AIRBORNE LASER SCANNING TECHNOLOGY AND ITS POTENTIAL FOR APPLICATIONS IN GLACIOLOGY

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ABSTRACT:

Glaciers are important sources for water supply and valuable indicators for climate change processes. In several countries glaciers have already been monitored for many years by public authorities or research institutions. International services exist with the aim to compile and to make available collected data. Changes in glacier geometry and glacier mass balance are the key issues for glacier monitoring. Traditionally aerial photogrammetry played a key role in supporting glacier fieldwork. In recent years the utilisation of modern remote sensing techniques for glacier monitoring was pushed forward and international projects and initiatives were launched. Airborne Laser Scanning has been established as a standard method for the acquisition of precise and reliable digital elevation data. However, only a few attempts have been made yet to utilise airborne laser scanning in glaciology.

This paper gives an overview on the possibilities and expectations on Laser Scanning Technology for glacier monitoring and the ongoing investigations in the frame of the EC funded OMEGA project. In this project 10 data acquisition flights covering two glaciological years are being carried out at a study glacier in Austria (Hintereisferner) and three data acquisition flights at a study glacier in Norway (Engabreen). Due to the dense coverage with data points accurate high-quality DEMs for the whole area of a glacier can be built effectively in short time. The potential of LS DEMs derived from airborne laser scanning for mapping glacier boundaries and morphological features is shown. A certain focus is laid on the multitemporal analysis of the laser scanner data which enables to quantify changes of glaciers both in area and volume. Future work is outlined, including comparison of the laser scanner data with data from other sources, glacier mass balance estimates, glacier movement studies and glacier surface classification.

1. INTRODUCTION

1.1 Glacier Monitoring

Glaciers presently cover about 10 per cent of the earth´s land surface and store about 75 per cent of the freshwater. In many regions they are important sources for water supply, they provide water for irrigating agricultural land (e.g. Central Asia), are significant sources for energy production (e.g. Norway) or are of importance for the tourism industry (e.g. Austria). In light of the global change discussion, the possible impact of climate change on glaciers and their use as freshwater source has become more important.

In environmental research glaciers are considered to be valuable indicators for climate change processes as they are sensitive to changes in local climate (Oerlemans 1994). Many approaches have been made towards the establishment of a relation between glacier behaviour and climate (e.g. Johannesson et al. 1989, Oerlemans 1994).

Of special interest in glaciology is glacier mass balance as an indication for the stage of the storage system glacier. Ideally, the mass change of a glacier would be monitored continuously. In reality however, this is impossible, since accurate measurements of mass balance are costly and time-consuming.

Consequently, it is common to define dates for mass balance measurements which could best represent the annual glaciological cycle of accumulation and ablation processes. The natural mass balance year is defined as the time between one minimum of glacier mass to the next, which in mid and high altitudes is normally from autumn to autumn next year. This is not determinable exactly for the entire glacier since accumulation may start in the higher parts of a glacier while ablation still takes place in the lower parts. Therefore it is common to establish the glaciological year for mass balance investigations from October 1st to September 30th in mid latitude. A better resolution is obtained when determining seasonal mass balances. These are winter and summer balances which represent the accumulation season and ablation season respectively.

There are different methods to derive values for the net mass balance of a glacier. Traditionally net balance is usually calculated using stakes for the ablation component and snow pits or snow cores for determining the accumulation component (Paterson 1994). For net mass balance estimations over longer time periods (e.g. a decade) the so called geodetic method is used. It means that surface models of an entire glacier for different dates are compared to each other and the relative volume change between the two dates is determined. This has often been accomplished using terrestrial and aerial photography and photogrammetry techniques. To obtain mass change values, the density for the changed volume must be approximated. Over longer time periods the density of ice (0,917 g/cm^3) can be used.

