Nordic Journal of Surveying and Real Estate Research 4:2 (2007) 24–39
submitted on 15 June, 2005
revised on 24 May, 2007
accepted on 8 August, 2007

Terrestrial Photography for Verification of Airborne Laser Scanner Data on Hintereisferner in Austria

Kari Kajuutti[1], Olli Jokinen[2], Thomas Geist[3] and Tuija Pitkänen[2]
[1] University of Turku, Department of Geography
FI-20014 University of Turku, Finland
kari.kajuutti@utu.fi
[2] Helsinki University of Technology,
Institute of Photogrammetry and Remote Sensing
FI-02015 TKK, Finland
olli.jokinen@tkk.fi
[3] alpS – Centre for Natural Hazard Management
Grabenweg 3, AU-6020 Innsbruck, Austria
geist@alps-gmbh.com

Abstract. *Digital elevation models derived from very different data sources – airborne laser scanning and terrestrial photography - have been produced from a test area on Hintereisferner glacier in Austria. The laser scanning system gave on the average one data point per square meter. Close range panoramic images were used for detailed surface modeling of a limited area reaching a spatial resolution of 25 cm × 25 cm and high precision in elevation. The data acquisition was synchronized and the data sets transformed to the same coordinate system for comparison. Terrestrial photography was proved useful to verify the precision of elevations in airborne laser scanner data and to visualize the reflection points of the laser beam, but it also addressed the need of careful and exact georeferencing. A precision better than 16–19 cm in elevation was verified for the laser scanner data after correcting differences in georeferencing by surface matching.*

Keywords. *Airborne laser scanning, terrestrial photography, precision verification, DEM, surface matching, glacier.*

1 Introduction

Airborne laser scanning is a method for deriving topographical information with high resolution and high accuracy. During the last decade, this technology has made a decisive step towards an operational method for a steadily growing variety of applications and for country-wide data acquisition. To date, airborne laser scanning has been repeatedly applied for glaciological investigations on the ice sheets of Greenland and Antarctica (e.g. Abdalati et al 2002, Csatho et al 2005, Krabill et al 2002) but only a few attempts have been made to utilise airborne laser scanning on mountain glaciers. During the OMEGA project (see Pellikka and Kajuutti 2005), there was a chance to apply airborne laser scanning to test glaciers in Norway and Austria in order to explore the potential and limitations of this technology for different applications in glaciology (Geist et al 2003). Ten data acquisition campaigns were carried out at the Austrian test site Hintereisferner between Oct. 2001 and Sept. 2003. A certain focus was laid on the multi-temporal change of glacier geometry. It was shown that digital elevation models (DEM) derived from airborne laser scanner data are accurate enough to be of significant value for different tasks in glaciology (Geist and Stötter in print). Probably the main advantage (e.g. compared with optical methods) is the ability to get reliable information for the entire glacier surface, even for snow and firn covered areas.

The elevation accuracy of laser scanner point measurements depends primarily on the error budgets of the system components which is discussed in detail in Baltsavias (1999). Generally a rough estimate for the vertical accuracy of points measured by airborne laser scanning is ±15 cm. Recent studies on glaciers in Svalbard show that ALS data are capable to calculate DEMs with a vertical accuracy of 0.05–0.10 m (Arnold et al 2006). Similar results find Geist et al (2005) for Engabreen (Norway). The accuracy of DEMs generally increases with decreasing terrain slope and increasing point measurement density (Kraus and Pfeifer 1998).

In earlier studies like Kennett and Eiken (1997) the elevation accuracy of the laser scanner data was estimated to be close to one meter. They compared Optech ALTM laser scanner data with ground profiles acquired half a year earlier with a kinematic GPS on Hardangerjokulen in Norway. The average change in elevation between the data acquisitions is consistent with changes in snow depth estimated from mass balance sounding and stake observations recorded one and a half months after GPS profiles and 12 days before laser scanning. An experiment with ScaLars II laser scanner was carried out on Unteraargletcher in Bernese Alps obtaining an elevation accuracy of 70–80 cm. Shadows from steep cliffs and debris covered areas proved too dark for sufficient reflectance affecting the measurement accuracy. Furthermore there were orientation differences between the laser scanner data and a reference DEM measured manually from aerial photographs. (Baltsavias et al 2001). Forsberg et al (2002) reported a RMS (root mean square) error of 63 cm at the cross-overs of laser strips on Geikie ice cap in Greenland. The sampling interval was relatively large and good INS (inertial navigation system) data were not available during the flight which lowered the achieved accuracy. Preliminary results from Hopkinson et al (2001) showed the elevations to be within 20 cm at adjacent points of overlapping swaths for all elevations acquired with an Optech ALTM 1225 laser scanner on the alpine Peyto glacier of the Wapta Icefields in the Canadian Rockies.

