ANALYSIS OF THE SPATIO-TEMPORAL DEVELOPMENT OF SNOW SURFACE WETNESS IN A HIGH ALPINE AREA USING TERRESTRIAL LASER SCANNING REFLECTIVITY

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ABSTRACT: One indicator that provides information about the state of snow melting and snow pack stability is the liquid water content (LWC); however, it remains a challenge to measure LWC over large areas with current methods. The major aim of this study is to build a basis for more efficient snow wetness analysis using Terrestrial Laser Scanning (TLS) reflectivity data. The combination of TLS 3D locational data with snow reflectivity information on a hyper-temporal scale provides a tool for non-destructive LWC measurement and change detection on avalanche prone slopes and over a larger spatial scale.
Fieldwork consisted of concurrent TLS acquisitions (Riegl VZ-4000 and VZ-6000) and in situ snow samples along a transect at Lake Weisssee within the Kaunertal Glacier Ski Resort, Austria (2500 m a.s.l.). A Denoth meter was used for in situ LWC measurements. It was found that TLS reflectivity data could be used to map wet snow areas based on the different spectral reflectivity. In situ LWC samples correlate well with TLS reflectivity. Reflectivity at the snow surface decreases diurnally and seasonally from March to May because of increasing LWC. Furthermore, results show that the TLS VZ-4000 (operating at NIR λ 1550 nm) is capable to record moderately wet snow surfaces; thus, widely applicable for research and practitioners because its operating wavelength is eye safe.

KEYWORDS: Terrestrial laser scanning, snow surface, reflectivity, liquid water content

1. INTRODUCTION

As the snow packs in mountainous regions are subject to constant change the accurate assessment of snow properties is important, but challenging. One indicator that provides information about the state of snow melting is the liquid water content (LWC), the amount of water within the snow that is in the liquid phase. Increasing LWC from intense solar radiation or from rain on snow events facilitate rapid wet snow metamorphism. A high LWC influences the stability of the snowpack (Baggi and Schweizer, 2009; Mitterer et al., 2011) increasing the avalanche risk and meltwater runoff within the catchment. Even tough the LWC is a measure of high significance for wet-snow avalanche prediction, flood forecasts (Weber et al., 2010; Prasch et al., 2013) and reservoir management (Koch et al., 2011), it remains difficult to measure with conventional techniques. Methods to measure snow wetness have to be quick and preferably non-destructive because any disturbance to the snowpack may change its structure, thus affecting snow metamorphism and the distribution of liquid water.

Current methods to measure the LWC lack the spatial resolution, are destructive to the snow pack, inaccurate and not efficient (Techel and Pielmeier, 2011). As it is difficult to simulate and model snowpack dynamics in the rough terrain of the mountains, airborne and satellite remote sensing methods have been used for the estimation of snowpack properties such as snow covered area and albedo (Dozier and Painter, 2004; Schaffhauser et al., 2008), snow wetness detection (Maetzler et al., 1997), mapping of avalanche release and run-out zones (Bühler et al., 2009; Eckerstorfer et al., 2016) and glaciological applications to detect changes in glacier volume and dynamics (Sailer et al., 2012). However, the rough topography and highly variable weather conditions in alpine regions present drawbacks in the application of air- and space borne remote sensing techniques.

Within this work a new method to analyse the spatio-temporal development of snow wetness is proposed. LiDAR (Light Detection And Ranging) is an active, highly accurate remote sensing technique which measures the x,y,z location of surfaces based on a line-of-sight and time of

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flight (TOF) distance measurement (e.g. Höfle and Pfeifer, 2007; Eitel et al., 2013; Deems et al., 2013). The technology can be applied from the ground with the LiDAR instrument mounted on e.g. a tripod (Terrestrial Laser Scanning, TLS) or from the air on board of an airplane or a helicopter (Airborne Laser Scanning, ALS). LiDAR has large potential for snow hydrological applications, as it is non-destructive to the snow pack and can be applied without exposition to avalanche terrain. TLS has been used for snow depth measurements (e.g. Prokop et al., 2008; Egli et al., 2011; Deems et al., 2015; Lopez-Moreno et al., 2017).

Furthermore, LiDAR systems are not only recording 3D locational data, but also additional data categories such as laser return intensity (LRI), which is a measure for the surface reflectivity in the emitted wavelength (or multiple-wavelengths) and thus is useful for obtaining spectral information about chemical and biophysical surface properties. In combination with an additional time dimension from repeated laser scans a temporal component can be added for change detection and to monitor snow surface processes.

