HIGH QUALITY DEMS FOR GLACIER MONITORING – IMAGE MATCHING VERSUS LASER SCANNING

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ABSTRACT:

Glacier monitoring is of great importance since glaciers are influencing essential areas of life like water supply, energy production, flood protection and tourism. Furthermore, the variation of glaciers is a sensitive indicator for local and global climate change.
One method for the computation of mass balances of glaciers is based on high quality DEMs derived with remote sensing techniques. During the establishment of the new Austrian glacier inventory a new approach for semi-automatic DEM generation from aerial images has been developed in order to reach best quality for the DEM with a minimum of effort for manual verification and editing. Within the OMEGA project (**O**perational **M**onitoring System for **E**uropean **G**lacial **A**reas) the Vernagtferner, a **g**lacier which is monitored permanently has been covered with airborne laser scanning and aerial images. This way it was possible to process both, the aerial images and the laser data and to evaluate both methods with respect to accuracy, economic efficiency and overall suitability. The paper summarizes the advantages and disadvantages of both methods for glacier monitoring.

1. INTRODUCTION

High quality DEM generation is of great importance for glacier monitoring. Aerial Photogrammetry with semi-automatic DEM generation by image matching proved to be a suitable tool for high quality DEM generation (Würländer, Eder, 1998). The Chair for Photogrammetry and Remote Sensing of the Technical University Munich together with the Commission of Glaciology of the Bavarian Academy of Science has been deeply involved in the establishment of a new Austrian glacier inventory from aerial images taken in the years 1997 – 2002. First experiences have shown, that the generation of the required high quality DEM is the most time consuming task. Therefore the procedure has been optimised, introducing a new approach for analysing the accuracy of the matched points by means of a-priori knowledge of the terrain surface. In chapter 2 the new approach for semi-automatic DEM generation from aerial images is introduced. Chapter 3 deals with the experiences of laser scanning in a high mountain area, chapter 4 compares both methods to answer the question "matching or laser scanning"?

2. KNOWLEDGE BASED VERIFICATION OF MATCHED DEM

2.1 Experiences and considerations

In principle, automatic capturing of DEM by image matching should be well suited in glacier regions, as usually no objects like houses or trees are found in this inhospitable areas around glaciers. On the other hand, the geometric and radiometric conditions of high mountain and glacier areas cause a lot of problems for DEM generation by image matching methods and also for manual point measurements at analytical plotters. These conditions are for instance

- very steep and curved terrain surface,
- regions not visible in one or more aerial images,
- extremely rough surfaces like rock or glacier areas with a lot of crevasses and
- low textured areas caused by shadows or snow.

Experiences with automatic DEM capturing in glacier regions (Baltsavias et al., 1996 / Würländer, Eder, 1998) show the negative influence of these conditions and lead to the cognition, that high quality DEMs for glacier regions can only be earned by semi-automatic methods.
For the new Austrian glacier inventory high quality DEM generation has to be done for a total area of about 2.000 km^2. A large part of this work was carried out at the Chair for Photogrammetry and Remote Sensing of the Technical University Munich, capturing glaciers in the Ötztal, Stubai and Zillertal alps with an total working area of about 750 km^2 in the years 1999 to 2003. Based on the experiences mentioned above semi-automatic capturing of DEM from digitised aerial images was found as the most efficient and accurate method for DEM generation.
The available matching software is the product TOPOSURF, integrated in the digital stereo workstation PHODIS-ST (Dörstl, Willkomm, 1994). Verification of the matched points is realized by 3D vector overlay within the stereo model and adapted measurement routines.
Carrying out the first part of the work mentioned above, some difficulties and lacks for efficient verification have been recognized and can be summarised as follows:

a) The correction of points is much more time consuming than a simple point measurement, as correction means different actions like

- identifying the false point,
- picking the point,
- re-measurement of this point and

– confirming the measurement.

b) False points often lay in low textured areas, where measurement within the original photographs on analytical plotters is much better than measurement within the digitised images with a digital resolution of 8 bit.

c) Verification and measurement in steep areas, especially near ridges, is rather complicated as it is difficult to find out the correct stereo match of the regular distributed points that are often incorrect in this areas.