On glaciers, an elevation accuracy of 10 cm is achievable with a kinematic GPS in differential mode (Jacobsen and Theakstone 1997). GPS surveys can be performed over relatively large areas and repeated acquisitions along the same profiles are possible with a real-time kinematic GPS. However, the distance between adjacent GPS profiles is usually large when compared to the point density of laser scanner data. On the contrary, within a small test area terrestrial photographs could be adequate for the digitization of all the details in surface topography whenever there is enough texture for correspondence matching. Terrestrial photographs could also give visual information from where the laser beams have reflected instead of providing only the coordinates which is the case in GPS measurements. Terrestrial photography has been used in glacier studies for more than a century. Modern cameras and development in image processing have made it possible to produce very precise DEMs from terrestrial photographs. The precision of object coordinates in the direction parallel to the image plane depends mainly on the precision of image measurements and the scale of the photographs while the precision of the object coordinate in the viewing direction depends also on the base-distance ratio. Uncertainties in the control points used for solving the relative orientation of the images reduce the accuracy of 3-D points reconstructed. However, the control points can usually be measured more precisely than the actual surface points and therefore the uncertainties in the actual image measurements are more significant (Pöntinen 1994). The accuracy can also be affected by incorrect camera calibration parameters. In this study, we apply a regular digitization pattern in the ground coordinates and measure the elevations from convergent panoramic images viewing the scene from the side so that the measured object coordinate is roughly parallel to the image plane. Using a calibrated Olympus Camedia C-1400L digital camera having a focal length of 9.2–28 mm, we expect to achieve a precision of a few centimetres in elevation when the measuring distance is 5–15 m and the precision of image measurements is one pixel. The elevation figures may vary within the scene coverage just because of the texture and position of the pixel in the image. Panoramic imagery was selected because it has the advantages of a wide-angle image such as a possibility to get close to an object and to decrease the number of control points (Haggrén et al 2001).

In this paper, we show that terrestrial photography can be used for verifying the precision of elevations in airborne laser scanner data and to visualize where the laser beams have reflected from on mountain glaciers where other ground truth data do not exist or are difficult to acquire. As a typical alpine valley glacier Hintereisferner (6.3 km^2) in Tyrol, Austria was chosen as a test glacier and a small area from the ablation area of the glacier was selected as a test field for the verification. The properties of the glacier surface in the test area are discussed and the data acquisitions and production of terrestrial photography (TP) DEMs are described in Section 2. The verification results after registering the data sets accurately by a surface matching algorithm are presented in Section 3. Conclusions and ideas for future research are addressed in Section 4.

2 Materials and methods

2.1 Glacier surface in the test area

The area to verify elevations in the laser scanner data was selected on the basis of the requirements of the terrestrial photography. There were not many suitable places available for close-range photography because of the unstable moraines on the glacier sides. In order to keep the camera stable, it would be best to have the camera stand on the bedrock. Furthermore the georeferencing would be easier in the case the DEM will include areas which are not moving. The area (Figure 1) chosen from the left side of the ablation area of Hintereisferner (looking downstream) was not an optimal place but, anyhow, it turned out a decent target for DEM production. Because of the loose gravel, the camera was placed on a flat area on the glacier surface. The terrestrial photography area consisted of a sediment covered ice ridge with some bare ice also visible. The particle size of the sediment layer varied from less than a cm up to some stones with diameter of about 20 cm. Most likely there had been an old melt water channel, but the stream had changed its route closer to the glacier margin and an oblong dirt cone like hillock developed in place of the old channel. (cf Drewry 1972). On Hintereisferner, there are lots of debris on the glacier surface close to the glacier sides and snout. This is also the case in the terrestrial photography area.

Figure 1*. The glacier surface at the terrestrial photography test area. Hintereisferner Aug 12, 2003.*

Resolution is one of the key words what comes to glacier remote sensing meaning spatial, temporal as well as spectral resolution. The type of the glacier surface has a major influence on the spectral reflection changing from the almost 100% of fresh snow down to even 10% of dirty ice (Gao and Liu 2001). Climatic environment and quickly changing weather conditions affect the shape and structure of an ice surface. However, the ice is not necessarily clean. In the case of valley glaciers like Hintereisferner, rock debris has fallen onto the glacier from the surrounding ridges. The thickness and distribution of this supraglacial debris has a major influence on the structure of the ice surface. (Benn and Evans 1998, Benn et al 2003, Kirkbride 1995). The surface consists only rarely just of flat ice but is merely full of features of different shapes and sizes. In the area of this study, the most acting processes are melt water and glacier movement together with the valley slope and its variabilities. Melt water erodes channels on the ice surface and in places of open crevasses the channels disappear into the englacial channel system. Crevasses are a typical consequence of the slope changes at the glacier bottom. Melting and refreezing of ice are common phenomena during the summer causing numerous amounts of small surface features that form and reform throughout the melting season. These features can be very unstable making them rechange or disappear in a moment. The melting is strongly affected by the amount of the supraglacial debris because the debris absorbs more sunlight than clean ice. This means that a thin debris layer or small particles will increase melting in the area. On the contrary, a more than 1−3 cm thick layer as well as stones larger than about 20 cm will start insulating the ice and reduce melting (Kajuutti 1989, Liestøl 1989, Nakawo and Rana 1999, Østrem 1959). On Hintereisferner different kinds of debris covered ice ridges and cones are common features close to the glacier margins (Kajuutti and Pitkänen, submitted).