In several countries glaciers have already been monitored for many years by public authorities or research institutions. There are international services with the aim to compile and to make available the collected data, such as the World Glacier Monitoring Service in Zurich, Switzerland (e.g. Haeberli et al. 1998). In

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recent years the utilisation of remote sensing data for glacier monitoring was pushed forward and international projects and initiatives were launched, e.g. GLIMS (Global Land Ice Measurements from Space) which is mainly based on ASTER satellite data (GLIMS 2003). In addition there are smaller scale projects like the OMEGA project (see below).

1.2 Airborne Laser Scanning and Glaciology

Airborne Laser Scanning has established itself as a standard method for the acquisition of precise and reliable digital elevation data. The main application of airborne laser scanning technology is topographic surveying, especially in wooded areas (Ackermann 1999). To date, only a few attempts have been made to utilise airborne laser scanning for glaciological purposes (e.g. Favey et al. 1999, Favey 2001, Kennet and Eiken 1997). Some experience with laser profiling has been gained in Greenland (e.g. Garvin and Williams 1993, Krabill et al. 2000, Thomas et al. 2000) and Alaska (Adalgeirsdottir et al. 1998, Echelmeyer et al. 1996, Sapiano et al. 1998).

Since many glaciers are located in high mountain areas there are special conditions for the applications of airborne laser scanning. The rugged topography with large elevation differences over short distances necessitates expert navigation skills and can cause problems with airborne laser scanning systems with limited range for data acquisition. In addition the complex and sometimes quick changing weather conditions could cause problems for on-sight navigation of the plane and can force interruptions of data acquisition campaigns.

Compared to traditional aerial photogrammetry techniques laser scanning has three main advantages: (I) It may be used independently of surface texture and external light sources; (II) it generally gives denser and more accurate measurements under the given conditions and (III) the establishment and maintainance of ground control points is not necessary, with exception of a GPS reference station in the close vicinity. Therefore, the area of interest for glacier monitoring may be expanded to the entire glacier including the remote firn areas, which are not accessible by photogrammetric means either because of lack of texture or due to the fact that no suitable. ground control points can be located.

In flat and snow covered parts of a glacier, airborne laser altimetry may be able to reach an expected vertical accuracy of 0.2 m, as shown over the Greenland Ice Sheet (Garvin and Williams 1993). In such case, photogrammetry can compete only by increasing the image scale to almost 1:5000. At Unteraarferner it was shown that a determination of the surface elevation change distribution is feasible to an accuracy of 0.5 – 0.7 m as the data acquisition rate and the quality of measurements depends on the slope of the surface and is reduced over crevassed areas (Favey et al. 1999). Kennett and Eiken (1997) stated that the accuracy of surface elevations is affected principally by uncertainties in laser range (ca 7 cm) and GPS position (ca 10 cm).

Baltsavias et al. (2001) present a quantitative and qualitative evaluation of different algorithms for the digital analysis of aerial photographs in glaciated areas along with a comparison between photogrammetry and laser scanning regarding accuracy and point density.

1.3 The OMEGA project and the study sites

The investigations presented are part of the EC-funded OMEGA project, the main objective of which is the development of an Operational Monitoring system for European Glacier Areas. The monitoring system is aimed to offer accurate and up-to-date information. This objective is achieved by

1) evaluating and utilising the full potential of airborne and satellite remote sensing techniques for operational glacier monitoring,
2) designing a monitoring system which can utilise different types of earth observation data and connect them with meteorological and glaciological in-situ data,
3) constructing a regional glaciological database for the OMEGA study glaciers (Pellikka et al. 2001).

One major aspect for the achievement of the objectives is the generation and utilisation of digital elevation models from spaceborne and airborne data. In this context the airborne laser scanning technology provides the link between satellite based remote sensing techniques and the ground truth of in-situ measurements on the glaciers. Besides the provision of calibration data for other techniques (e.g. RADAR measurements) the possibilities and limitations of laser scanning as an independent method for mass balance measurements are investigated and evaluated.

