which appropriately transfers the aircraft information to all cells within the scan swath. This information is then used in combination with data sets of the surface characteristics to determine the laser geometry on a cell-by-cell basis.

To maximize the accuracy of the model, *the aircraft heading angle* (i.e. the angle between flight direction and aircraft orientation) and *north convergence* (i.e. the difference between UTM grid north and geographical north) were modelled and accounted for in all calculations. This was deemed necessary since both of these parameters varied considerably within a given flight path.

To illustrate how the geometric characteristics were calculated, an example is made here of the angle of incidence f , as shown in Figure 6.

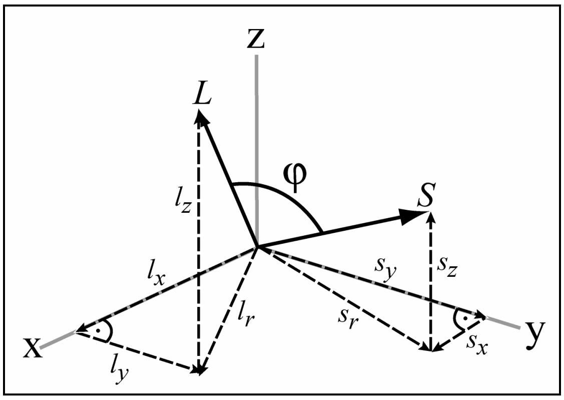

Figure 6. Vector components of the *angle of incidence j* .

The x-, y- and z- components of the surface normal vector *S* were calculated as follows,

$$s_z = \cos a \quad (1)$$

$$s_x = s_r \times \sin f \quad (2)$$

$$s_y = s_r \times \cos f \quad (3)$$

where a = surface angle
f = surface exposition
$s_r = \sin a$

The laser vector *L* was calculated similarly, however a conditional statement needed to be employed to distinguish between right-hand and left-hand sides of the flight path. j was then calculated for each cell location in a given scan swath using the following equation,

$$\cos j = \frac{l_x s_x + l_y s_y + l_z s_z}{\sqrt{l_x^2 + l_y^2 + l_z^2}\sqrt{s_x^2 + s_y^2 + s_z^2}} \quad (4)$$

where φ = angle of incidence
l_x, l_y, l_z = x-, y-, and z- components of *L*
s_x, s_y, s_z = x-, y-, and z- components of *S*

2.2.4 Laser Intensity Modelling consisted of developing two types of LIMs:

Simple Laser Intensity Models (SLIMs) utilized a *simple* interpolation technique, whereby laser points were converted directly into TINs and then directly into Grids, *without* neighbourhood interpolations. This technique required minimal processing time (e.g. 10 minutes per scan swath) while producing high quality images. Seven SLIMs were generated; one for each flight path ($SLIM_{path1-6}$) and one including all laser points within the study area ($SLIM_{all}$).

For each cell location within areas of overlap, at least two scan swaths overlap each other. Hence for most of these locations, both a maximum and minimum intensity value exists. The ***composite* LIMs (CLIMs)** were generated using conditional statements that select either the maximum or the minimum values from the six (path-oriented) SLIMs.

The first three composite models were useful for conducting statistical analysis. $CLIM_{max}$ contains the maximum intensity values within all overlap areas, while $CLIM_{min}$ contains the minimal values and $CLIM_{delta}$ the difference of the two models.

A fourth composite model, $CLIM_{maxall}$, was developed for qualitative analysis and for imaging purposes. It contains $CLIM_{max}$ values within overlap areas and all remaining intensity values where only one scan swath was present. Since the intensity typically declines with increasing distance from the flight path, utilizing only maximal values within the overlap areas results in a gradual transition from one scan swath to the other. As shown in Figure 7, the resulting CLIM is *free of typical overlap patterns* which are present in most laser imaging.