Recognizing these problems in stereo verification of matched points, considerations have been made to improve the accuracy and the efficiency of the semi-automatic matching procedure. As shown in figure 1, an additional analysing tool was established, using a priori knowledge of the terrain and additional information about the matched points.

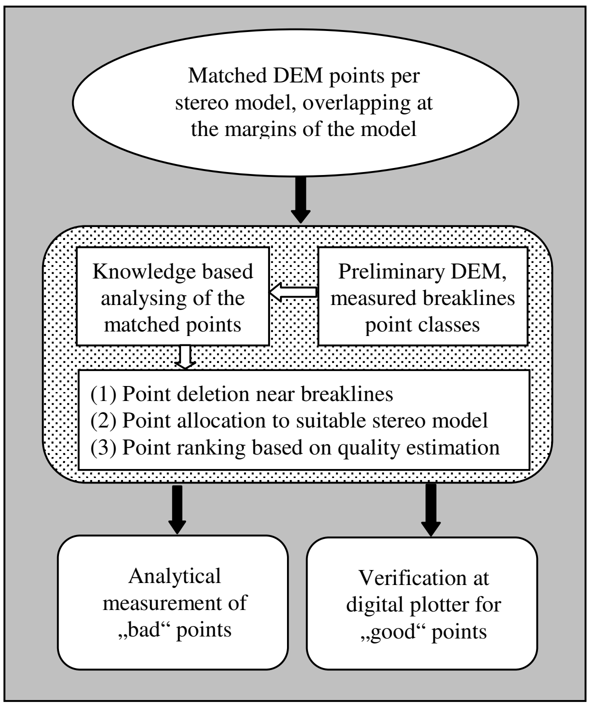

Figure 1: Semi-automatic matching strategy for high mountain DEM

The results of this tool are point to model allocation for points in areas of model overlap and a quality ranking and sorting of the matched points for further verification. The strategy and results are explained in the following chapters.

2.2 Allocation of terrain points to suitable stereo models

First of all matched points near measured breaklines are deleted, as verification of these points is often complicated like mentioned above and not necessary for terrain description.

For DEM generation of extensive regions a lot of aerial images with partly overlapping model areas are processed. Usually the central regions of the models are selected or the DEM of overlapping regions are merged together with interpolation methods.

But, in high mountain areas the orientation of the terrain to the camera positions often is very different from image to image, leading to effects like very small angles between projection ray and terrain surface or hidden terrain regions. These effects, caused by steep terrain features, occur mainly at the border of the images and therefore also at the border of the stereo models. Height measurement is often difficult or impossible in such regions.

As the border regions usually are in addition covered by the neighbouring stereo model with different insight to the terrain, choosing the most suitable stereo model for point measurement can significantly improve the overall accuracy of DEM points. Therefore the preliminary DEM and orientation parameters of the images are used to calculate the angle between the surface normal vector of the terrain and the projection rays to the aerial images for each point of the matched DEMs in the areas of overlap. Thus each DEM point can be allocated to the most suitable model (see figure 2).

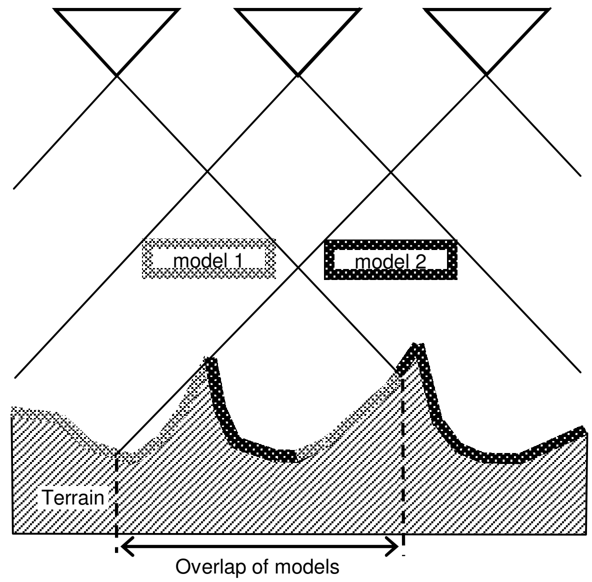

Figure 2: Allocation of terrain points to suitable models in mountainous terrain

2.3 Ranking of matched points based on quality estimation

The third step of knowledge based point analysing tries to estimate the quality of the matched DEM points. Useful information for that task can be derived from the preliminary DEM and the quality assessment of the matching procedure, and in the special case of glacier measurement also the area covered by glaciers. Initially all points are ranked in the medium quality class 3. Better ranking up to class 2 or 1 and worse ranking down to class 4 or 5 depends on

– quality assessment provided by the matching software,
– height difference between the matched point and the corresponding height in the preliminary DEM and
– the angle between the surface normal vectors of matched DEM and preliminary DEM

Height differences in glacier areas are mainly caused by natural changes. Therefore the additional information about glacier areas can be used to adapt the ranking strategy.

