SURFACE MODELLING FOR ALPINE GLACIER MONITORING BY AIRBORNE LASER SCANNING AND DIGITAL PHOTOGRAMMETRY

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ABSTRACT

The here presented research is part of a project on “Mass Balance Determination of Glaciers with the Use of State-of-the-art Remote Sensing Methods and a Numerical Flow Model”. To achieve the aims of the project, observations from remote sensing and ground-based instruments are combined in a numerical model. Remote sensing involves digital aerial images and laser scanning. Other technologies, like SAR, are problematic in the steep, mountainous Swiss terrain. Required products from remote sensing is a surface model of the whole glacier with an accuracy of ca. 0.5–1 m in time periods of 1–5 years. The Unteraargletscher, Bernese Alps, Switzerland, has been chosen to test both methods, as this glacier has been extensively studied by glaciologists during the past decade.
In 1998, the images and the laser data were acquired with small time difference, thus a comparison of the two measurement techniques becomes feasible. Regarding laser data processing, different aspects like system description, flight planning, position and attitude determination, transformation to the Swiss map coordinate system, fit of overlapping laser strips and problems encountered are presented. Three selected digital photogrammetric systems (Match-T, LHS DPW 770, and VirtuoZo) were used for the 1998 photographs. The results were evaluated using accurate manual measurements at an analytical plotter. The different matching algorithms and strategies, occurred matching problems due to low texture, shadows, steep slopes etc. and a quantitative and qualitative evaluation of the results are presented. Finally, a comparison between photogrammetry and laser scanning regarding accuracy and point density will be made.

1 INTRODUCTION

1.1 Background

Monitoring volume changes of small alpine glaciers is important for a number of reasons. Alpine glaciers are sensitive to changes in local climate (e.g. Orlemans, 1994), and may contribute significantly to sea level variations (Meier, 1984). Estimates of volume changes can be used to validate calculations of net mass balance based on traditional stake methods (Funk et al., 1997), and to test theoretical concepts about the response of glaciers to changes in climate (Jóhannesson et al., 1989). An alternative to the time consuming glaciological method (stake measurements) for estimating net mass balance is to use volume changes from a set of digital elevation models (DEMs) from two different time periods. Up to now this product was derived manually by analytical photogrammetry. For that, periodic images in scale 1:10 000–1:15 000 flown in August or September were used. The aim of the presented research was to automate and speed up this process and improve the spatio-temporal density and accuracy of the measurements.

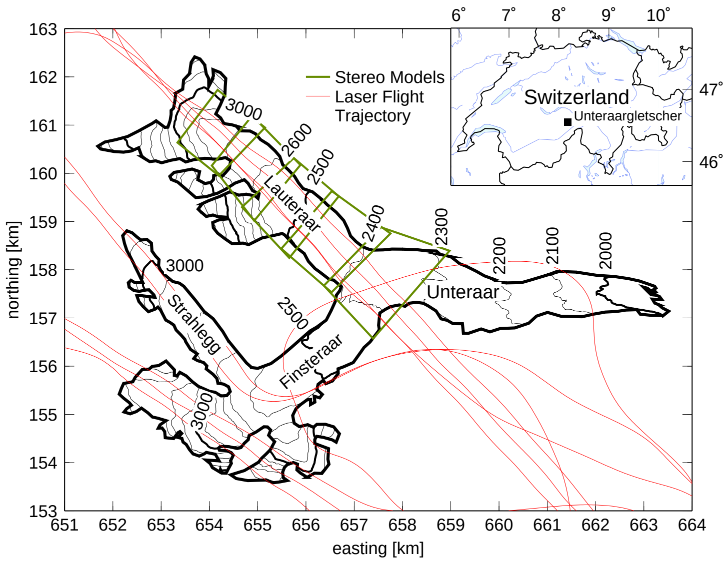
Airborne laser altimetry has only recently been introduced to glaciology. First tests with laser profiling on glaciers has been done e.g. by Echelmeyer et al. (1996) and Geiger et al. (1994). DEMs over the Greenland ice sheet with 10–20 cm accuracy in height were measured by NASA using a scanning laser altimeter first by Garvin and Williams (1993) and later by Thomas et al. (1995). Kennett and Eiken (1997) have made laser scanning measurements of a Norwegian glacier with a nominal accuracy in height of 10–20 cm. In evaluating the performance of the laser scanning system used for the Unteraargletscher, similar results in terms of height accuracy were found (Favey et al., 1999a). In the following, we investigate the quality of DEMs derived from laser scanning and photogrammetry.

