Remote Sensing of Environment 127 (2012) 118–129

Contents lists available at SciVerse ScienceDirect

Remote Sensing of Environment

journal homepage: www.elsevier.com/locate/rse

Uncertainty assessment of multi-temporal airborne laser scanning data: A case study on an Alpine glacier

Philip Claudio Joerg *, Felix Morsdorf, Michael Zemp

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

A R T I C L E I N F O

Article history:
Received 15 March 2012
Received in revised form 5 August 2012
Accepted 11 August 2012
Available online 24 September 2012

Keywords:
Airborne laser scanning
LiDAR
Uncertainty assessment
Error propagation
Mountain glacier
Glacier change
Multi-temporal
Digital elevation model

A B S T R A C T

In glaciology, volumetric changes from multi-temporal digital elevation models (DEMs) serve to validate and calibrate glacier mass balances from traditional in situ measurements. In this study, we provide a thorough uncertainty assessment of multi-temporal airborne laser scanning DEMs based on: (a) applying a statistical error model, (b) comparing laser echoes to reference points and surfaces, and (c) developing a physical error propagation model. The latter model takes into account the measurement platform characteristics, components of the measurement process, and the surface properties. Such a model allows the estimation of systematic and stochastic uncertainties for single laser echoes, as well as for distributed surfaces in every part of the study site, independent of the reference surfaces. The full error propagation framework is applied to multi-temporal DEMs covering the highly undulating terrain in the Findelengletscher catchment in Canton Valais, Switzerland. This physical error propagation model is able to reproduce stochastic uncertainties in accordance with measurements from reference surfaces. The high laser point density in the study site reduces the stochastic uncertainties over the whole glacier area to negligibly small values. However, systematic uncertainties greatly influence the calculation of mass changes and lead to corrections of the thickness change of up to 35%.

1. Introduction

Since the 1990s, digital elevation models derived from airborne laser scanning (ALS) have been increasingly used for a wide range of applications (Shan & Toth, 2009). In the last decade, regional to nation-wide surveys have been carried out using ALS, including regions with potential relevance for glacier research, e.g. in Austria and Norway (Geist et al., 2003), and in Switzerland (Geist et al., 2003; Luethy & Stengele, 2005). As the costs associated with ALS are decreasing and the initial datasets are being updated, the prospect of multi-temporal ALS data will sustain new applications, not only in forestry (Yu et al., 2004) but also in natural hazards (Casas et al., 2011; Ventura et al., 2011). However, to make sure that these applications can be used best, new means of validation and uncertainty assessment will need to be implemented (Hopkinson et al., 2008), especially since ALS is a constantly evolving technology, and changing systems and/or survey configurations will result in different datasets with varying accuracies.

In the domain of glaciology, mass balance is traditionally measured in situ using ablation stakes and snow pits, including density measurements. Additionally, different methods are applied to inter-/extrapolate from discrete measuring locations to the entire glacier to calculate the so-called direct glaciological mass balance (cf. Østrem & Brugmann, 1991). To account for the possible accumulation of systematic errors from these seasonal or annual measurements, an independently derived geodetic mass balance at decadal intervals is required (Haug et al., 2009; Huss et al., 2009; Zemp et al., 2010). The standard geodetic method applied is digital elevation model (DEM) differencing from photogrammetric sources (e.g. Haug et al., 2009). However, photogrammetric DEM extraction is hindered by the low contrast often found in alpine environments. ALS has proved to be useful in overcoming the shortcomings of photogrammetric DEMs as it directly measures surface elevations (e.g. Geist, 2005; Kennett & Eiken, 1996).

