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# Calibrating laser scanner data from snow surfaces: Correction of intensity effects

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A B S T R A C T

Terrestrial laser scanning data have become more and more commonly used in cryospheric studies as the commercial instruments are getting cheaper and more user-friendly. We have studied the usability of laser scanning intensity data in remote sensing of snow-covered surfaces by focusing on two topics: the effect of incidence angle on the intensity data and the depth which the backscattered laser beam represents. The measurements were made with a phase-based laser scanner using 650–690 nm wavelength. For some of the snow backscatter vs. depth studies measurements were also made with a pulse-based scanner at 905 nm. The incidence angle effect was studied by rotating a snow surface sample relative to the scanner and measuring the difference in the intensity values. The experiment was repeated for different snow types. The snow pack layer that the backscattered laser signal represents was studied by inserting black metal plates horizontally into the snow pack and measuring the changes in the intensity values with plates at different depths. The results suggest that the snow type has no effect on the incidence angle effect and that for dry snow the backscattering of the laser beam takes place from the very surface, but for wet snow, the majority of the signal is backscattered from 0.5 to 1 cm depth. An empirical correction function for the incidence angle effect is also presented.

## 1. Introduction

As the climate is changing rapidly, it is crucial to understand the processes that affect the climate systems. The behavior of snow and ice cover in the changing climate is still fairly poorly known and that introduces considerable uncertainty to the climate models. Better understanding is required on the links between snow geophysical and scattering properties, changing snow and ice-covered area, timing of snow melt, and the surface albedo, which is an essential climate variable (ECV) defined in the Implementation Plan for the Global Observing System for Climate in Support of the United Nations Framework Convention on Climate Change (UNFCCC) (http://unfccc.int/2860.php). Tilt effects are also crucial because they affect the measurement of snow and glacier albedo. Therefore, knowing the effect of incidence angle of the incoming radiation to the snow/ice surface is important in these applications. The measurement geometry effects and their correction have been recently studied by Sicart et al. (2001)) and Weiser et al. (2015). The improvement of the global climate models requires data sets that cover large areas. In practice, this means satellite products. The validation of these products would benefit from in situ data that covers large areas. However, these data are typically not available. Terrestrial laser scanning (TLS) and mobile laser scanning show great potential for gathering the data for validation as well as for analysis (e.g., Egli et al., 2012; Kenner et al., 2011; Kukko et al., 2013).

Terrestrial laser scanning applications on snow surfaces have concentrated on the use of range data (Arnold et al., 2006; Helfricht et al., 2014; Hood and Hayashi, 2010; Prokop, 2008; Prokop et al., 2008; Várnai and Cahalan, 2007). It has proven to be a useful method for mapping inaccessible and dangerous areas, such as potential avalanche sites (for example, Schaffhauser et al., 2008). Some first attempts have been made to use the airborne laser scanning intensity for glacier surfaces (Höfle et al., 2007; Lutz et al., 2003), but the TLS intensity data have, to the best of our knowledge, not yet been widely applied for snow-covered surfaces. The laser reflection and multiple scattering in the snow layer also plays an important role in the usability of TLS range data from snow surfaces. Prokop (2008) found limitations in the application of TLS range measurements for operational avalanche forecasting: if the snow surface was wet and the snow grain size was large (N1 mm), only 50% of the emitted laser signal was received, depending on the angle of incidence. To improve the applicability of TLS data, more accurate knowledge on the incidence angle effect is important. It is also important to know how much the diffuse reflection of laser entering

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the snowpack contributes to the backscattered signal being detected (cf. Kaasalainen et al., 2006). This is particularly important in mobile laser scanner applications, which typically span a larger area than stationary TLS, resulting in a great variety of incidence angles and point densities, which, in turn, affect the accuracy of results.

Calibrated laser scanner intensity data can be used in segmentation and classification of the range data (Höfle et al., 2007; Yan et al., 2012). Radiometric calibration systems have been developed to enhance the comparability of different scans (Ahokas et al., 2006; Coren and Sterzai, 2006; Höfle et al., 2007; Kaasalainen et al., 2009; Wagner et al., 2006). In our previous studies on the applicability of laser scanning on snow surface mapping (Anttila et al., 2011; Kukko et al., 2013), we have found some challenges related to the measurement and calibration of TLS data: one of these is the considerable effect the incidence angle has on the intensity data (e.g., Anttila et al., 2011). We have found that the object backscattering properties affect the incidence angle effect (Kaasalainen et al., 2011; Krooks et al., 2013). The backscattering properties of snow depend on the grain size and shape (Kaasalainen et al., 2006) and the surface structure (Zhuravleva and Kokhanovsky, 2011). However, our previous studies have suggested that the snow type may have no effect on the incidence angle effect (Anttila et al., 2011). In this paper, we address this issue by studying the mean intensity value of several different snow surfaces in different incidence angles.

To relate the snow intensity parameters to grain properties, it is important to know how much the laser signal penetrates into the snowpack, and, most importantly, which part of the snow layer the backscattered signal represents. Prokop (2008) has studied this using the range data by placing reflective foils and blankets on the snow and comparing the range data of the different surfaces. He found that there was a less than 1 cm difference in the surface height values. We have studied the same topic using the intensity values. We placed matt black painted metal plates horizontally in the snow pack at different depths and measured the changes in the intensity value. We repeated the measurements with different snow types.