2.2 Synchronization of data acquisition

The data acquisition for this study consisted of two parts: airborne laser scanning and terrestrial photography performed on the glacier surface. In order to make the data comparison reliable, it was very important to be able to make the data acquisitions at the same time. The rapidly changing weather conditions and the availability of a suitable aeroplane at the time terrestrial photographers were in the study area made the simultaneous requirement a logistic challenge. During the first attempts a study period was chosen well in advance and the terrestrial photography team was in the study area waiting the aeroplane to arrive. It turned out, however, that the weather is too incalculable and would require a disproportionately long field campaign at that time of the year. The more successful solution was to wait for a period of most likely good weather and negotiate a flight possibility for one of those days. The field crew was then sent to the glacier. This required that the persons involved in the field work were able to stay on stand by even for weeks. Finally, the data acquisition was achieved almost simultaneously on successive days September 18 and 19, 2002, and simultaneously on the same day August 12, 2003.

In September 2002, the terrestrial images were taken about 20 hours after the laser scanning. The gap was because originally two terrestrial photography areas were selected and it was possible to photograph only one at a time. It appeared afterwards that the geometry was much better in the images photographed later and therefore this site was chosen for the DEM production (Kajuutti and Pitkänen, a manuscript submitted). However, the time difference is considered to be of minor importance, because melting for the given weather conditions can be estimated to be no more than 5 cm/d and the ice movement in the terrestrial photography area no more than 10 cm/d.

Table 1. *Flight and system parameters for the airborne laser scanner data acquisition campaigns.*

Laser scanning system	**ALTM 3033**	**ALTM 2050**
Average height above ground during data acquisition	900 m	1,150 m
Measuring frequency	33,000 Hz	50,000 Hz
Scan frequency	29 Hz	30 Hz
Scan angle	±20 deg	±20 deg
Average point distance achieved	1.0 m	0.8 m
Data acquisition campaigns	18.9.2002	12.8.2003

Table 2*. Comparison of elevation of laser scanning points with a reference surface derived from a geodetic survey of the control area "Zwieselstein soccer field" (laser points – DEM control area).*

Date	**Laser points on control area**	**max ΔZ [cm]**	**min ΔZ [cm]**	**Mean ΔZ [cm]**	**Std ΔZ [cm]**	**Laser points with |ΔZ| ≤30 cm**
18.9.2002	909	32.0	–32.0	–3.0	9.8	99.7%
12.8.2003	8,836	50.0	–42.0	–0.3	9.5	99.9%

2.3 DEM production

The laser scanning flights were performed by TopScan GmbH, Germany, with different Optech ALTM laser scanning systems in September 2002 and August 2003 (see Table 1 for the main flight and system parameters). The primary results of the data acquisitions were three-dimensional (x, y, z) point coordinates. The georeferencing of the points was performed via a GPS receiver on board and differential correction with GPS data from two reference stations located at Patscherkofel and Krahberg. The vertical accuracy of the laser measurements was checked at a control area surveyed with a tacheometer (a football field in Zwieselstein – results see Table 2). Raster DEMs with cell sizes of 1 m and 5 m were calculated from the point data using the SCOP++ software with the implemented linear prediction algorithm (Pfeifer et al 2001). Figure 2 shows a hillshade visualisation of the 1 m DEM.

The terrestrial photography DEMs were reconstructed from stereo pairs of panoramic images (Figure 3) having a single record of 1,280 × 1,024 pixels. A cross slide was placed between the camera and a tripod in order to keep the images concentric while rotating the camera. Panoramic sequences consisted of three images with an overlap of approximately 30%. The images were combined using a two dimensional projective transformation with an algorithm presented by Pöntinen (2000). The absolute orientations of the panoramic images were solved using known ground control points (GCPs) existing in the neighborhood and measured with a tacheometer (Kajuutti et al 2003). A digital elevation model was digitised from the absolutely oriented panoramic images of September 2002 using Intergraph Z/I digital workstation software as a regular grid of 25 cm ground resolution while a sparser and irregular pattern in most parts of the area was used for the August 2003 images resulting in an average length of sides of triangles of 88 cm in the TIN model and covering an area about five times larger than in September 2002. The resolutions of the TP DEMs were considered reasonable when compared to the point density of laser scanner data. (Kajuutti and Pitkänen, submitted).

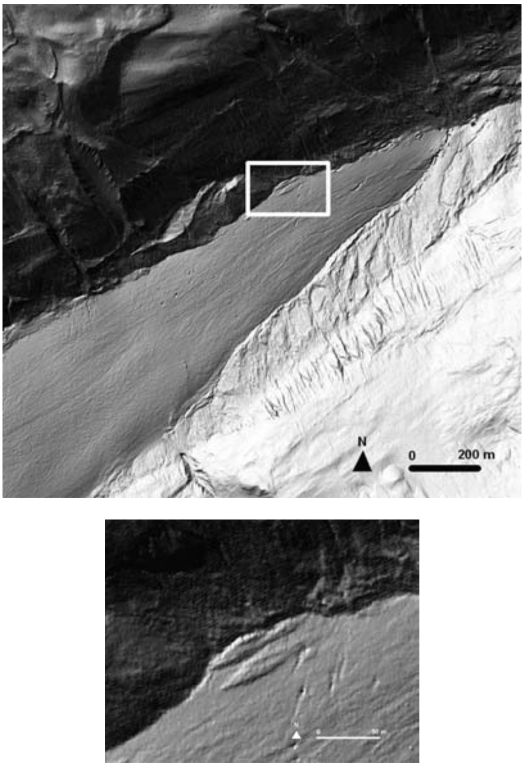

Figure 2. *Hillshade of the DEM (cell size 1 m) derived from laser scanner data showing the tongue of Hintereisferner (above). Below is an enlargement from the upper image with a white frame indicating the place of the TP DEMs used in this study.*