The parameters for point ranking have been optimised testing the results of the different classes of point quality at the digital stereo workstation to minimize miss-classification and effort for verification.

An example of the ranking strategy is given in table 1 for the height difference between matched points and preliminary

DEM. The theoretical height accuracy σ_Z is derived from height above ground.

Height difference to preliminary DEM	Ranking of points outside glacier	Ranking of points on glacier area
$< 0.5*\sigma_Z$	2 classes up	1 class up
$0.5*\sigma_Z$ to $1.0*\sigma_Z$	1 class up	Same class
$1.0*\sigma_Z$ to $3.0*\sigma_Z$	Same class	Same class
$3.0*\sigma_Z$ to $10.0*\sigma_Z$	1 class down	Same class
$> 10.0*\sigma_Z$	2 classes down	1 class down

Table 1. Example of point ranking

2.4 Verification and valuation of results

After ranking based on quality estimation the matched DEM points are sorted in different files depending on the estimated quality class. Thus the "bad" points (usually classes 4 and 5) quickly can be re-measured at an analytical plotter, while "good" points (usually classes 1 to 3) can be checked at digital stereo workstations. Time consuming correction of points at the digital stereo workstation is reduced significantly.

Miss-classifying of points mainly depends on the quality of the preliminary DEM. As DEM capturing in glacier areas often means multi-temporal measurement, high quality preliminary DEM is available in many cases.

Typical miss-classified points are points at the glacier tongue, often classified as "bad" points caused by really existing terrain changes (height and orientation). On the other hand these areas are very important for glaciology and therefore best verification of these points is of high interest.

In total the presented semi-automatic matching strategy including the tool of knowledge based point analysing is about five times faster than traditional analytical point measurement and about two times faster than conventional point verification at digital stereo workstations.

The geometric aspects used for searching of best suited stereo models could be used further on for efficient point capturing in image blocks with large overlaps (up to 80%) as usually available when capturing images from low altitude in mountainous areas. Building additional stereo models with the images after next, the height accuracy can be improved for valley regions. The allocation of the DEM points to the best suited stereo models then could be automated by the presented software tool. This tool could also be expanded to select best suited images for ortho mosaics.

3. LASER SCANNING IN GLACIER AREAS

During the last decade airborne laser scanning has made a decisive technical improvement and has become a standard and well-accepted method for the acquisition of topographic data for many applications. First investigations in high mountain areas have shown good results (e.g. Favey, 2001). Also accuracy evaluations in comparison with aerial image matching have been made (Baltsavias et.al. 2001).

The results presented in this paper are based on data captured for the EU-funded OMEGA project. Its main objective is the development of an **O**perational **M**onitoring system for **E**uropean **G**lacier **A**reas, aiming to offer accurate and up-to-date information based mainly on remote sensing technology (Pellikka et al. 2001).

One major aspect for the achievement of the objective is the generation and utilisation of digital elevation models from spaceborne and airborne data. In OMEGA digital elevation models of following sources are constructed: VHR satellite data (IKONOS, EROS), aerial photography (analogue and digital), terrestrial photography, airborne SAR, airborne laser scanning.

The method of DEM capturing by airborne laser scanning is expected to reach high accuracy for mountainous applications and will be therefore introduced and investigated in detail.