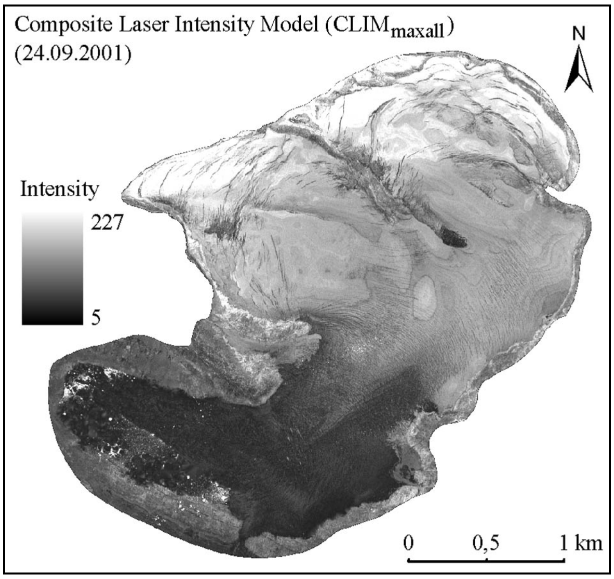

Figure 7: Within areas of overlap, $CLIM_{maxall}$ contains only the maximum intensity values, resulting in a continuous "overlap free" image from the six scan swaths.

2.2.5 Comprehensive Modelling with CLIMs was made possible by generating a *flight path* Grid for each CLIM, depicting the flight path of origin for each intensity cell. This Grid was used as a link to create geometry data sets (stemming from multiple flight path geometry data sets) for each CLIM. As shown in Figure 8, as for $CLIM_{maxall}$ this enabled the evaluation of the geometry of the strongest intensity values for the entire study area.

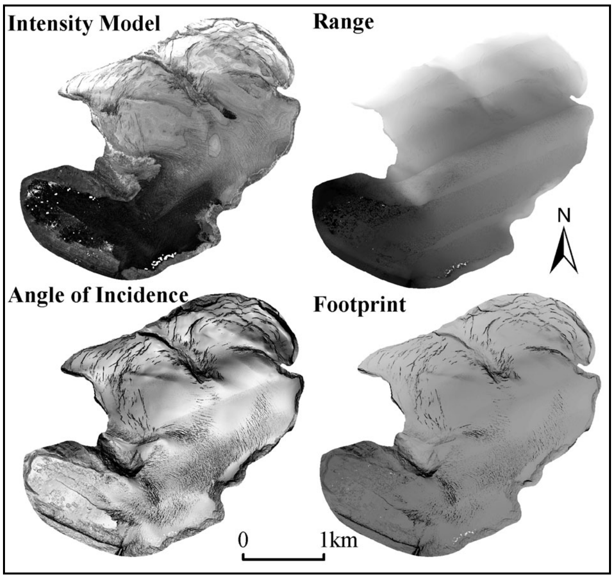

Figure 8 depicts $CLIM_{maxall}$ and its the three geometry Grids.

3. INTERPRETATION

3.1 Comprehensive Analysis Overview

Two types of data analysis were conducted; Grids were analysed qualitatively in ArcMap, while statistical data sets were analysed using ArcInfo Workstation 8.2 and SPLUS. In both types of analysis, the main objectives were: 1) identify relationships between intensity and the three laser geometry variables (range, angle of incidence, and footprint size). 2) identify relationships between intensity and surface elevation. 3) examine the strength and variability of the intensity with and without surface classes, in order to determine if the surface classes have differentiable reflection characteristics.

3.2 General Intensity Characteristics

A comprehensive analysis of this study is described by Lutz (in prep.).

3.2.1 Geometry-dependent overlap patterns: Evaluation of the path-oriented LIMs revealed a strong cross-path negative correlation between the angle of incidence, range, and footprint size and intensity, here reffered to as *cross-path fading*. Consequently, where flight paths overlap one another, the greatest variability of intensity values existed near edges of overlap. Hence, the $SLIM_{all}$ contained discrete geometry-dependent overlap patterns.

These patterns were non existent in $CLIM_{maxall}$. Since the maximum intensity values of each path decreased gradually toward their respective edges, the transition from cell values of one path to the next was gradual. Hence, the geometry-dependent overlap pattern was eliminated (Figure 9).