There are two OMEGA study sites in Norway and Austria. Engabreen (38 km^2) is an outlet of the West Svartisen ice cap, situated in a maritime climate close to the Atlantic coast in Nordland, Northern Norway. The altitudinal range is from almost 1600 m a.s.l. to close to sea level. Annual precipitation in the area can exceed 2000 mm. There exist long records of glaciological data from Engabreen, including data of the change in front position since 1903, aerial photo documentation since 1945, continous mass balance measurements since 1970, and more recently bottom topography mapping (e.g. Kjøllmoen 2003). Hintereisferner is a typical valley glacier in the Central Eastern Alps, Tyrol, Austria. The glacier extends from ca 3700 m a.s.l to 2500 m a.s.l. elevation and covers about 8 km^2. Its volume is about 0.5 km3 of ice and its maximum thickness was 250 m in 1996. The Hintereisferner test site contains Hintereisferner itself and adjacent Kesselwandferner. The site has been chosen as it is well investigated since more than 100 years, especially regarding mass balance measurements (e.g. Kuhn et al. 1999).

2. DATA ACQUISITION AND DEM GENERATION

The primary goal for the data acquisition at both study sites is the coverage of a glaciological year which can be divided in a winter accumulation and a summer ablation period. The secondary goal was to achieve a dense as possible coverage of the ablation period in order to get an idea concerning the melting processes. For this purpose 3 flights were planned for Engabreen and 10 flights for Hintereisferner in Austria.

The laser scanner data acquisition within OMEGA is conducted by TopScan GmbH, Steinfurt, Germany, with an Optech ALTM 1225 laser scanner (see Tab 1). Over Hintereisferner 7 out of 10 data acquisition flights have been finished within the glaciological year 2001/2002, three flights are left for the glaciological year 2002/2003. All three data acquisition flights were completed over Engabreen within the glaciological year 2001/2002 (9/2001, 5/2002, 8/2002). During each campaign the entire area of Engabreen was scanned within 2-3 hours. Tab. 2 shows data characteristics of the first data acquisition flight over Engabreen in September 2001.

Measuring Frequency	25.000 Hz
Scanning Angle	+/- 20°
Scanning Frequency	25 Hz
Laser Wavelength	1064 nm
Max. operating altitude above ground	2000 m

Tab. 1. Selected technical parameters of the Optech ALTM 1225 laser scanner

Area	ca 62 km^2
Number of flight paths	28
Swath width	ca 650 m
Average altitude above ground	ca 900 m
Number of data points (X, Y, Z; I)	29.572.046
Density of data points	476.968 points/km^2
Average distance between data points	1.5 m

Tab. 2. Data characteristics of the data acquisition flights at Engabreen from 24/09/01

After the acquisition the raw data were preprocessed by TopScan. The preprocessing comprises the determination of the absolute position of the laser scan system during the flight by analysis of the time-synchronized GPS and INS data, calculation of the relative coordinates, system calibration and finally calculation und delivery of the coordinates in WGS 84 format. A detailed overview on the preprocessing steps is given by Wever and Lindenberger (1999).
In Austria the data of two permanent GPS receiving stations (Krahberg and Patscherkofel) could be used for the differential correction. In Norway GPS reference data had to be collected at a geodetic point (Holandsfjord) besides the data of a permanent receiving station (Bodø). At both sites football fields (In Halsa/Norway and Zwieselstein/Austria) were surveyed and used as calibration areas.

The primary product of data acquisition are coordinates (x, y, z) of single reflections from which the shape of the glaciers surface can be derived. The high density of these points allows for the generation of high resolution DEMs. For the multitemporal analysis GRIDs were interpolated from all data points within each of the data sets using the SCOP++ software. No filtering procedures were applied. From these DEMs in GRID-format standard products such as shaded reliefs or contour lines were derived for visualisation.

3. RESULTS

The project is in progress and the results have a preliminary status in this stage. Checks of data quality and two application examples show the potential of airborne laser scanning technology for glacier monitoring purposes.

