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# Computation of a distributed glacier surface albedo proxy using airborne laser scanning intensity data and in-situ spectro-radiometric measurements

Philip C. Joerg *, Jörg Weyermann, Felix Morsdorf, Michael Zemp, Michael E. Schaepman

*Department of Geography, University of Zurich, Winterthurerstrasse 190, CH-8057 Zurich, Switzerland*

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ABSTRACT

In recent years, multi-temporal topographic measurements from airborne laser scanning (ALS) have been increasingly used as a source of spatially explicit and accurate information to calculate geodetic glacier mass balances. Simultaneous to collecting topographic data, most ALS instruments record the backscattered intensity for each laser emission and therefore provide additional information on the reflectance characteristics of the surveyed surface. Along with air temperature, the surface albedo of snow and ice was identified as a major driving factor of glacier melt. Consequently, better knowledge on the spatial distribution of the glacier albedo could substantially improve energy balance based glacier melt modeling. In this study, we collected on-glacier spectro-radiometric and albedometer measurements to serve as a ground reference to radiometrically calibrate high resolution ALS intensity data into a distributed albedo proxy map. This method resulted in an albedo proxy with values between 0.6 on the glacier tongue and 0.9 on fresh snow in high altitudes. 99.6% of all values fell within the albedo boundary conditions, i.e. values between 0 and 1. Corrected near-infrared ALS intensity data provided a distributed product that allows simulating albedo in glacier energy and mass balance models more realistically. Remaining challenges are (i) a different surface albedo response in the visual part of the electromagnetic spectrum, (ii) the low radiometric resolution of the ALS system for higher intensity values, and (iii) an insufficient correction of the snow bi-directional reflectance distribution function (BRDF).



## 1. Introduction

Glacier ablation is primarily driven by air temperature and net solar radiation (e.g. Ohmura, Bauder, Müller, & Kappenberger, 2007). The glacier surface energy balance describes the amount of energy available for melt and depends not only on the incident radiation, but also on the energy uptake efficiency (cf. Wiscombe & Warren, 1980). This important factor is the surface bi-hemispherical reflectance, further on called albedo, defined as the ratio of reflected to incident radiation, and strongly influencing ablation (Oerlemans, Giesen, & Van Den Broeke, 2009; Schaepman-Strub, Schaepman, Painter, Dangel, & Martonchik, 2006). Snow albedo is inversely correlated with snow grain size and the concentration of impurities in the snow pack whereas ice albedo is mostly dependent on the content of debris and smaller sized mineral and biogenic cover (Brock, Willis, & Sharp, 2000; Oerlemans et al., 2009). Typical value ranges for snow (firn, ice) albedo from measurements and used for glacier energy and mass balance modeling range between 0.6 and 0.9 (0.3–0.55, 0.2–0.35) (e.g. Cuffey & Paterson, 2010; Greuell, Knap, & Smeets, 1997; Klok & Oerlemans, 2004; Machguth, Paul, Hoelzle, & Haeberli, 2006).

Current glacier energy and mass balance models rely on single or multiple albedo values which are usually estimated from literature or modeled, e.g. by simulating albedo as a function of aging snow or snow depth, and often assumed to be spatially homogeneous on a larger part on the glacier surface (Klok & Oerlemans, 2004; Machguth et al., 2006). To improve these assumptions, the albedo can either be measured directly on the glacier (Brock et al., 2000; Sugiyama, Yoshizawa, Huss, Tsutaki, & Nishimura, 2011) or derived from remote sensing data (Knap, Brock, Oerlemans, & Willis, 1999; Stroeve et al., 2005). However, the spatial distribution of albedo on a glacier can be highly variable (Sugiyama et al., 2011) and the spatial resolution of a satellite instrument might not be satisfactory for the application on smaller valley type or mountain glaciers. In addition, passive optical measurements depend on the sun as an illumination source and contain directional effects as a result from isotropic, volumetric and geometrical–optical scattering (summarized as bi-directional reflectance distribution function (BRDF) effects; for terminology see Schaepman-Strub et al. (2006)).

In the past decade, the measurements of the geodetic elevation change of glaciers using airborne laser scanning (ALS) provided operational data (e.g. Abermann, Lambrecht, Fischer, & Kuhn, 2009; Geist, 2005; Joerg, Morsdorf, & Zemp, 2012). As a side product to topographic information, most airborne laser scanning systems record the

* Corresponding author. Tel.: +41 44 635 6522.
*E-mail address:* philip.joerg@geo.uzh.ch (P.C. Joerg).

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backscattered intensity providing surface reflectance information in one narrow spectral band (e.g. 1 nm sampling width). For glacier laser scanning applications, typically the near-infrared part of the electromagnetic spectrum is used. Lutz, Geist, and Stötter (2003) showed that a near-infrared wavelength is particularly well suited to derive information on snow and ice characteristics. However, to make use of this information, the data has to be radiometrically corrected for different physical effects (Höfle & Pfeifer, 2007; Kaasalainen et al., 2011; Vain, Kaasalainen, Pyysalo, Krooks, & Litkey, 2009). Finally, the ALS measures in a monostatic configuration, having the same illumination and observation geometries.

In this study, we derive a spatially distributed glacier surface albedo derived from radiometrically calibrated ALS intensity data. However, as only one single narrow band in the near-infrared part of the electromagnetic spectrum is provided by our ALS system, the resulting product is seen as an albedo proxy. To provide suitable reference data, we synchronously collected in-situ spectral reflectance and albedo values at different altitudes on the Alpine glacier. We use the on-glacier reference data from spectro-radiometric measurements at four different locations to derive the broadband albedo. Additionally, we correct all-day albedometer measurements at a single location for topographic effects of the inclined glacier surface and perform a sky view correction to eliminate the influence of the surrounding higher regions on the broadband albedo. Furthermore, we physically pre-process ALS intensities to derive a homogeneous data set, including an assessment of two types of bi-directional reflectance distribution functions (BRDF) of snow. Subsequently, we correlate the corrected ALS intensities with the reference in-situ albedo to generate an albedo proxy map. Finally, we assess and discuss the derived albedo map for its validity and some persistent uncertainties, including a comparison with a broadband albedo map derived from a synchronous multi-spectral aerial camera data set.