Figure 3. *Terrestrial photography DEM viewed together with one of the panoramic images. Hintereisferner, September 2002.*

The coordinates of the GCPs used in the absolute orientation of the panoramic images of 2002 were originally in zone M28 of the reference system of the Military Geographic Institute in Austria using the Gauss-Krüger projection of the Bessel 1841 ellipsoid with the central meridian at 10 deg 20 min East (www.geocities.com/CapeCanaveral/1224/prj/at/at.html) while the laser scanner data were in zone 32 of the Universal Transverse Mercator projection of the WGS84 ellipsoid having the central meridian at 9 degrees East (Pearson 1990). The TP DEM of 2002 was thus transformed from the local system to the UTM one via an inverse map projection of Gauss-Krüger to the Bessel ellipsoid, change of datum from Bessel to WGS84, and a map projection to the UTM system. Different formulae for the map projection or its inverse given in (Karlsson 1993, Lankinen et al 1992, Pearson 1990) were tested and the results were the same within two millimeters. Information about the height of the geoid with respect to the Bessel and WGS84 ellipsoids was obtained from Bundesamt für Eich- und Vermessungswesen as a 3'×5' grid which was interpolated for the area of the TP DEM. The Bursa-Wolf model (Lankinen et al. 1992) was applied in the change of the reference ellipsoid. The location of the area varied 2−10 meters when different values for the parameters of the seven parameter Helmert transformation given in (www.geocities.com/CapeCanaveral/1224/dat/dat.html, Schmidt 2003) were used.

In order to avoid uncertainties related to different reference coordinate systems, a check point was measured with a GPS at the terrestrial photography site during the second field campaign on August 12, 2003. The TP DEM of 2003 was thus georeferenced directly in the UTM32/WGS84 system. Seven old GCPs located on bedrock surrounding the glacier were also measured with the GPS during August 10−13, 2003. The GCPs and two additional ones available in both reference coordinate systems were used to calculate the parameters of the Helmert transformation between the reference ellipsoids for transforming the TP DEM of 2002. Another team led by Institute of Digital Image Processing at Joanneum Research, Austria, measured nine check points on the glacier with another differential GPS equipment on August 12, 2003.

3 Verification results

3.1 External accuracy

The accuracy of elevations in the laser DEMs was first evaluated against seven GCPs on bedrock and nine check points on the glacier located about 20 km a way from the calibration field in Zwieselstein. Table 3 shows that the elevations of the 2002 and 2003 laser DEMs of 5 m ground resolution are more than two meters below the GCPs on the average while the elevations of the 2003 laser DEM are more than three meters below the check points on the glacier on the average. At six check points, the differences in elevation are 2.2 m on the average while at three uppermost points, the differences in elevation increase up to 6.2 m evidently due to horizontal shifts between the laser DEM and check points. Since the standard deviations of differences in elevation are clearly smaller than the RMS ones, the differences in elevation are due to systematic errors in one or both of the data sets being compared. The GPS measurements at the GCPs on rock and on the glacier were made with two different systems and the data were processed independently. Both GPS data sets indicate similar differences with respect to the 2003 laser DEM, suggesting systematic errors in the elevations of this laser DEM. Although reasons for the systematic errors are not crucial from the perspective of this research having the emphasis on precision estimation, the phenomenon warrants a short discussion. We have two potential explanations for the systematic errors. The first source of elevation error raises from the long distance between the calibration and target area. The second one relates to different reference coordinate systems. These matters are discussed briefly below.

Table 3. *Signed distances (differences in elevation in IPP) between corresponding points of various data sets.*

Date	Data sets	Mean [m]	Std [m]	RMS [m]
18.09.02	5m laser DEM – GCP	–2.24	0.56	2.30
18.09.02	Laser points – TP DEM originally (diff. in elev.)	2.11	0.49	2.17
18.09.02	Laser points – TP DEM after IPP matching	0.04	0.16	0.16
18.09.02	Laser points – TP DEM after ICP matching	0.01	0.18	0.18
12.08.03	5m laser DEM – GCP	–2.31	0.68	2.40
12.08.03	5m laser DEM – GPS glacier	–3.15	1.55	3.47
12.08.03	Laser points – TP DEM originally (diff. in elev.)	–0.71	0.50	0.87
12.08.03	Laser points – TP DEM after IPP matching	–0.02	0.19	0.19
12.08.03	Laser points – TP DEM after ICP matching	–0.03	0.44	0.44

The calibration field was required to be as planar as possible and its orientation may have been used in the georeferencing of the laser scanner data by TopScan. A football pitch sufficed the requirements for an ideal calibration field and therefore, the nearest suitable football field was selected, located about 20 km away in Zwieselstein. The long distance between the site and the calibration field may, however, turn out to be a compromise, since it may somewhat deteriorate the accuracy. An error of 0.006 degrees in the inclination of the calibration plane will cause a height error of 2 m at a distance of 20 km. This matter cannot be controlled or verified afterwards without new measurements at the calibration field.