3.1 The principle of airborne laser scanning

Airborne laser scanning integrates a Global Positioning System (GPS) receiver for determining the position of the sensor, an Inertial Navigation System (INS) for determining the attitude of the sensor and the scanning system using laser technology. All components are time–synchronized. Different technical solutions for the laser scanning system exist. With the laser scanning system used in this study (Optech Airborne Laser Terrain Mapper - ALTM 1225) the laser beam is swept perpendicular to the ground track, thus producing an even distribution of data points. The density and distribution of the data points depend on the scan angle, the scan frequency, the height above ground, the aircraft speed, the swath overlap and the reflectance characteristics of scanned surface. A comprehensive overview on laser scanning technology is given by Ackermann (1999). The high accuracy and dense coverage (more than 500.000 points per km^2 are possible) give the possibility of generating high-quality DEMs.

3.2 Data acquisition and pre-processing

In OMEGA the possibilities and limitations of airborne laser scanning as an independent method for glaciological applications are investigated and evaluated (Geist et al. 2003). For this purpose 10 data acquisition flights were organised by the Institute for Geography, University of Innsbruck and carried out between 10/2001 and 9/2003 over glacier areas in the Rofen valley, Ötztal Alps, Austria.

The laser scanner data acquisition was conducted by TopScan GmbH, Rheine, Germany, with an Optech ALTM 1225 laser scanner (see table 2).

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

Table 2. Parameters of the Optech ALTM 1225 laser scanner

After the acquisition the raw data were pre-processed by TopScan. The pre-processing 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 and delivery of the coordinates in WGS 84 format. The primary product of data acquisition are coordinates (x, y, z) of single reflections. A detailed overview on the pre-processing steps is given by Wever and Lindenberger (1999).

Data of two permanent GPS receiving stations (Krahberg and Patscherkofel) were used for the differential correction. The football field in Zwieselstein (Ötztal/Austria) was surveyed and used as calibration area.

3.3 Investigation of the Vernagtferner data set

In August 2002 the Vernagtferner, one of the glaciers included in the OMEGA project and monitored permanently by the Commission of Glaciology of the Bavarian Academy of Science, was covered by laser scanning. The final data set was delivered several months after the flight date due to geo-referencing problems.

The laser points have been transformed from UTM (WGS84) into the Austrian Gauss-Krüger system, since the existing control points and photogrammetric data are available in this system. For accuracy assessments eight test areas have been determined with different material properties (ice, snow, rock, debris) and terrain inclination. Within these test areas check points have been measured with differential GPS. The results are given in table 3.

Test area	Number of check points	RMS error offset corrected [m]	Offset [m]
Rock 1	70	± 0.23	+0.12
Snow	59	± 0.08	+0.03
Debris	171	± 0.14	-0.13
Ice	510	± 0.29	-0.21
Profile (ice)	40	± 0.11	-0.19
Moraine	78	± 0.16	+0.80
Rock 2	37	± 0.25	+0.54
Rock blocks	128	± 0.26	+0.78

Table 3. Results of the accuracy check by GPS check points

As common in high mountain surveying, triangulation points are signalised by stone pyramids and usually are used as ground control points in photogrammetry. It was possible to locate some of these points within the laser data. The positions of the top point of the pyramid formed by the laser data mainly correspond properly to the position of the bench mark given by ground coordinates. For checking the height value, the difference to the "nearest neighbour" of the surrounding laser points was computed at 7 bench marks. Table 4 shows that the heights of the laser points obviously are lower than the benchmark heights because the corresponding laser points normally don't match the top of the pyramid. Therefore instead of stone pyramids other kind of control information like geometrically plane objects (e.g. roofs) should be used (see also Kraus, Pfeifer, 1998). However, such objects hardly can be found in high mountain areas.

Bench mark	Height difference (m)
STM 1	-0.70
STM 2	-0.74
STM 3	-0.71
STM 4	-0.75
STM 6	-0.40
Gabel (Hut)	-0.70
STM 7	-0.76

Table 4. Height differences at bench marks (stone pyramids)

A further indication on the quality of laser data is given by checking the consistency of overlapping strips. For this reason a small test area within overlapping strips was investigated. After generating a 1m DEM contours with an interval of 0.5 m were derived. In figure 3 the contours are superimposed with the laser data from adjacent strips. It is obvious that the waves are caused by the height differences of the adjacent strips. The height difference can be estimated by graphical interpretation to about 0.5 m.