Based on previous investigations, it was shown that digital image matching can lead to good results, if gross errors can be reliably detected and excluded (Baltsavias et al., 1996). These results were for the lower part of the glacier and the tongue, where generally sufficient texture exists. However, for the upper firn parts of the glacier with only snow and ice, matching was expected to be problematic. Airborne laser altimetry (ALA) is a promising method for DEM generation of snow-covered areas as it may be used independently of surface texture and external light sources, it generally gives denser and more accurate measurements for the given conditions, plus the cumbersome task to establish and maintain GCPs for photogrammetry is not needed, with the exception of a GPS reference station in the vicinity of the region.

To permit a comparison of the two technologies, regions in both the lower and upper glacier part were measured by the two methods. This permits a comparison, also including time and costs considerations, so that an optimal operational procedure for glacier monitoring can be chosen. This research is a part of an ongoing project which aims at determining the mass balance distribution of glaciers through the use of remote sensing methods and a numerical flow model, without resorting to direct field measurements (Guðmundsson and Bauder, 1999).

1.2 Available Datasets

(a) Lauteraargletscher



(b) Map of Unteraargletscher and its contributaries

Figure 1: Photograph of Lauteraargletscher and map of Unteraargletscher and its contributaries Lauteraargletscher, Strahlegggletscher and Finsteraargletscher showing the location of the test site. The laser scanning flight trajectory, as well as the approximate boundaries of the stereo models are drawn in red and olive respecively. The stereo models are numbered from north-west to south-east as 0099, 9997, 9795, 9593, 9392. Contour interval: 100 m

The laser employed was ScaLars II of the Institute of Navigation, Univ. of Stuttgart, on an airplane equipped with GPS and INS. This semiconductor laser diode transmitter operates with a wavelength of 810 nm, which guarantees a good signal reflection on snow and ice, and also provides intensity images by measuring ground reflectivity (Wehr and Lohr, 1999). The laser beam divergence is 1 mrad. The laser unit uses the multifrequency CW sidetone ranging method, and performs an elliptical scanning pattern with a measurement rate of 7.5 kHz and scanning angles of ±9.7° and ±13.6° in and perpendicular to flight direction respectively. The swath width is thus about 300–500 m at 600–1100 m height above ground. GPS measurements for positioning were acquired at a rate of 2 Hz using two double frequency Trimble SSI receivers, one on board the aircraft, the other as reference station on the ground at a fixed, known location about 15 km away from the glacier. For attitude determination, an inertial system of iMAR GmbH, Germany, with a rate of 100 Hz was used. Additionally, a GPS antenna array placed on fuselage, wings and tail of the aircraft was used to eliminate gyro drift effects in a loosely-coupled implementation (Favey et al., 1999a). The aircraft used for the laser flights as well as the photogrammetric flights was a De Havilland Twin Otter of the Swiss Federal Office of Topography.

Three laser measurement campaigns, in 97, 98, and 99, took place. The 97 results showed some problems and will not be treated further (Favey et al., 1999b). Imagery data were processed for the years 97 and 98. In 98, the images and the laser data were acquired with a time difference of only 2 weeks, thus a comparison of the two measurement techniques becomes feasible. In the photogrammetric processing of the 1998 images, 3 digital photogrammetric systems (Match-T, LHS DPW 770, and VirtuoZo) were compared, using in some cases multiple matching strategies and degrees of preprocessing.

The six B/W images forming a strip and covering the Lauteraargletscher were scanned with 14 microns at a Zeiss SCAI. The used RC 30 camera had a focal length of 152 mm and the average image scale was 1:13 000. The overlap was ca. 60% for the inner models and 80% for the two outer ones (0099 and 9392). The expected height accuracy based on the assumption of 1 pixel mean error for the matching was 0.3 m and 0.6 m for the inner and outer models respectively. Table

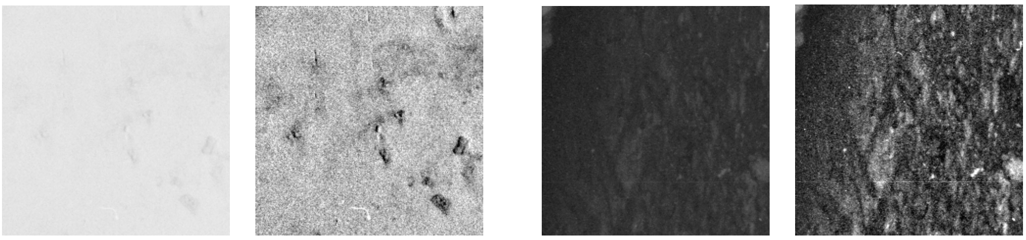
Stereopair or dataset[2]	Mean ∇Z [1][deg]	Max ∇Z [1][deg]	Z-range [m]	Min Z [m]	Max Z [m]	# of points
0099	23.9	56.2	442.4	2621.4	3063.8	538
9997	18.9	56.9	469.3	2508.2	2977.5	787
9795	16.8	56.6	374.6	2440.0	2814.6	811
9593	18.0	59.3	452.1	2354.4	2806.5	896
9392	12.9	57.3	414.7	2260.8	2713.3	1186
All-DTM	17.6	59.5	803.1	2260.8	3063.8	4218
All-CLIF	40.3	59.3	798.4	2265.5	3063.8	1458
All-GLAC	9.2	42.4	792.5	2260.8	3053.2	2760
All-BRKLIN						584

[1]Gradient Z computed from an interpolated 50 m regular grid with Sobel.

