AUTOMATIC GLACIER SURFACE ANALYSIS FROM AIRBORNE LASER SCANNING

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ABSTRACT:

Glaciers are interesting phenomena to scientists, mountaineers and tourists. Glaciers have a great impact on the local economy, power generation and water supply. Furthermore, the behaviour of glaciers is influenced by climate variations, such as changes in temperature. Monitoring glaciers can therefore give valuable insight to glaciologists. Two aspects of glaciers that can be monitored are the delineation of a glacier and the crevasses within a glacier. In this paper it is presented how these two aspects can be detected automatically from Airborne Laser Scanning (ALS) data.

The delineation of a glacier can be derived from ALS data by setting up a classification of the elevation model into the classes *glacier* and *non-glacier surface*. The smoothness, which is calculated from the ALS data, is used as classification criterion. Crevasses within the glacier can be detected by assuming that they are deviations from a regular glacier surface without any crevasses. Such a surface can be calculated with techniques from Mathematical Morphology. Given the assumption that crevasses have a V-like shape, the bottom of the crevasse and the two edges can be reconstructed from the point data. ALS data that was acquired at the Hintereisferner in Tyrol, Austria was used for testing the algorithms. Both the delineation of the glacier and the detection of crevasses give good results in the presented approach. However, the delineation of the glacier might fail if many crevasses cause exceptions to the smoothness criterion. Crevasses are sometimes not detected due to snow bridges. The quality of the reconstruction of crevasses is hard to assess due to the lack of reference data at the test location. Data acquisition with a higher point density and the acquisition of reference data for crevasses with Terrestrial Laser Scanning are recommended to independently check the result.

1. INTRODUCTION

Glaciers are sensitive indicators for climate change processes and have a significant impact on water supply in some regions. Several authors have shown that there is a relation between melting of glaciers and several climatologic parameters, including temperature (Oerlemans, 1994). Glaciers are also of great economic interest on a regional scale. In some regions hydro-power generation, drinking water supply and tourism rely heavily on the existence of glaciers. For these regions, a good understanding and monitoring of glaciers is of vital interest.

For many decades, measurements of glacier length variations and glacier mass-balance have been made in differing ways with the purpose of monitoring the dynamics of the glacier. This was done by means of terrestrial measurements, or by using aerial based data such as photogrammetry. In the European Union funded research project "Operational Monitoring System for European Glacial Areas (OMEGA)", several methods for glacier monitoring were explored, including Airborne Laser Scanning (Geist et al., 2005). Results from this project show the potential of ALS data for different applications in glacier research, thereby following up earlier attempts to utilise ALS on mountain glaciers (Baltsavias et al., 2001; Kennett and Eiken, 1997; Rees, 2005).

With the increasing availability of ALS data, automated approaches can be used to find specific properties of glaciers. Some of the information that can be extracted from the datasets is the extent of the glacier and the location of glacier crevasses. Crevasses are cracks in the upper surface of a glacier, formed by tension acting upon the brittle ice. They can be deep and thus dangerous for travellers on glaciers. Using ALS data to detect and reconstruct crevasses, will assist glaciologists to get more insight into ice dynamics.

Research in other fields of application has already shown that ALS data can be used with a high degree of automation. Objects such as buildings (Vosselman and Dijkman, 2001) and trees (Kraus and Pfeifer, 1998) can be detected automatically from the data. However, automated surface analysis has not yet been applied to glacier surfaces. Climate change sensitive objects, as glaciers are, will be monitored more intensively in future, necessitating automated approaches. In this paper methods for the automatic delineation of glacier areas will be presented and compared. Subsequently, a method for detecting and finally reconstructing crevasses will be presented.

2. DATA SETS

The methods presented were tested on ALS data that was acquired within the OMEGA project. One glacier in this project was the Hintereisferner in Tyrol, Austria. It is a typical valley glacier located in the Ötztal Alps. Up to now, 13 epochs of laser scanning data are available for the Hintereisferner. These datasets were acquired between October 2001 and September 2006 in different seasons of the glaciological year. The datasets acquired in the OMEGA project are documented in Geist and Stötter (2007). For the work in this paper, the data acquired on

August 12th 2003 (HEF9) and October 5th 2004 (HEF11) was used.

The acquisition of these two datasets was performed with the Optech ALTM 2050 and the Optech ALTM 1225 respectively. HEF9 had a mean flying height of 1150 m. For HEF11 the average flying height was 1000 m above the surface. The minimum slant range was 460 m, while the maximum was 1980 m. An average point distance of 0.8 m for HEF9 and 0.7 m for HEF11 was achieved. The vertical accuracy over a control area was $\sigma = 0.095$ m for HEF9 and $\sigma = 0.075$ m for HEF11. The full information of the points, i.e. values for first pulse, last pulse and intensity, is stored in a PostgreSQL database that can be connected to the GRASS GIS (Höfle et al., 2006). The other data sets were not yet added to the database at the time of writing. Additionally, the data was transformed to a 1 m resolution raster using a nearest neighbour interpolation method on the last pulse returns. The use of last pulse data increases the chance of getting points on the bottom of the crevasses. These resulting rasters form the input for the algorithms presented in the following sections.