## 2. Study site and data

### 2.1. Study site

Our study site encloses the Findelengletscher (46° N, 7° 52′ E) located in the Canton Valais, Switzerland. This valley-type glacier is one of the larger ones in the Alps with an area of more than 13 $km^2$ (in 2010). As it covers an elevation range from 2600 m up to 3900 m a.s.l., it is expected to sustain multiple decades from now on, despite the strong retreat in the last decades (cf. Glaciological Reports, 1881–2010). Since 2004/05, glaciological mass balance measurements were available (Machguth, 2008; Machguth et al., 2006) serving as a baseline within a long-term mass balance monitoring program.

Four days before the in-situ and ALS measurements in September 2010, a snowfall event covered the entire Findelengletscher with a layer of fresh snow. The typically present end-of-summer differentiation between snow, firn, and ice including transition zones in between these facies types became consequently indistinct. Snow depth measurements at ablation stakes revealed that at the day of the campaign, about 0.05–0.10 m of snow was still present on the tongue (2600 m a.s.l.), though melting fast. In higher altitudes, the snow depth generally increased with high spatial variability, to a maximum measured snow depth of 0.28 m at 3413 m a.s.l.

### 2.2. ALS data

On September 29, 2010, the ALS (Optech Inc., ALTM Gemini) was used on board a Pilatus Porter fixed-wing aircraft to retrieve topographic information in order to support the in-situ glaciological mass balance measurements. The weather during data acquisition was cloud-free with an excellent visibility. The built-in surveying system consisted of a pulsed laser, whose emissions were deflected across the flight track using an oscillating mirror. The range distance of each laser emission is calculated by the two way time-of-flight between the ground and the emitter/detector, under the assumption of a constant speed of light. A global positioning system (GPS) coupled with an inertial navigation system (INS) provided position and attitude of the aircraft. These data, together with the range measurement and instantaneous angle of the deflecting mirror, allowed allocating a coordinate in a given reference system for each ground projected field of view (Wehr & Lohr, 1999).

The entire glacier area was surveyed from a nominal flight altitude of 1000 m above ground (cf. Table 1 and Fig. 1). A second acquisition at a lower nominal flying altitude of 600 m above ground and a higher pulse repetition frequency (PRF) and higher resolution was performed as well, but only covered the lower parts of the glacier. Additionally, two flight trajectories at a higher altitude of 2800 m above ground were acquired for a large portion of the glacier area to investigate the effects on the accuracy of this lower point density digital elevation model (DEM) and the behavior of the recorded intensity compared to the standard setup flown at 1000 m above ground.

Point cloud data were available in binary LAS format including intensity values represented as digital numbers (DN) and the flight path data was available as smoothed best estimated trajectory (SBET) data set with a 250 Hz position and attitude recording rate. The emitted laser power was calculated from sensor calibration reports provided by the manufacturer of the scanning system (Optech Inc., data not shown) and the power was assumed to be stable for each respective pulse repetition frequency setting during the entire flight.

### 2.3. ADS 80 data

On the same day as the ALS data was acquired, an independent flight campaign with an Airborne Digital Sensor (Leica Geosystems AG, ADS 80) was performed by the Federal Office of Topography (swisstopo). The camera collected data in the blue (420–492 nm), green (533–587 nm), red (604–664 nm), and near-infrared (833–920 nm) parts of the electro-magnetic spectrum. Although the camera would provide multi-angular data for photogrammetry purposes, we limited the processing to the nadir multispectral data. Data collection took place on 11:14 UTC at an altitude of 7600 m a.s.l. on an east–west oriented flight trajectory. The flight strip covered most of the Findelengletscher; about 12% in the southernmost part were not covered.

### 2.4. Ground reference data

To investigate and calibrate the ALS intensity and ADS reflectance measurements, we used a twofold approach. To monitor changes in the snow surface and solar irradiance during the flight campaigns, we installed an albedometer (Kipp & Zonen CM 7B) at 3118 m a.s.l. on a part of the glacier with a gentle slope of approx. 3° to the west. The albedometer consisted of two oppositely mounted zenith and nadir facing pyranometers measuring the broadband radiation between 305 and 2800 nm over each hemisphere. Combining both measurements provides the bi-hemispherical reflectance (BHR), also called the (blue sky) broadband albedo (Schaepman-Strub et al., 2006). The area of the albedometer's location was covered by laser returns from three

**Table 1**
Data acquisition parameters for the respective flying height.

| Date of acquisition | Sept. 29, 2010 | | | |
|---|---|---|---|---|
| Sensor employed | Optech ALTM Gemini | | | |
| Average flying height | [m a.g.l.] | 600 | 1000 | 2800 |
| Pulse repetition frequency (PRF) | [kHz] | 100 | 71 | 33 |
| Scanning angle | [degrees] | ±15 | ±15 | ±20.1 |
| Line scanning frequency | [Hz] | 39 | 39 | 13.7 |
| Across-track overlap | [%] | 40 | 50 | 35 |
| Average point density | [$Pt/m^2$] | 14.4 | 8.2 | 0.4 |
| Laser wavelength | [nm] | 1064 | 1064 | 1064 |
| Beam divergence (1/e) | [mrad] | 0.25 | 0.25 | 0.25 |