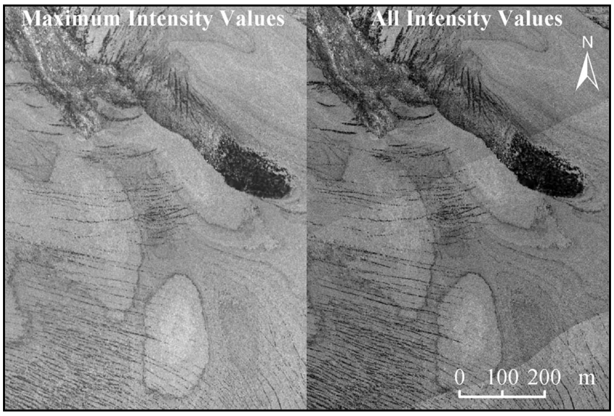

Figure 9

3.2.2 Range or surface elevation dependent trends: A strong correlation existed between signal intensity and range, as shown in figure 7. Statistical correlations within the surface classes supported this observation (snow r = -0.80; ice = -0.80; rock = -0.63). Similar correlations were identified between intensity and surface elevation. Although the range is inversely dependent on surface elevation (since the aircraft elevation is relatively constant), the strong correlation with surface elevation could suggest that intensity values are affected by an elevation-dependent surface characteristic, such as the presence of free-water, which, by the given weather conditions, would be dependent on the surface energy balance.

3.3 Intensity Characteristics of Surface Classes

As summarised in Figure 10, the main surface classes possesses differentiable intensity characteristics.

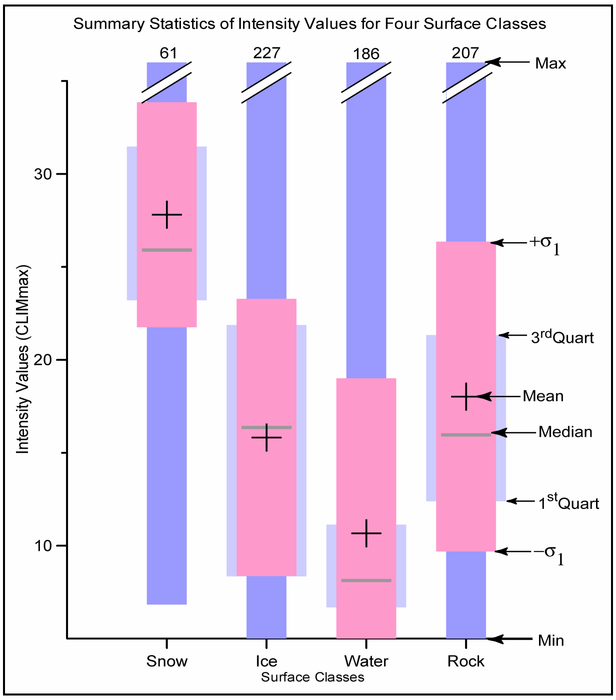

Figure 10: Descriptive statistics of the four main classes

3.3.1 Snow surfaces maintained relatively high intensity values, although the coefficients were smaller than those suggested for optical light (e.g. Paterson, 1994:59). The maximum values in the upper regions may be due to drier pack composition than in lower regions.

3.3.2 Ice surfaces maintained significantly weaker intensity signals than that of snow. Hence, the snow-ice boundary was more evident in the laser (infrared) image than in the optical orthophoto image, as shown in figure 12. Blue ice surfaces, which were barely identifiable in the orthophotos, possessed significantly weaker intensity values than old fern and white ice, making them easily identifiable. Figure 9 contains such a specimen (in both images: right of center).