3. GLACIER DELINEATION

For the detection and reconstruction of crevasses, it is required to limit the search area to the parts of a Digital Elevation Model (DEM) where a glacier can be found. This is done by automatically calculating the delineation of a glacier. Afterwards, the crevasse locations are detected and individual crevasses are reconstructed. The glacier delineation is not only of interest because it forms an important input to the crevasse detection algorithms, it is also an interesting result on itself. Delineations from repeated measurements can for instance be used to monitor the growth or decay of a glacier.

In the presented method it is assumed that the measurements are organised as a rasterised DEM. An example of such a DEM representing a glacier and the surrounding mountains is presented in Figure 1.

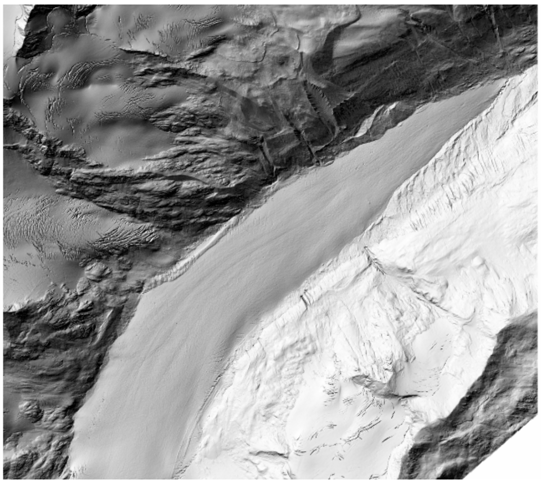

Figure 1. Shaded relief view of the tongue of Hintereisferner

Determining the delineation is essentially a classification of the pixels into the classes “glacier” and “non-glacier”. The process of classification is well-known from Remote Sensing where it normally involves the analysis of multispectral image data and the application of statistically based decision rules. This spectral data is now absent, but other criteria can be developed for the decision rules:

- Criterion 1: Smoothness
- Criterion 2: Connectivity
- Criterion 3: Hydrological constraints

Criterion 1 is based on the surface characteristics as they can be derived from the elevation data. The ice surface that makes up the glacier is much smoother than the surface of the surrounding bedrock. There are several ways to find the smooth areas in the DEM. One method is to calculate the variance of the best fitting plane in a certain region of cells. The size of this region depends on some surface properties and the grid sampling interval. By setting upper and lower boundaries to the variance, the smooth areas can be classified as glacier. The result of this calculation is a new map $\mathbf{\Sigma}$ which contains the variance of n surrounding points in each pixel $\mathbf{\Sigma}(r,c)$. The classification is now simply defined as applying a threshold t to this map:

$$\begin{cases} \mathbf{C}(r,c) = TRUE & for\ \mathbf{\Sigma}(r,c) < t \\ \mathbf{C}(r,c) = FALSE & for\ \mathbf{\Sigma}(r,c) \geq t \end{cases} \quad (1)$$

Alternatively, smoothness can be determined by segmenting the area first. For smooth areas we assume that the first derivative of the surface remains constant. Areas with constant first derivatives can be grouped in segments. If these segments are large enough, the surface that belongs to them can be considered smooth. In image processing, the first derivative of the data is usually called the gradient ∇z.

$$\nabla z = \begin{pmatrix} \dfrac{\partial z}{\partial x} & \dfrac{\partial z}{\partial y} \end{pmatrix}^T \quad (2)$$

Numerically the gradient can be computed with the Sobel filter. Vosselman et. al. (2004) and Hoover et. al. (1996) treat different methods for segmentation in order to recognise structure in elevation models. One of the segmentation algorithms treated is the split-and-merge algorithm. For this work such a segmentation algorithm based on quad trees is used. The algorithm was designed by Gorte (1996) and has the advantage that it allows to segment on multiple bands simultaneously. In this case the x- and y-gradient images are the two bands on which the segmentation algorithm operates. After segmentation, we get a high number of different segments, which should now be classified in one of the classes ‘glacier’ and ‘non-glacier’. Only if a segment is relatively large, the surface can be called smooth. The problem of classifying glacier pixels can therefore be translated to the problem of selecting segments that are greater than a certain predefined area. By applying this classification method, the parts of the terrain that can be considered smooth are selected, resulting in the classification map $\mathbf{C}$.

Tests show that the results using the classification or the segmentation are practically equal. The size of differences observed fall within the grid resolution. In comparison to the variance based classification the segmentation method is computationally much more efficient because calculating the gradients requires less computational effort than fitting the planes through the data. However, when fitting the planes, slope and aspect come as a side product, which may be interesting for other purposes.

Criterion 2 involves the connectivity of pixels classified as glaciers surface. In glaciology a glacier is considered as one large connected mass, mainly consisting of ice. Using connected component labelling, the result from the classification on criterion 1 can be improved by applying the connectivity constraint.