Another source of inaccuracy may be due to the different reference coordinate systems used. The tacheometer measurements in the calibration field of the laser scanner data were linked to a known control point given in the M28 coordinate system and transformed to the WGS84 system by Bundesamt für Eich- und Vermessungswesen. Unfortunately, no GPS measurements were carried out in the calibration field to check that the transformed tacheometer measurements were consistent with the GPS measurements on the glacier.

Further comparisons show that the elevations of the 2003 laser scanner data are 1.7 m below the check point at the terrestrial photography site. On the other hand, the elevations of the 2003 terrestrial photography DEM extrapolated to the position of the check point are also about 1.5 m below this point which suggests that either the georeferencing of the TP DEM is not correct or the coordinates of the check point are erroneous. Based on the comparisons with the GPS measurements, it is not surprising that differences in elevation appear between the laser scanner data and TP DEMs. The comparison of 2002 data may also be affected by inaccurate values of the height of the geoid or of the parameters of the Helmert transformation applied in the transformation between the two coordinate systems from M28 to UTM32/WGS84.

3.2 Internal accuracy

In order to verify the precision or internal accuracy of elevations in the laser scanner data, the laser scanner data were registered into the same coordinate system with the TP DEMs using a surface matching algorithm (Jokinen 2000). The algorithm minimizes the mean of the squares of weighted differences in elevation between the data sets without exactly known corresponding points when an initial registration is given. The weights include an adaptive weighting of the differences in elevation and differences in the direction of the surface normal between established corresponding points updated during iteration. The precision of elevations in the TP DEMs can also be incorporated in the weights but it was not done here as the precisions had not been estimated during the DEM production. The ground coordinates can be considered as a parametric domain of the elevations so that the matching algorithm belongs to the category of Iterative Parametric Point (IPP) algorithms (Jokinen 2000) where the corresponding points are determined directly in the parametric domains of the data sets. We tested also the Iterative Closest Point (ICP) algorithm (Besl and McCay 1992) where the corresponding points of one data set are the closest points on the TIN surface of the other data set. We searched first the closest vertex and calculated then the closest point within the triangles neighboring the closest vertex. The same weighting was used for both ICP and IPP algorithms.

The results in Table 3 show that the IPP algorithm converged closer to a minimum than the ICP one as the RMS distances between corresponding points are smaller for the IPP one both years. The algorithms provided approximately the same solution for the 2003 data but for the 2002 case, the ICP solution looked more correct than the IPP one when inspected visually. It was found that both algorithms were sensitive to the initial registration. The TP DEMs contained points from one side of the hillock only while the other side was occluded. The point density of the laser scanner data was high for airborne data but it was low if compared to fluctuations in the surface shape of the very detailed TP DEM of 2002. The surface shapes of the TP DEM and triangulated laser scanner data were thus rather different in the overlapping area which evidently affected the performance of the surface matching algorithms. To cope with this, a larger area was digitized from the terrestrial photographs of 2003.

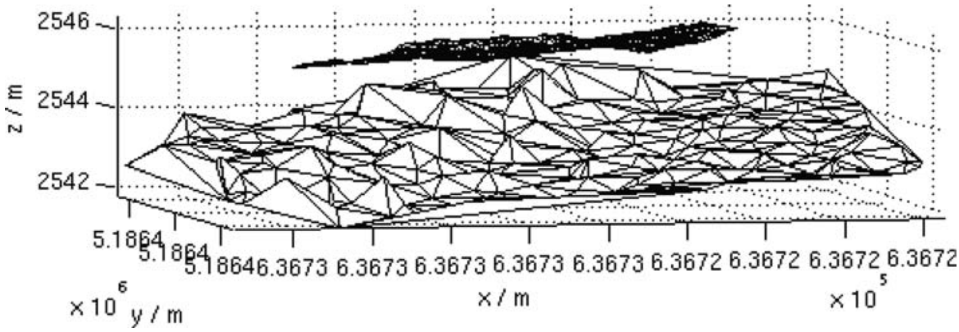

Figure 4a. *Terrestrial photography DEM and triangulated laser scanner data according to the original georeferencing. Hintereisferner, September 2002.*

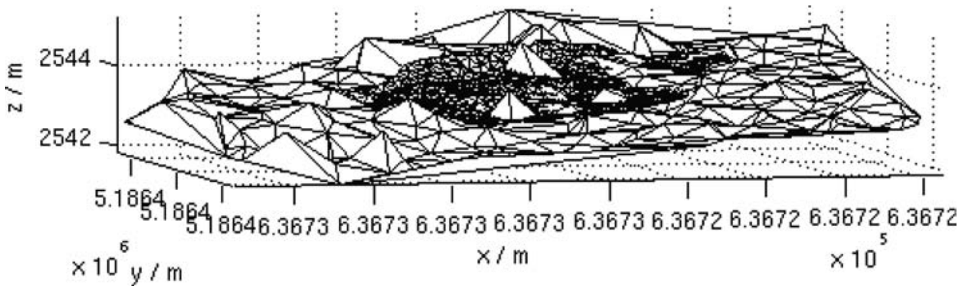

Figure 4b. *Terrestrial photography DEM and triangulated laser scanner data after ICP matching. Hintereisferner, September 2002.*