3.1 Data Quality

At Engabreen test glacier the DEM derived from airborne laser scanner data is compared with calibration areas and GPS profiles. The comparison with single points of the existing geodetic network is in progress. The quality check procedures at Hintereisferner will start in 2003.

The precision of z-coordinate values of the airborne laser scanner DEM is analysed using the deviations in z-directions from the DEM of the calibration area (football field in Halsa).
The football field was surveyed with a total station before the first data acquisition flight, providing a reference surface for the calibration of the laser scanner data. The calibration area was scanned before and after the data acquisition over the glacier. Tab. 3 shows statistical values of the comparison for the first two data acquisition flights.

	Date	
	24/09/01	28/05/02
Calibration Area	Halsa	Halsa
Number of points	3231	3361
Max ?h [cm]	30,0	35,0
Min ?h [cm]	-31,0	-25,0
Mean ?h [cm]	0,3	0,2
Standard deviation [cm]	8,8	8,3

Tab. 3. Statistical values of the comparison between the data sets (DEM LaserPoints – DEM calibration area) for the specified dates (provided by TopScan GmbH)

The state-of-the-art technology for georeferencing glaciological in-situ data is (differential) GPS. This is the standard with which the position determinations from laser scanner measurements must be compared.
During the laser scanner flight on 28/05/02 GPS reference profiles were measured simultaneously on the glacier surface. 5959 point measurements were recorded along a ca 24 km profile using an Ashtech Z-Surveyor receiver with antennas mounted on a tripod on a snow mobil. For differential correction a second receiver was running at the geodetic control point Holandsfjord. The comparison of the GPS z-values with the z-values of the laser scanner DEM for the corresponding x,y-coordinate shows minimal deviations (2.7 cm +/- 7.5 cm).

3.2 Mapping of glacial and geomorphological features

For first visual interpretation a shaded relief was derived from the laser scanner DEMs with standard GIS software (ESRI Arc GIS). Due to the very small interpolation distance (see Tab. 2) the surface of the glacier is by far better represented than by any other technique yet applied. Even small geomorphological details are represented. Fig. 1 shows some examples from the Hintereisferner test site, like crevasses of different size, boulders on moraine ridges and remnants of dead-ice of an ice-fall event that took place in July 2001.

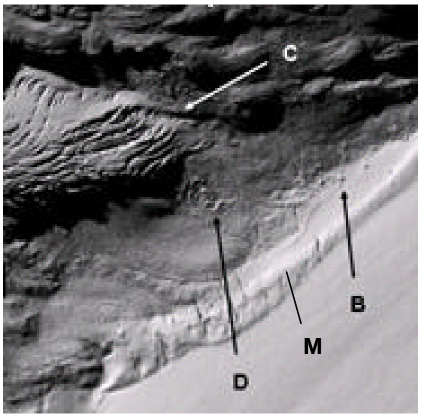


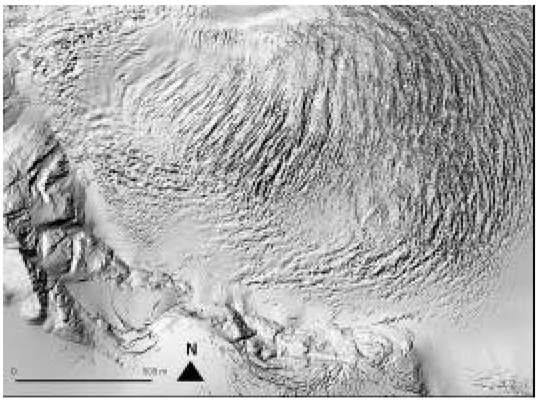
Fig.1. Confluence area of Langtaufererjochferner and Hintereisferner (Tyrol, Austria), data acquisition 10/10/01.
B = boulders C = crevasses D = ice boulders M = medial moraine

This highly accurate surface representation allows systematic mapping of glacier geometry e.g. of the glacier outline which is an important issue in glacier monitoring. In the glacier forefield moraines and other morphological features can be documented and former extents of the glacier can be reconstructed which is an important issue for climate change studies.