The last criterion that is used to improve the delineation is related to the hydrological properties of glaciers. Given some exceptional circumstances, glaciers generally flow downwards. Consequently, the notion of a catchment area also applies to glaciers. A catchment is the area in which all water, ice or snow flows to the same single outlet. Any pixel classified as glacier should therefore lie within the catchment area of the glacier. This criterion is therefore used to limit the extent of the glacier. Most GIS software contains methods to calculate such a catchment boundary from a DEM.

In the end, the results of the three criterions can be combined to get the final delineation of the glacier. A further improvement of the glacier surface could be obtained by using intensity based segmentation. (Höfle et al., 2007)

4. CREVASSE DETECTION

4.1 Detection using Mathematical Morphology

In order to extract crevasses from a DEM and visualise their locations, we try to create a flat surface with only non-zero values at crevasse locations. The part that has to be removed from the original DEM is the glacier surface as well as the elevation of underlying bedrock. The physical meaning of these elevations would be a glacier in which no crevasses were formed. In order to obtain this surface some techniques from mathematical morphology are used.

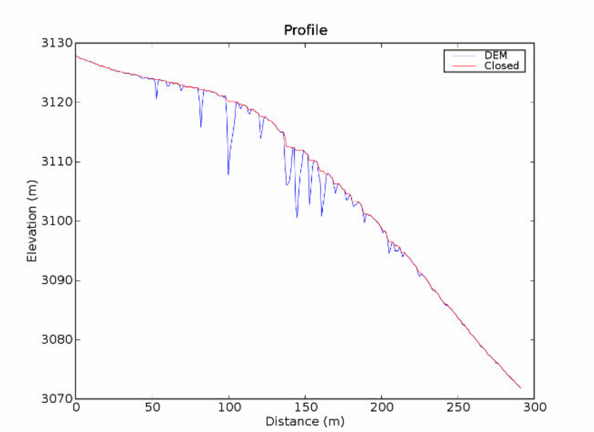

Figure 2. Cross section of a glacier with the result of the closing operation

Mathematical morphology is the theory of the analysis of spatial structures in data sets. It works like a convolution, but uses decision operators instead of multiplication. A morphological filter is used to detect or modify structural elements in the image, i.e. the morphology of the terrain. Provided that the structuring element is larger than the width of the crevasse, the closing filter will close all crevasses, effectively removing them from the glacier surface. Figure 2 shows a profile of the glacier after performing the closing filter. Having generated this surface of a glacier without crevasses, the closed surface is subtracted from the original data, an operation that is known as Black Top Hat. Applied to the DEM, the resulting dataset will be zero over the whole terrain, except for the locations with a crevasse. Given the DEM $\mathbf{H}$, the Black Top Hat operation is now defined as:

$$\mathbf{H}_{\mathbf{crev}} = BTH(\mathbf{H}) = \phi(\mathbf{H}) - \mathbf{H} \tag{3}$$

where $\phi(\mathbf{H})$ represents the closing operation over the DEM. Because the filter closes the crevasses horizontally, the filtered surface is not exactly a surface without crevasses because this will be a sloped surface. This problem was solved by detrending the data first, so that the horizontal closing gives the correct result. This detrending of the DEM, i.e. removing the large scale relief features, can for instance be done by top-hat filtering with a very large window size.

4.2 Setting the structuring element size

After detrending, the crevasse-less glacier surface should be perfectly flat. This means that a flat structuring element can be used, i.e. a structuring element where the shape is defined by the value '1'. The size of the structuring element can be seen as a definition of how long (or how far) the morphology in the structuring element holds. Often, the correct filter size is hard to determine. In this work a novel method is explored to formalise the structuring element size using a variogram of the terrain. A variogram is a measure of the variance between data as a function of distance. The theoretical variogram is defined as:

$$\gamma(d) = \tfrac{1}{2} E\left\{\left[\underline{h}(p+d) - \underline{h}(p)\right]^2\right\} \tag{4}$$

Where p is a point in the DEM, $\underline{h}(p)$ the height of that point and d the distance from that point. Figure 3 gives the theoretical variogram based on the Gaussian model for a selected small part of the glacier surface. For comparison, the scatter- and experimental variograms are displayed as well. The values found after fitting the Gaussian model were a range of R = 369 m and a sill σ^2 = 1.3 m^2.

From the theoretical variogram, measures of variance in the terrain can be related to the size of the structuring element. For instance, field measurements with a Terrestrial Laser Scanner on the Hintereisferner in the summer of 2006 showed that a variance of 0.06 m^2 (0.25 m standard deviation) can be expected within a small area on the glacier. The variogram relates this to a structuring element size of 10 m in diameter.

The shape of the structuring element depends on the anisotropy of the glacier. The amount of anisotropy can be determined by calculating a directional variogram. On a perfect isotropic surface, the variogram will be equal in all directions, yielding a disk shaped structuring element. On anisotropic surfaces, the directional variogram is used to form an ellipse-shaped structuring element. In this study only isotropic structuring elements were applied.