Figure 5. *Triangulated laser scanner data projected onto one of the terrestrial panoramic images after IPP matching. Hintereisferner, September 2002.*

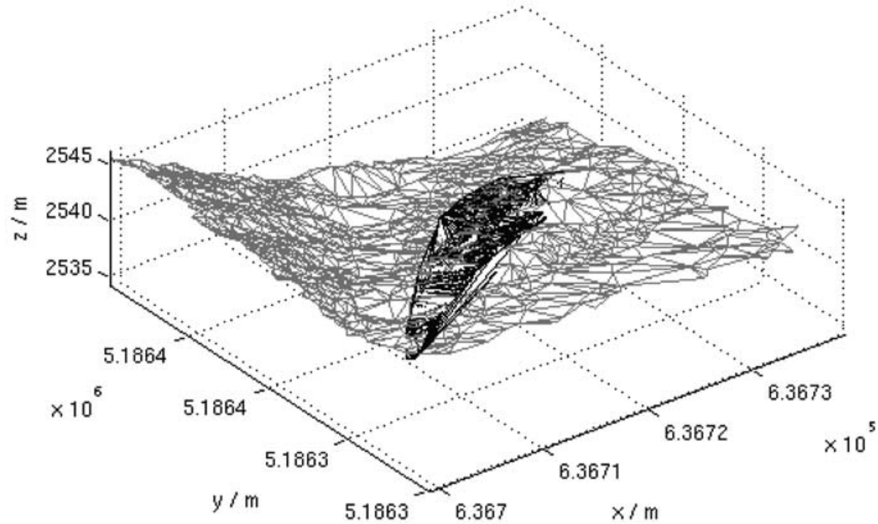

Figure 6a. *Terrestrial photography DEM and triangulated laser scanner data after IPP matching. Hintereisferner, August 2003.*

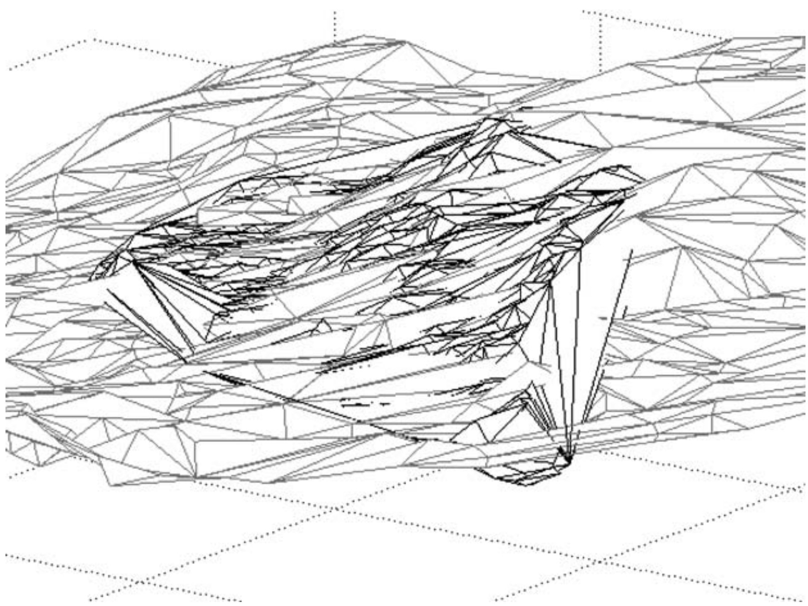

Figure 6b. *A close-up of Fig. 6a.*

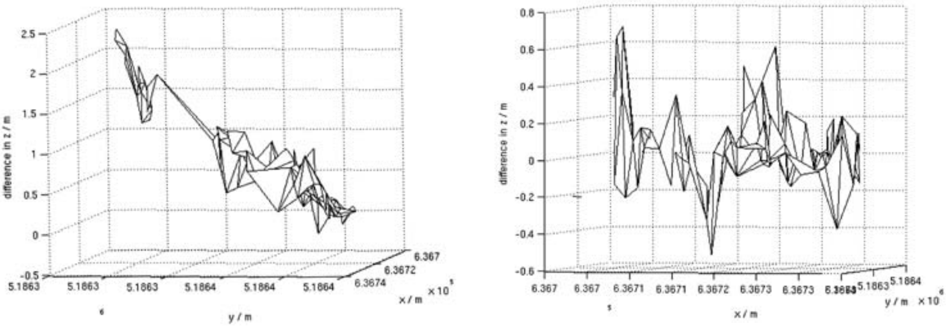

Figure 7. *Elevations of the terrestrial photography DEM minus elevations of the triangulated laser scanner data a) according to the original georeferencing and b) after IPP matching. Hintereisferner, August 2003.*

Figure 4 illustrates the TP DEM and triangulated laser scanner point cloud of 2002 before and after ICP matching. A systematic difference is clear according to the original georeferencing while after surface matching no systematic errors are perceivable although some points with large residuals distinguish as peaks emerging above the TP DEM surface. The targets where the laser beams have reflected from can be investigated in Fig. 5 where the registration has been solved by IPP matching with a manually given correction to the initial registration. The registration result for the 2003 TP DEM and triangulated laser scanner data after IPP matching is shown with a close-up in Figs. 6a-b. The differences in elevation are evaluated at the ground coordinates of the laser scanner data in Fig. 7. It appears that the orientation of the data sets is different in addition to differences in elevation according to the original georeferencing in Fig. 7a. These systematic differences have been corrected by IPP matching in Fig. 7b.