The studies presented in this paper are made on taiga snow in the boreal forest zone. After the introduction, in Section 2, we present the methodologies used for both the experiments. In Section 3, we present the results, and in Section 4, we discuss the results in more detail.

## 2. Methods

The measurements used in this study were made in Kirkkonummi, Southern Finland (60.1°N, 24.5°E). The snow in Southern Finland is typical taiga snow with ice lenses and various layers of different density and crystal type (Sturm et al., 1995). The relevant geophysical properties of each measured snowpack, including crystal types and sizes, layer structure of the snow pack and surface roughness, were documented during the measurements. In addition to these, overall weather conditions, such as air temperature, were monitored for the periods of measuring. The relevant weather and snow properties are introduced along the measurements.

The laser scanning measurements of this study were made with Leica HDS6100, which uses 650–690 nm wavelengths. The beam diameter at exit is 3 mm, and the beam divergence is 0.22 mrad. The range measurements are based on phase detection. The wavelength dependency of the incidence angle effect was studied using measurements made with Hyperspectral Lidar (HSL) developed at the FGI (see Hakala et al., 2012, for more details on the HSL). For snow backscatter vs. depth measurements, data obtained with a Sick LMS151 laser scanner have also been included to compare the results from a phase-based scanner to those with a pulsed one. The Sick scanner is a pulsed 905 nm scanner with an 8 mm beam exit diameter and 15 mrad beam divergence. Therefore, the laser spot diameter on the sample surface can be considered much larger than that of Leica HDS6100.

The intensity detector of the LeicaHDS6100 scanner used here has been found to be linear and follow the $R^2$ dependence (R being the range) of the radar range equation (Wagner et al., 2006) at distances greater than 10 m (Kaasalainen et al., 2011):

$$P_r = \frac{P_t D_r^2}{4\pi R^4 \beta_t^2}\sigma \tag{1}$$

where $P_r$ is the received power, $P_t$ is the transmitted power, $D_r$ is the receiver aperture, $R$ is the range, and $\beta_t$ is the transmitter beam width. $\sigma$ is the backscatter cross section, which is related to target reflectivity and the measurement geometry. In this study, all parameters, including the range $R$, remained constant, except for $\sigma$, which depends on the incidence angle (cf. Kaasalainen et al., 2011; Shaker et al., 2011).

According to Höfle and Pfeifer (2007), the $\sigma$ depends on the incidence angle as follows:

$$\sigma = \pi\rho R^2 \beta_t^2 cos\alpha \tag{2}$$

where $\rho$ is the target reflectance, $R$ is the range, $\beta_t$ is the laser beam width and $\alpha$ is the incidence angle. Placing plates in the snowpack affected the surface reflectivity, which is also contained in the cross section parameter $\sigma$ (Wagner et al., 2006).

### 2.1. Incidence angle

To measure the incidence angle effect a sample of the snow pack was carefully cut from the snow pack without destroying the surface structure (see Fig. 1). The sample was cut by using a thin plastic box, where it was kept during the measurements. The surfaces of the snow samples were approximately 20 cm × 20 cm, and the snow sample was approximately 6–8 cm thick. The surface of the snow sample was scanned several times with each scan having the box (and the snow sample) in a different angle relative to the scanner. Similar measurements were made in different days having different snow types. Images of the surface crystals together with weather information for each day can be seen in Table 1. The crystals have been classified according to Fierz et al. (2009). The different snow types cover fresh dendritic snow, needles, metamorphosed snow, fresh wet snow, and old wet snow.

The incidence angle relative to the snow surface was controlled by rotating the snow sample with an URB100CC rotation stage (Newport, Irvine, CA) (see Fig. 1). The rotation stage was mounted to an aluminum frame along with a mirror. The laser beam was reflected to the sample surface by the mirror. The distance between the laser source, and the sample (via mirror) was about 5 m. The use of a mirror allowed the rotator to turn the sample to greater angles of incidence, and still hold the sample upright enough for the surface to remain intact. During the data analysis, a plane was fitted to the data sets to calculate the incidence angle more accurately.

To investigate the wavelength dependence of the incidence angle effect, multi-wavelength measurements with HSL were carried out in February 21, 2012, using a setup similar to the monochromatic TLS measurements. The backscattered intensity of the continuous light source was recorded at eight wavelength channels (554.8 nm, 623.5 nm, 691.1 nm, 725.5 nm, 760.3 nm, 795.0 nm, 899.0 nm, and 1000.4 nm) for a wet, melting snow sample (see Table 1 for more details on the measurement conditions).

To ensure the stability of the measurement setting a four-step Spectralon® (Labsphere Inc.) reflectance target of 12%, 25%, 50%, and 99%, reflectance was placed in each scan near the snow sample. The 99% backscattering panel values for each scan were compared to ensure the comparability of the different scans. The stability of the snow sample during the measurements was controlled in several ways. Air temperature was measured during the whole set of measurements near the sample to make sure that the changing temperature did not cause too