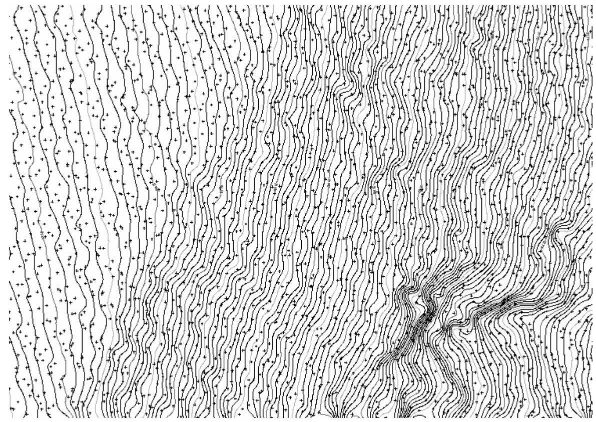

Figure 3. Contours showing "wave effect"

4. COMPARISON OF IMAGE MATCHING AND LASER SCANNING

Within the OMEGA project an image flight over the Vernagtferner glacier has been carried out in August 2003. The colour images with a mean image scale of 1: 16.000, taken by a standard RMK TOP camera (focal length 154 mm) have been used for semi-automatic DEM generation (s. Chapter 2). The exterior orientation was reconstructed using some of the bench marks, also used for checking the laser data in order to ensure for consistent geo-referencing. This way the laser DEM and the DEM from aerial images can be compared, taking into account, that there is a time difference of one year.

4.1 Test area glacier tongue

A test area was defined, including the glacier tongue and the forefront of the glacier. The captured laser data show considerably varying point density. Sparse reflectance can be recognized especially on the wet ice surface and on the streams (see figure 4 and 5). A 2.5 m spaced DEM was generated both from the laser data and the aerial images. The shaded relief models (Figure 6 and 7) show more details in the laser DEM than in the DEM from image matching.

For a detailed inspection height differences at the DEM grid points have been calculated and colour coded (Figure 8). It is obvious that there was a considerable height decrease at the glacier tongue (up to 5 m) and at the upper right part of the test area caused by melting debris covered ice. For accuracy consideration only the non ice covered area can be investigated. The colour coded height differences in this area show a constant shift of about 0.5 m.

Calculated offsets between matched DEM, laser DEM and GPS check points are presented in table 5. Offsets may be caused either by an error of the exterior orientation of the aerial images or by a systematic error of the laser points. It seems that laser scanning is the more accurate method. Exact statements, however, needs to evaluate the local behaviour of the different height systems, i.e. geometrical heights for GPS measurements and orthometric heights for photogrammetric ground control. The difference between the height systems, called geoid undulation, can vary significantly in high mountain areas.