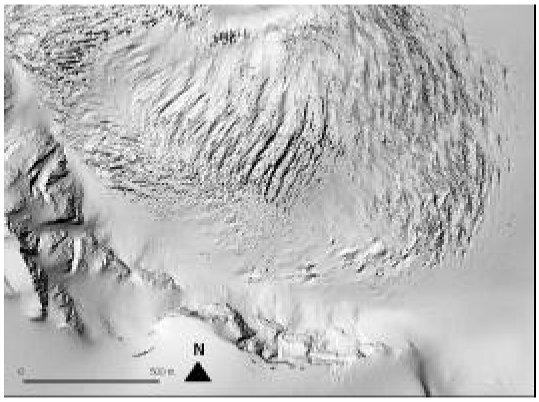
3.3 Multitemporal Analysis – Change Detection

The multitemporal analysis and evaluation of the derived Digital Elevation Models (DEMs) provides a means to detect changes at the glacier surface in terms of elevation. Therefore it can be used for calculating the changes of glacier ice volume in time (?V/?t).

a



b



c

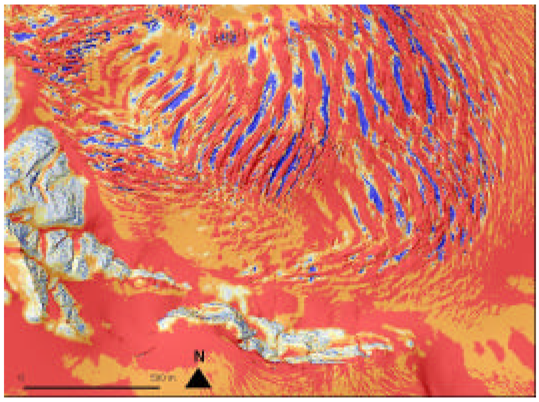


Fig. 2. Detail of Engabreen.
2 a shows the shaded relief of the DEM from the data acquisition flight in September 2001,
2 b shows the shaded relief from the data acquisition flight in May 2002 and
2 c shows a visualisation of the elevation difference between both DEMs ($DEM_{May} – DEM_{Sep}$) with the categories: dark blue > 2m, light blue 2m – 0.2m, white < +/- 0.2m, orange -0.2m – 2m, red < 2m.

In Fig. 2 a part of Engabreen is visualised for the data acquisition flights in September 2001 and May 2002. Again the potential of the data for morphological interpretation is made clearly visible as features such as small crevasses can be identified and mapped.
In the initial multitemporal evaluation, it was made apparent that snow had accumulated at the end of the winter period in May 2002 (Fig. 2 b), covering a substantial part of the crevassed area which was nearly snowfree in September 2001 (Fig. 2 a). The image representing the elevation change (Fig. 2 c) confirms and quantifies this observation. Areas in red and orange indicate higher surface elevations in May, easily explained by winter snow accumulation. Blue colour indicates lower surface elevations in May, most likely caused by crevasses which had opened or moved during winter time. White areas indicate insignificant changes in elevation. These areas correlate closely with the exposed bedrock surface.

4. CONCLUSION AND OUTLOOK

4.1 Conclusion

Knowledge on glacier surface topography and its changes is a fundamental input for many applications in glaciology. In recent years modern remote sensing technologies gain significance in glacier monitoring, one of it is airborne laser scanning. The method provides highly accurate and precise DEMs of glacier surfaces which have due to technical or financial limitations, not been achieved so far. The results presented show the potential of the DEMs for exact mapping of glacier geometry and of even small morphological features. Multitemporal analysis and evaluation of the derived DEMs allow the detection of elevation changes at the glacier surface with a vertical accuracy better than 0.2 m. Hence, airborne laser scanning can be used for calculating changes in glacier volume in time.