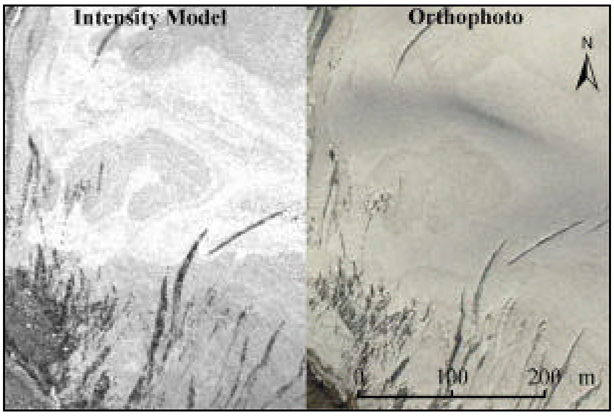

Figure 11: Comparison between intensity model (left) and orthophoto (right). The intensity model differentiates the snow-ice boundary more clearly than the orthophoto.

3.3.3 Rock surfaces possessed highly variable intensity values on a local scale. This was mainly due to varying footprint sizes which resulted from heterogeneous angles of incidence.

3.3.4 Water surfaces possessed spectral characteristics. The pro-glacial lake, as shown in figure 7, reflected strong signals to the three flight paths of origin when the angle of incidence was close to zero. This "hot spot" characteristic was also evident on rock and ice surfaces to a limited extent, potentially due to free-water, in the form of water films on melting ice or small pools.

3.4 Evaluation of Geometry Modelling

The geometry modelling accurately depicted the laser range, as suggested by the high correlations (see 3.2.2). This is expected, since the range is calculated using simple variables (?Height$_{Surface-Aircraft}$ and ?Horiz.Dist.$_{Surface-Aircraft}$). Modelling of the angle of incidence was limited by DEM resolution. Small (but for the footprint significant) surface features could not be accurately represented in the DEM. At the given resolution, the angle of incidence can only be accurately modelled on relatively homogeneous surface with gradual changes. This would explain why the rough rock surfaces possessed relatively low correlations between intensity and footprint size.

4. CONCLUSION

The investigations have determined the following:

1) Variation of intensity values due to *cross-path fading* can be fully eliminated using the composite laser intensity modelling methodology (see section 2.2.4).
2) The remaining variation of intensity values correlates significantly with:

a. laser range
b. surface elevation
c. surface class

3) "Correcting" intensity values for the possible range-dependent variation is inappropriate, since this variation may be due to surface characteristics that are elevation dependent.
4) The main surface classes can be distinctly identified in the intensity models. In some instances, they surpass the orthophotos in their ability to distinguish surface features.
5) The angle of incidence was identified as a primary factor for intensity values reflected off the pro-glacial lake and off surfaces that potentially were wet or contained pools of water.
6) The footprint area and the angle of incidence appear to play an important roll in determining the intensity values of heterogeneous surfaces, such as serac fields, loose rock debris and some bedrock forms. However, due to the DEM resolution, these relationships could not be definitively determined.

Further developments of intensity and geometry modelling should consider the following possibilities:

1) Field observations should be conducted simultaneously with ALS campaigns to precisely determine the surface conditions affecting signal intensity and thereby improving the accuracy of ALS-based classification methods.
2) The laser beam penetration depth and its affect on intensity should be determined for all relevant surface types. Preliminary tests on an adjacent study area have suggested that the laser beam penetrates snow surfaces up to 28 cm (Lutz, in prep.). Depending on signal interpretation, the intensity may potentially represent sub-surface characteristics.
3) Since the geometry modelling is solely dependent on the aircraft data and the DEM, increasing the accuracy of these inputs will improve the accuracy of the geometry data sets. In turn, this reveals any correlations that exist between the intensity values and the geometry characteristics. Current campaigns being conducted within Project OMEGA acquire point densities of ca. 900'000 points/km^2 - nearly doubling the resolution that was used for this study. Utilizing these data sets to create higher resolution DEMs will help determine the effects of the angle of incidence and the footprint size on the intensity values of various surface types.
4) Intensity models can be compared with surface energy balance models to identify possible relationships intensity-elevation relationships.
5) The application of *dual lasers systems* in ALS systems will enable multi-spectral classifications of glacial surfaces using data from a single flight campaign.

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