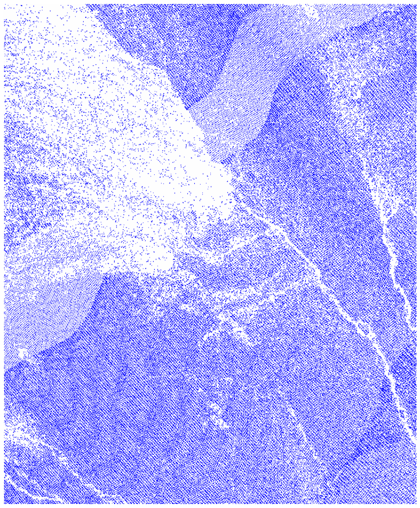

Figure 4. Captured laser data for test area

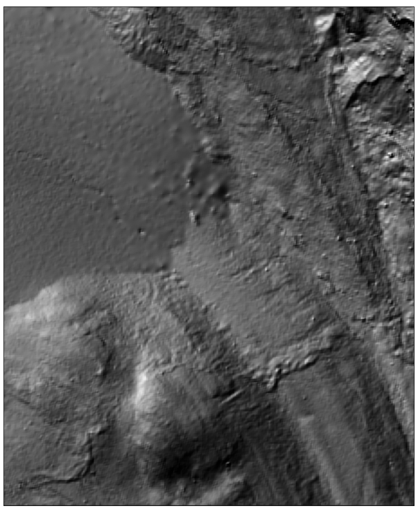

Figure 6. Shaded relief model based on laser data

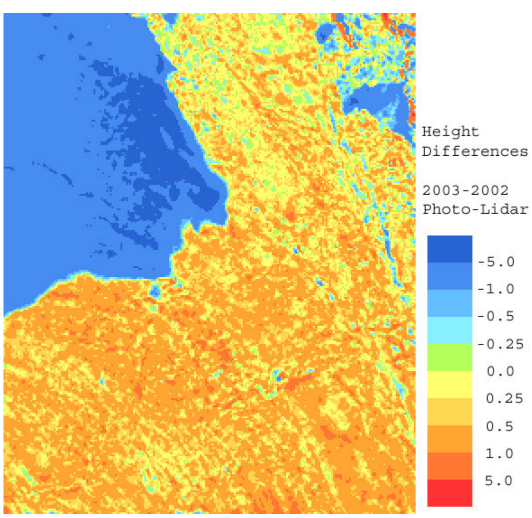

Figure 8. Colour coded height differences

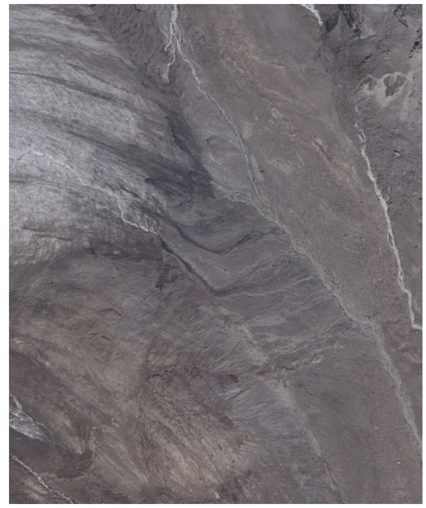

Figure 5. Ortho image of test area

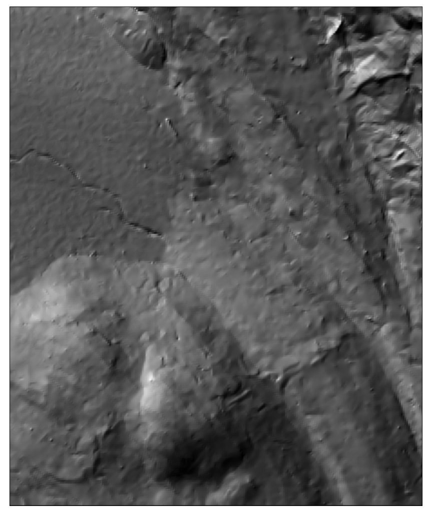

Figure 7. Shaded relief model based on image matching

Difference	Offset [m]	$\sigma_{(Offset)}$ [m]
Laser - Matching	- 0,44	± 0,31
Laser – GPS-control	- 0,13	± 0,14
Matching - GPS-control	+ 0,31	/

Table 5. Evaluation of height differences in none ice covered area

4.2 Assessment of both methods for glacier monitoring

A general and comprehensive comparison between photogrammetry and laser scanning is already given by Baltsavias (1999). In the meantime laser scanning technology has improved and the presented investigation is focussed on high quality DEM for glacier monitoring. There are some particularities which have to be considered in alpine regions:

Weather conditions:
In glacier areas we are faced to difficult weather conditions. Cloud coverage and wind conditions are changing rapidly. Furthermore the glacier should be imaged when a special

phenomena is reached (e.g. maximum extent of ablation). For image flights only a few days per year are available. Laser scanning with its active sensor can be used also if the light conditions are to poor for an image flight.

Problem strip overlap:

To cover the Vernagtferner glacier two image strips had to be flown, while in laser scanning 11 strips were necessary. This means, that the operating time for the data acquisition is considerably higher for laser scanning than for an image flight. In Photogrammetry with automatic aerial triangulation and bundle block adjustment a well known and operational technology for the adjustment of image blocks is given. In laser scanning the adjustment of adjacent strips is not yet solved and is object of various research projects.

Geo-referencing:

Image orientation in Photogrammetry can be done either by control points or direct geo-referencing by GPS/INS. A combination of both strategies leads to the most accurate and reliable results.

In laser scanning the exact measurement of the flight trajectory and the inclinations of the system is essential and the accuracy of the dataset is depending mainly on this issue. In alpine regions the availability of permanent GPS reference stations and the knowledge about the geoid undulation often is limited.