Several studies have focused on the application of ALS to glacier surface mapping or volume changes (e.g. Abermann et al., 2009; Favey et al., 1999; Geist, 2005; Kennett & Eiken, 1996; Knoll & Kerschner, 2010). To date, ALS accuracy assessments have been conducted using reference surfaces (Favey et al., 1999; Geist, 2005), ground control points (Hodgson & Bresnahan, 2004; Hopkinson & Demuth, 2006) and theoretical or statistical error modeling approaches (Filin, 2003; Goulden & Hopkinson, 2010a; Huising & Gomes Pereira, 1998). In glaciology, stochastic uncertainties in airborne laser scanning DEMs are considered to be lower than other DEM-providing methods. In ALS, vertical accuracies are given between ±0.1 m and ±0.3 m (Abermann et al., 2010). However, estimations of uncertainties are usually based on numbers from data providers or are measured using reference surfaces or points, and may therefore not cover stochastic uncertainties present at the study site (e.g. glacier) itself. Additionally, it is not always clear

---

* Corresponding author. Tel.: +41 44 635 5215.
E-mail address: philip.joerg@geo.uzh.ch (P.C. Joerg).

0034-4257/$ – see front matter © 2012 Elsevier Inc. All rights reserved.
http://dx.doi.org/10.1016/j.rse.2012.08.012

which scale these stochastic uncertainties refer to, i.e. whether they refer to a single measurement (e.g. single laser return), a single raster cell or even the stochastic uncertainty of a whole study site. Furthermore, systematic uncertainties in DEMs directly influence the effects of elevation changes, but are often not considered.

In this study, we developed and implemented a three-step approach to estimate both the systematic and the stochastic uncertainties in DEMs derived from ALS data. First, we checked for co-registration and elevation-dependent errors between each pair of DEMs. In a second step, we compared the location of single laser echoes to reference points and surfaces within the study site. Following this, we used a physical error propagation model to explain the uncertainties found in the previous method and attribute them to their sources. A validation of the physical error propagation model was carried out on reference surfaces and extended to the full point cloud of each ALS survey. Finally, we applied our framework to compute changes in glacier thickness from multi-temporal DEMs and to assess the related uncertainties statistically.

2. Study area and data

2.1. Study site

The Findelengletscher is a temperate valley glacier located in the Swiss Alps (46° N, 7° 52′ E, Fig. 1) in Canton Valais, close to the village of Zermatt, Switzerland. With its area of more than 13 km^2 and a length of about 6.7 km (2010), it is one of the larger valley-type glaciers in the Alps. Since its Little Ice Age maximum extent in c. 1850, when it was 10.4 km long and 19.96 km^2 in area (Maisch et al., 2000), the glacier has retreated, interrupted by three shorter time periods of glacier re-advance (in the 1890s, 1920s, and 1980s). Furthermore, the Findelengletscher and its former tributary Adlergletscher separated in the 1990s and are now independent ice bodies.

The Findelengletscher is considered a worthwhile study site for glaciological investigations for several reasons: (1) the surface is almost completely free of debris and its slope is fairly constant, which facilitate the delineation of the glacier and in situ measurements are possible on almost every part of the glacier; (2) the glacier ranges from 2600 m a.s.l. up to 3900 m a.s.l. and is therefore assumed to sustain multiple decades of strong melt (Farinotti et al., 2011); and (3) the infrastructure of the nearby Zermatt ski resort with its cable cars and helicopter-base facilitates access to the glacier.

The Findelengletscher has been the target of glaciological research in the past (Collins, 1979; Iken & Bindschadler, 1986), and length variation measurements have been available since 1885 (Glaciological Reports, 1881–2010). These indicate that the glacier retreated by about 1900 m in total up to 2010. Huss et al. (2010) reconstructed the seasonal mass balances of the Findelengletscher from 1908 to 2008 using distributed mass balance modeling based on digital elevation models (DEMs) and driven by climate and field data. The reported cumulative specific mass balance of the Findelengletscher for the last century is approximately −26 m water equivalent (w.e.).