4 Discussion and conclusions

In this paper, it was shown that terrestrial photography is a feasible method for the precision verification of elevations derived from airborne laser scanner data. Furthermore the possibility to visualize the reflectance points of the laser beams proved useful in small test areas on mountain glaciers where adequate ground truth data do not exist or are difficult to acquire. Much attention was put to the synchronization of the data acquisition which was solved with a detailed field work planning and succeeded twice. Some unexpected problems appeared while processing the data acquired during the first campaign in September 2002. The terrestrial photography DEM was georeferenced in a local M28 coordinate system as all the tacheometer measurements had used that system for a long time. The laser scanner data were, however, in the UTM32/WGS84 system. The TP DEM had to be transformed to the UTM32/WGS84 system using parameters having possibly inaccurate values which affected the comparison results. During the second field campaign in August 2003, check points were measured with a GPS at the TP site, on the surrounding mountains, and on the glacier. Considerable differences in elevation were, however, observed between the GPS measurements and TP and laser DEMs. In order to verify the precision or internal accuracy of elevations in the laser scanner data, the data sets had to be registered accurately into the same coordinate system which was achieved by surface matching. After surface matching, the RMS differences in elevation between the laser scanner data and TP DEMs were 16–19 cm which gave upper bounds for the noise levels in the elevations of the laser scanner data while the noise levels in the elevations of the TP DEMs were supposed to be a few centimeters. The very detailed TP DEM of 2002 covered a rather small area (43 m^2) compared to the point density of the laser scanner data which affected the performance of the surface matching algorithm. This was taken into account in 2003 when a larger area (226 m^2) was digitized but with lower resolution. New valuable information was obtained about the problems encountered and how the photographing should be carried out in future field campaigns. The correct georeferencing of the TP DEMs should be ensured in advance using double-checked GPS measurements. Terrestrial photographs should be recorded from different viewpoints and positions to cover larger areas and so that geometrically well defined targets can be identified and matched from both TP DEMs and laser scanner data. The latter could be carried out by using colourful painted markers having a suitable geometry. As the terrestrial photographs are recorded from a very different distance and angle compared to the airborne data acquisitions, the different size and visibility requirements of the markers should be taken into account carefully.

Acknowledgements. The authors are grateful to the European Commission for financial support. The study was done as a part of the OMEGA project (EVK2-CT-2000-00069 in the 5th framework). We also want to thank TopScan GmbH, Rheine, Germany as well as our project colleagues for the close cooperation.

References

Abdalati, W., W. Krabill, E. Frederick, S. Manizade, C. Martin, J. Sonntag, R. Swift, R. Thomas, W. Wright and J. Yungel (2002). Airborne laser altimetry mapping of the Greenland ice sheet: application to mass balance assessment. *Journal of Geodynamics* 34: 391–403.

Arnold, N.S., W.G. Rees, B.J. Devereux and G.S. Amable (2006). Evaluating the potential of high-resolution airborne LiDAR data in glaciology. *International Journal of Remote Sensing* 27(6): 1233–1251.

Baltsavias, E. (1999). Airborne laser scanning: basic relations and formulas. *ISPRS Journal of Photogrammetry and Remote Sensing* 54(2–3): 199–214.

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

Benn, D.I. and D.J.A Evans (1998). Glaciers and glaciation. 734 pp. Edward Arnold, Oxford.

Benn, D.I., M.P. Kirkbride, L.A. Owen and V. Brazier (2003). Glaciated valley landsystems. In D.J.A. Evans: Glacial landsystems, 372–406. Arnold, Malta.

Besl P.J. and N.D. McKay (1992). A method for registration of 3-D shapes. *IEEE Transactions on Pattern Analysis and Machine Intelligence* 14(2): 239–256.

Csatho, B., T. Schenk, W. Krabill, T. Wilson, W. Lynons, G. McKenzie, C. Hallam, S. Manizade, and T. Paulsen (2005), Airborne Laser Scanning for High-Resolution Mapping of Antarctica, Eos Transactions American geophysical union 86(25): 237–238.

Drewry, D.J. (1972). A quantitative assessment of dirt-cone dynamics. *Journal of Glaciology* 11(63): 431–446.

Forsberg, R., K. Keller, and S.M. Jacobsen (2002). Airborne lidar measurements for Cryosat validation. In: *IGARSS 2002, IEEE International Geoscience and Remote Sensing Symposium, 24th Canadian Symposium on Remote Sensing*, Toronto, 3:1756–1758.

Gao, J. and Y. Liu (2001). Applications of remote sensing, GIS and GPS in glaciology: a review. *Progress in Physical Geography* 25(4): 520–540.

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

Geist, Th., H. Elvehøy, M. Jackson, and J. Stötter (2005). Investigations on intra-annual elevation changes using multitemporal airborne laser scanning data – case study Engabreen, Norway. *Annals of Glaciology*, 42: 195–201.