The major aim of this study is to build a basis for more efficient snow wetness analysis. For this purpose the potential of hyper temporal TLS reflectivity for the identification of wet snow surfaces is explored and compared to conventional measurements with a dielectric device (Denoth meter).

2. METHODS

2.1 Fieldwork

Fieldwork consisted of concurrent TLS acquisitions (Riegl VZ-4000 and VZ-6000) and in situ snow sampling at ten locations along an east west transect at Lake Weisssee within the Kaunertal Glacier Ski Resort, Austria (2500 m a.s.l.). During each TLS scan in situ point scale samples of 1) snow density (ρ), 2) snow depth (sd), 3) snow permittivity (ε), and 4) hand test were measured three times at each snow pit. The snow pits were located on different slope expositions and the snow pit walls were facing south to provide shading conditions for the measurements.

2.1.1 Denoth meter

Snow permittivity (ε) was measured with a dielectric device, Denoth meter (Denoth, 1989). Together with a concurrent density measurement the LWC can be derived based on the empirical relation (Denoth, 1989):

$$\varepsilon = 1 + 1.92\rho + 0.44\rho^2 + 0.187\theta + 0.0045\theta^2$$

2.1.2 Terrestrial Laser Scanning

A snow-free scan was recorded in September 2016 and four snow scanning campaigns were launched from March to May 2017. During each campaign two scans a day from two scan positions were conducted and the campaigns were coordinated with the Sentinel-1A/B satellite overflights to make the data comparable to the ENVEO Sentinel-1 wet-snow maps (Nagler et al., 2016). In addition to the TLS Riegl VZ-4000 operating at NIR λ 1550 nm, the Riegl VZ-6000 (λ 1064 nm) was used during the field campaign in May 2017. The shorter wavelength makes this scanner better suitable to record reflections from ice, snow and firn. However, at this wavelength the reflectivity is expected to be less sensitive to changes in LWC. In addition, eye exposure to the direct as well as the reflected laser beam is hazardous.

2.2 Data processing

The snow-free scan was geo-referenced and registered with an ALS point cloud from 2010 (Fey and Wichmann, 2016) using an iterative closest points algorithm (ICP). An ICP based registration is not suitable for snow scans because the surface between snow-free and snow scan changes. Registration of the snow scans was performed by searching tiepoints and planes in snow free areas (e.g. ski station walls, pillars, avalanche protections, roads etc.) in the snow-free and snow scan.

The point clouds were gridded into 0.5 x 0.5 m digital elevation models (DEM). In a subsequent step, the DEMs were used to generate DEMs of difference (DoD) between the snow-covered grids and the snow-free reference grid. This method was applied for each scan date and time separately. The resulting snow-covered polygons were used to clip the corresponding z-value grids in order to obtain the snow depth.

In addition to the scanner's automated range correction (Pfenningbauer and Ullrich, 2010), a topographic correction was implemented in order to make the reflectivity data comparable among days and transferable to other areas. For this purpose a linear regression of mean incidence angles and mean reflectivities at the ten target locations from both scan positions was established.

Point clouds with corrected reflectivity were clipped with the snow-covered polygons within the LIS PRO 3D extension of SAGA GIS and rasterized for further analysis.

A linear regression model was established based on the relationship of in situ measured

LWC and TLS VZ-4000 reflectivity for the months March to May.

The final snow wetness maps, LWC (%) were manually classified into four classes according to the International Classification of Seasonal Snow on the Ground (Fierz et al., 2009). The same classification categories (dry, moist, wet and very wet) were used to display the LWC of the Denoth meter in situ measurements.

3. RESULTS AND DISCUSSION

In situ measurements showed a clear increase of snow density and LWC at the snow surface in the months March to May (Fig. 1). LWC increased to 4.75 - 8.37 % in April, and the highest LWC was measured as 7.73 - 9.20 % in the morning of May. Lower values in the afternoon might be due to liquid water flowing into deeper layers of the snowpack (funicular regime).

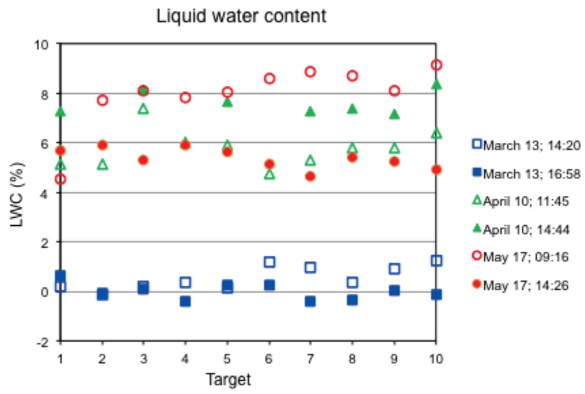

Figure 1 In situ measured LWC at the ten target locations along the transect at Lake Weisssee.