Direct glaciological mass balance measurements started on the Findelengletscher in 2004/05 as part of a larger research project

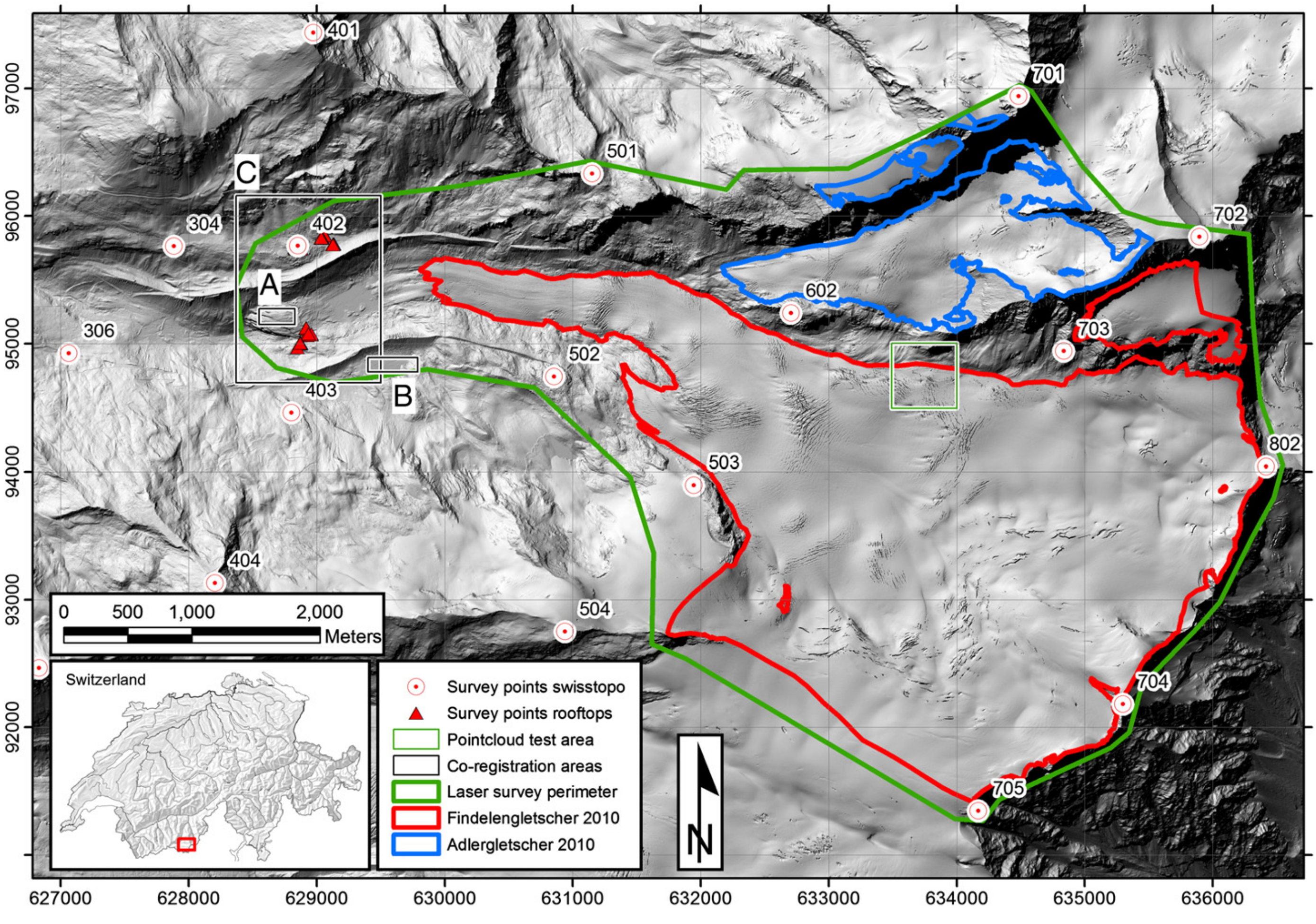

Fig. 1. Shaded relief of the Findelengletscher catchment. The ALS perimeter and glacier outlines 2010 are shown, as well as surveyed surfaces (triangles), reference fix points (circles), and co-registation evaluation areas.