Geist, Th. and J. Stötter (in print). Documentation of glacier surface elevation change with multi-temporal airborne laser scanner data – case study: Hintereisferner and Kesselwandferner, Tyrol, Austria. *Zeitschrift für Gletscherkunde und Glazialgeologie*.

Haggrén, H., M. Nuikka, H. Junnilainen and J. Järvinen (2001). *Photogrammetric approach for archaeological documentation of an ancient road*, CIPA 2001, International Symposium Surveying and Documentation of Historic Buildings – Monuments – Sites, Traditional and Modern Methods, Potsdam University (Germany), September 18–21, 2001

Hopkinson, C., M. Demuth, M. Sitar, and L. Chasmer (2001). Applications of airborne LiDAR mapping in glacierised mountainous terrain. In: I*GARSS 2001, IEEE International Geoscience and Remote Sensing Symposium,* Sydney, 2: 949–951.

Jacobsen, F.M. and W.H. Theakstone (1997). Monitoring glacier changes using a global positioning system in differential mode. *Annals of Glaciology* 24: 313–319.

Jokinen, O. (2000). *Matching and Modeling of Multiple 3-D Disparity and Profile Maps.* Doctoral thesis, Acta Polytechnica Scandinavica, Mathematics and Computing Series No. 104, Espoo.

Kajuutti, K. (1989). Jäätikön pinnalla olevan materiaalin vaikutus jäätikön sulamiseen (The effects of supraglacial debris on the melting of glacier ice). *Terra* 101(3): 261–264.

Kajuutti, K., T. Pitkänen, T. Geist, J. Heiskanen, and P. Pellikka (2003). Comparison of terrestrial photographs and laser scanner in production of digital elevation models for glaciers. Proceedings of EGS-AGU-EUG Joint Assembl*y*, Nice.

Kajuutti, K. and T. Pitkänen (in press). Close-range photography and DEM production for glacier change detection. *Zeitschrift für Gletscherkunde und Glazialgeologie* vol 41, 2007.

Karlsson, T. (1993). Handbok till mätningskungörelsen: geodesi (Handbook to measurements in geodesy), GPS. Lantmäteriverket. Gävle.

Kennett, M. and T. Eiken (1997). Airborne measurement of glacier surface elevation by scanning laser altimeter. *Annals of Glaciology* 24: 293–296.

Kirkbride, M.P. (1995). Processes of transportation. In Menzies, J. (ed.): Modern glacial environments, 261–292. Butterworth-Heinemann Ltd., Oxford.

Krabill, W., W. Abdalati, E. Frederick, S. Manizade, C. Martin, J. Sonntag, R. Swift, R. Thomas and J. Yungel (2002). Aircraft laser altimetry measurement of elevation changes of the Greenland ice sheet: technique and accuracy assessment. *Journal of Geodynamics 34:* 357–376.

Kraus, K. and N. Pfeifer (1998). Determination of terrain models in wooded areas with airborne laser scanner data. *ISPRS Journal of Photogrammetry and Remote Sensing* 53(4): 193–203.

Lankinen U., M. Martikainen, and J. Santala (1992). Maastomittauksen laskentakaavoja (Calculation formulas for terrain measurements). Reports of Institute of Geodesy and Cartography 21, Helsinki University of Technology.

Liestøl, O. (1989). Kompendium i glasiologi (Compendium of glaciology). Meddelelser fra Geografisk institutt Universitetet i Oslo. Naturgeografisk serie. Rapport 15: 1–86.

Nakawo, M. and B. Rana (1999). Estimate of ablation rate of glacier ice under a supraglacial debris layer. Geografiska Annaler 81A(4): 695–701.

Østrem, G. (1959). Ice melting under a thin layer of moraine and the existence of ice cores in moraine ridges. *Geografiska Annaler* 41(4): 228–230.

Pearson, F. (1990). *Map Projections: Theory and Applications*, Boca Raton (FL): CRC.

Pellikka, P. & K. Kajuutti (ed.) 2005. Remote sensing of glacier area, topography and changes on Svartisen and Hintereisferner – Scientific results of the OMEGA project. *Turku university department of geography publications B6*. 83 pp. Digipaino, Turku

Pfeifer, N., P. Stadler, and C. Briese (2001). Derivation of Digital Terrain Models in the SCOP++ Environment. Proceedings – OEEPE Workshop on Airborne Laser scanning and Interferometric SAR for detailed Digital Terrain Models. Stockholm, CD-ROM.

Pöntinen, P. (1994). *Kolmiulotteinen videodigitointi* (3-D video digitizing). Master's thesis, TKK Institute of Photogrammetry and Remote Sensing, 55 p.

Pöntinen, P. (2000). *On the Creation of Panoramic Images from Image Sequences.* Licentiate's thesis, TKK Institute of Photogrammetry and Remote Sensing, 37 p.

Schmidt, R. (2003). Untersuchung verschiedener digitaler Geländemodelle hinsichtlich ihrer Eignung für die dynamische Lawinensimulation mit dem dreiphasigen Simulationsprogramm SAMOS. Diploma Thesis, Institute of Geography, University of Innsbruck (unpublished – in German).