3.1 TLS reflectivity

Similarly, laser signal reflectivity decreased seasonally and diurnally from March to May throughout the research area. Especially, April and May were clearly reduced compared to March, with April being less homogeneous and having patches of higher reflectivity on north-western slopes compared to the month of May (Fig. 2).

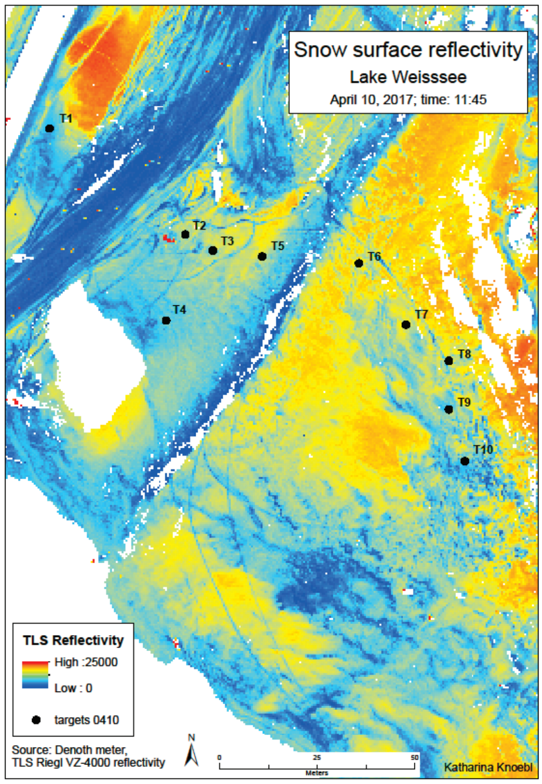

Figure 2: Map of the TLS VZ-4000 snow surface reflectivity on April 10, 2017 at 11:45. Scanned from scan position 1 (distance: ~300 m) to the research site Lake Weisssee.

Furthermore, results show that even the TLS VZ-4000 (λ 1550 nm) is capable of obtaining data on snow and moderately wet snow surfaces.

The two most important properties in terms of snow reflectivity are LWC and grain size. Increasing solar radiation and intensity throughout a day and the season causes clustering of the ice crystals due to wet snow metamorphism (Wiscombe and Warren, 1980; Green et al., 2002; Deems et al., 2015). As a result the TLS reflectivity at the snow surface is lower.

3.2 Liquid water content

Based on the linear regression model LWC was calculated as:

$$LWC = -0.0004721 * ref_{cor} + 10.3699$$

LWC measured in situ along the transect correlates with the TLS reflectivity data (Fig 3). Wetter snow surfaces had lower TLS reflectivity compared to the drier snow.

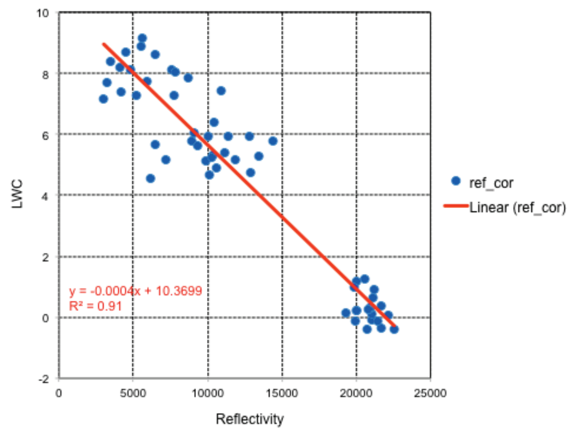

Figure 3: Linear regression of in situ measured LWC and TLS VZ-4000 reflectivity at the research site Lake Weisssee.

3.2.1 Diurnal development of LWC

Diurnal changes of snow wetness can be mapped from TLS reflectivity (Fig. 4 and 5). In situ measured LWC and spatial distribution of LWC derived from TLS reflectivity correlate well. Uncertainties appear close to the class limits.