Airborne laser scanning starts to compete aerial photography/digital photogrammetry which traditionally has been the most common supporting method in glacier monitoring and in deriving mass balance estimates over longer terms. In comparison airborne laser scanning is independent of surface texture and external light sources. It gives generally much denser and more accurate measurements and the task of establishing and maintaining GCPs can be avoided with the exception of a GPS reference station in the vicinity of the region.

4.2 Outlook

As the data acquisition in the project is almost completed the forthcoming work will have a strong focus on a more comprehensive data analysis, including:

Comparison with remote sensing data from other sources
In the project there has been considerable concentration on the simultaneous acquisition of different remote sensing data types. DEMs derived from different sources are constructed for the study areas in Norway and Austria. Besides airborne data as from laser scanning, aerial photography, digital camera and radar technology, DEMs will also be derived from very high resolution satellite data (IKONOS, EROS) and radar satellite data. DEMs based on terrestrial methods as stereo photography are available as well as the official DEMs provided by the national mapping authorities in different spatial resolutions (Pellikka et al. 2001).

While airborne laser scanner DEMs can deliver calibration data for other methods with a lower density of reference points for the DEM calculation, the quality of the laser scanning data will be validated with DEMs derived from terrestrial photography which are available for limited areas (ca 400 m^2) at both study sites. The acquisition of terrestrial photography could be performed simultaneously with several laser scanner flights. Currently the data are in the processing stage.

There is a high synergy potential in fusing laser scanner data with other modern remote sensing data, e.g. digital camera data which was recorded simultaneously during the data acquisition flight over Engabreen in September 2001. This potential will be evaluated.
In future the combination of high quality laser scanner DEMs and more operational InSAR technology might yield a high potential for glacier monitoring. A simultaneous airborne data acquisition campaign is planned over Engabreen in June 2003.

Glacier mass balance estimates
Measurements of volume changes can be used to validate calculations of net mass balance based on traditional stake methods (Funk et al. 1997). Volume can be transformed into mass using density values of snow (< 0.1 gr/cm^3), firn (about 0.4 gr/cm^3) and ice (about 0.9 gr/cm^3). For both study sites laser scanner data were acquired at the beginning and at the end of the glaciological year 2001/2002 as well as at the turn from the accumulation period to the ablation period, thus enabling estimations that can be compared with mass balance data derived by the direct glaciological method.
At Hintereisferner the analysis of 5 data sets acquired monthly during the summer period (5-9/2002) will give an interesting insight into temporal and spatial variation patterns of mass ablation which can yield valuable input data for existing snow melt models.

Glacier movement studies
With multitemporal tracking of distinguished features on the glacier surface (e.g. crevasses) both horizontal glacier motion and velocity can be reconstructed and compared with existing ice flow models.
At Engabreen glacier surface elevation changes were derived for the accumulation period 2001/2002 from two laser scanner DEMs models (9/2001, 5/2002). The comparison of the elvation change values with systematic snow depth soundings carried out during the data acquisition campaign in May 2002 allows for calculating the vertical component of glacier movement rates between September 2001 and May 2002.
The combination of laser scanner data and radar interferometry data promises valuable additional information.

Glacier surface classification
Optical sensors have been used widely for classifying ice and snow surfaces and there is a comprehensive knowledge of the reflectance properties of ice and snow (e.g. Hall and Martinec 1985). The Optech ALTM 1225 laser scanning system is operating in the near-infrared part of the electromagnetic spectrum (see Tab. 1). Therefore an individual reflectance behaviour on different surface types can be expected. For example it is obvious from evaluation of the point density distribution, that no reflectance and consequently no coordinate measurement is occuring on water bodies and wet surfaces.
All laser scanner data sets contain a value for the recorded laser intensity signals for every coordinate measurement (data format: x,y,z;I). First visualisation results of the signal intensity value show patterns that indicate dependencies on the acquisition geometry (range, scanning angle, footprint size) as well as on material properties at the surface. More comprehensive investigations on this topic are in progress (Lutz in prep.).

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