Accuracy:

The accuracy investigations based on terrestrial check points have shown, that laser scanning reaches an absolute accuracy of 0.1-0.2 m in snow and ice covered areas, while a constant offset up to 0.8 m was detected in test areas located on a rather steep moraine and in rock blocks. As the offset corrected RMS-value ranges between 0.1 and 0.3 m, the large offsets are clearly caused by systematic errors. This is confirmed also by the detected differences between adjacent laser strips up to 0.5m. In photogrammetry the accuracy potential of the laser data can only be reached using image flights with altitudes above terrain of about 1.000 to 2.000 meters.

5. CONCLUSION AND OUTLOOK

With semi-automatic DEM capturing based on aerial images a very operational and accurate method for glacier monitoring exists. Efficiency and accuracy can be significantly improved by additional considerations like knowledge based point analysing, adapted flight planning and digital sensors. Besides surface modelling the images contain a lot of radiometric information (colour, texture) for context derivation. In snow and firn areas, however, image textures are often not sufficient.

Airborne laser scanning provides a method which reaches high point density independently from the terrain texture. Therefore it offers new possibilities for glaciological research in areas covered by snow and firn, which is essential for data capturing in the accumulation period.

Accuracy potential of airborne laser scanning can be in the range of 0.1 - 0.3 m, but systematic errors of about 0.5 - 1 m have been detected in the practical results. Further investigations in direct geo-referencing of the laser data promise a noticeable reduction of these systematic errors.

Combined application of digital photogrammetry and airborne laser scanning, based on a homogenous system of GPS-reference and control points, is suggested as the best suited method for high accurate glacier monitoring.

6. AKNOWLEDGEMENT

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REFERENCES

Ackermann, F., 1999. Airborne laserscanning – present status and future expectations. *ISPRS Journal of Photogrammetry & Remote Sensing*. 54, pp. 64-67.

Batsavias, E., 1999. A comparison between photogrammetry and lasers scanning. *ISPRS Journal of Photogrammetry & Remote Sensing*. 54, pp 83-94.

Baltsavias, E., Favey, E., Bauder, A., Bösch, H., Pateraki, M., 2001. Digital surface modelling by Airborne laser scanning and digital photogrammetry for glacier monitoring. *Photogrammetric Record*, 17(98), pp. 243-273.

Baltsavias, E., Li, H., Stefanidis, A., Sinning, M., 1996. Comparison of Two Photogrammetric Systems with Emphasis on DTM Generation: Case Study Glacier Measurement. *IAPRS*, Vol. 31, Part B4, pp. 104-109.

Dörstl, Ch., Willkomm, Ph., 1994. PHODIS ST Digital Steroplotter: Automating Photogrammetric Operations and Workstation Design. *IAPRS,* Vol. 30, Part 3/1, pp. 188-193.

Favey, E., 2001. Investigation and improvement of airborne laser scanning technique for monitoring surface elevation changes of glaciers. Institut für Geodäsie und Photogrammetrie an der ETH Zürich. Mitteilungen Nr. 72.

Geist, Th., Lutz, E., Stötter, J., 2003. Airborne laserscanning technology and its potential for applications in glaciology. ISPRS Workshop on 3-D reconstruction from airborne laserscanner and INSAR data, Dresden, Germany. Proceedings, pp.101-106.

Kraus, K., Pfeifer, N., 1998. Determination of terrain models in wooded areas with airborne laser scanner data. *ISPRS Journal of Photogrammetry & Remote Sensing*. 53, pp. 193-203.

Pellikka, P., K. Kajuutti, R. Koskinen, M. Jackson, J. Stötter, H. Haggren, K.-M. Luukkonen, T. Guneriussen, A. Sharov, 2001. Development of an operational monitoring system for glaciers – synthesis of earth observation data of the past, present and future. Proceedings of International Workshop on Geo-Spatial Knowledge Processing on Natural Resource Management, pp. 283-288. Varese.

Wever, Ch., Lindenberger, J., 1999. Laserscanning – a mapping method gains ground. Photogrammetric Week 99, pp. 125-132.

Würländer R., Eder K., 1998. Leistungsfähigkeit aktueller photogrammetrischer Auswertemethoden zum Aufbau eines digitalen Gletscherkatasters, *Zeitschrift für Gletscherkunde und Glazialgeologie*, 34, pp. 167-185.