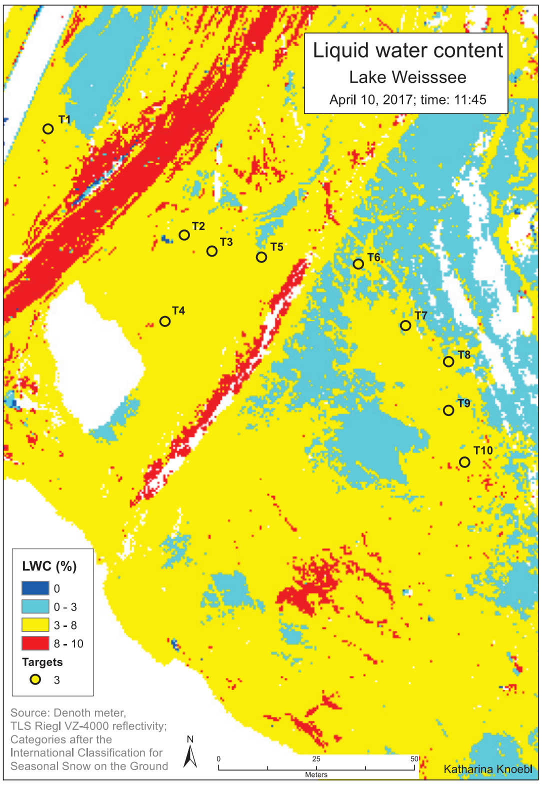

Figure 4: Map of the liquid water content (LWC) distribution at the snow surface at the research site Lake Weisssee on April 10, 2017 at 11:45. Data classified based on the linear regression of in situ LWC and TLS reflectivity. Yellow circles indicate the locations of in situ LWC measurements, category 3 (wet).

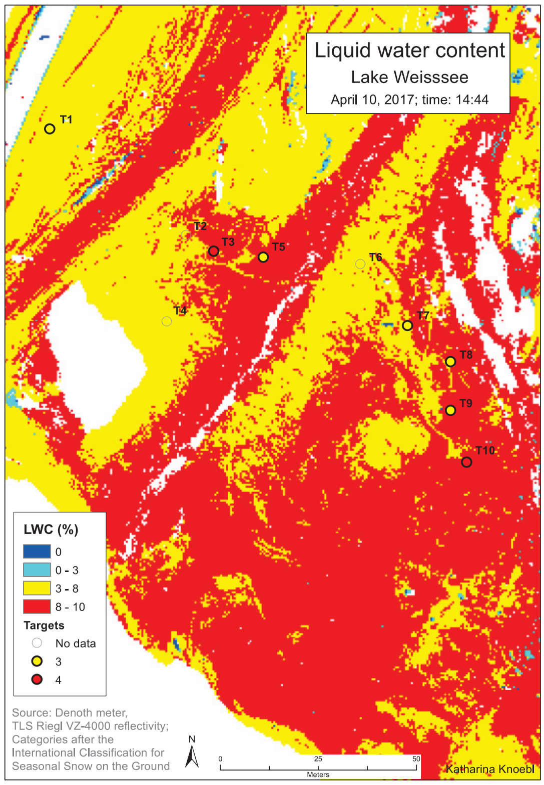

Figure 5: Map of the liquid water content (LWC) distribution at the snow surface at the research site Lake Weisssee in the afternoon of April 10, 2017 at 14:44. Yellow and red circles indicate the locations of in situ LWC measurements, category 3 (wet) and 4 (very wet).

4. CONCLUSION AND OUTLOOK

TLS reflectivity can be used as a high-resolution tool for the analysis of spatial LWC distribution and temporal changes of wetness. Thus, the method can be applied to aid in the spatially confined, time consuming and labour intensive point-scale in situ LWC sampling. Especially in hardly accessible mountainous terrain and near avalanche slopes this new method can be of advantage from a safety and practicality standpoint.

Furthermore, the TLS VZ-4000 (λ 1550 nm) is capable to record moderately wet snow surfaces. Thus, this TLS type provides a wide range of application options to practitioners for avalanche mitigation and hydrological purposes because its operating wavelength is eye safe.

In order to improve snow wetness estimation and potential influencing factors with TLS reflectivity measurements, more campaigns could be conducted. In addition, a thermal camera mounted to the TLS, as well as concurrent in situ snow temperature measurements and precise grain structure analysis could be incorporated. Furthermore, future studies could include models (e.g. radiative transfer models) to quantify and correct the effect of grain size. Moreover, the topographic correction of the reflectivity could be improved and a pulse shape deviation correction added to the scanner's automatic range correction to reduce uncertainty and increase accuracy.

With the recent enormous technological development, LiDAR is a very promising method for snow wetness analysis. Further research for LiDAR applications and processing workflows remain an important task in the future.

ACKNOWLEDGEMENTS

I would like to thank alpS for initiating the project; TIWAG and University of Vienna for providing the TLS, BFW for the Denoth meter, LASERDATA for the LIS PRO 3D tools, and Klaus Schneeberger, Elena Stoll and Anna Tilg for their support in the field.

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