[2]Reference data for whole area (DTM), glacier only (GLAC), mountain cliffs only (CLIF) and breaklines (BRKLIN).

Table 1: Some data about the reference dataset.

1 shows the characteristics of the terrain with large height range and steep slopes for most models. Model 0099 and 9997 were at the upper glacier part where more textureless snow and ice areas exist. The control and tie points were measured with ORIMA at a Windows NT DPW 770 system and the images were oriented together in a bundle adjustment with the help of 26 signalised points measured with theodolite and an accuracy of 1 dm. The a posteriori standard deviation of the adjustment was 5 microns, and as expected the residuals were higher at the border models (especially 9392). The image coordinates were corrected for refraction, lens distortion and earth curvature but no additional parameters were used in the bundle adjustment, since they could not be imported in the digital systems to be used for DSM generation. To check the accuracy of matching a reference dataset (see Table 1) was measured at a Wild AC1 analytical plotter. This included a regular grid of 50 m spacing and also some breaklines, as we wanted to check the matching accuracy at these important terrain features separately. The estimated accuracy of the measurements was 20 and 40 cm for the inner and outer models respectively. For each model a polygon covering the measured area was defined and this was used to define the match area of the digital systems. These polygons were also divided in areas covering only the glacier and the remaining one (mainly steep mountain cliffs, partly with shadows). This was important as for the project only the glacier was important but from a general point of view, we also wanted to compare the performance of the digital systems in difficult mountain areas.



(a) original (b) after Wallis (c) original (d) after Wallis

Figure 2: Left image pair: snow area, right image pair: shadowed cliff. The original image (c) has been stretched to allow visualisation.

The images were preprocessed with a Wallis filter (Baltsavias, 1991) for a radiometric equalisation of the images and especially a contrast enhancement. Latter was necessary particularly for the quite homogeneous snow and ice areas and the shadowed steep cliffs (see Fig. 2). A first test with DPW 770 showed that the Wallis-filtered images were better than the original ones, so they were used with all 3 digital photogrammetric systems.

2 PERFORMANCE OF DIGITAL COMPARED TO MANUAL PHOTOGRAMMETRY

2.1 Processing of digital versions

The digital systems compared were Match-T on SGI, a Windows NT DPW 770 from LH Systems and VirtuoZo on Windows NT (an SGI version of VirtuoZo was also tried but could not work with the 14 micron images; it seems that the system has an internal limit of ca. 25 microns). To have an objective comparison the same orientation coming from the bundle adjustment was used. At the time of the tests, we had not discovered yet how to import the orientation with VirtuoZo, so we repeated the orientation modelwise. This caused some differences to the other systems, but these differences were below the accuracy level of the matching systems. Also for reasons of objectivity, we tried to match with all systems the same area, with a grid spacing of 10 m, and 10 m integer grid node values. Unfortunately, this was not always possible. With DPW 770 a North-East oriented object grid with 10 m spacing was defined. The system does not allow rotation of the grid so that it could be aligned with the manually measured rectangular polygons. With Match-T this was possible (we also interpolated a North-East oriented 10 m regular grid and as expected the results (see Table 3) were very similar). However, with Match-T the raw measurements from which a regular grid is interpolated through robust filtering are very dense (e.g. 2.07 million raw points for 75 000 grid nodes). In a second version of Match-T, we used an adaptive grid strategy with densification factor 1, i.e. the grid spacing was adapted automatically to 5 m in steep areas and 20 m in flat areas, while at the rest remains 10 m. VirtuoZo uses an image grid. We tried to use a spacing of 55 pixels, corresponding ca. to 10 m on the ground, but the matching results were disastrous (nonsense contours, flattening of the cliffs, very visible boundaries between the matching blocks; VirtuoZo divides the overlap area in 9 horizontal stripes covering the overlap area from top to bottom). VirtuoZo seems that it needs an image grid pixel spacing which is similar to the patch size used for matching (15×15 pixels, corresponding to ca. 2.7 m object spacing). Thus, the VirtuoZo measurements were much denser. After matching, we however interpolated a 10 m regular grid, so that a more objective comparison to the other two systems could be made.

	VirtuoZo	Match-T/Version 1	DPW	Laser
Matching method	Area-Based	Feature-Based	Area-Based	NA
Patch size in last pyramid level (pixel/m)	15 / 2.7	NA	15 / 2.7	Laser footprint ca. 2 m
# of pyramid levels, incl. original image	4	9	6	NA
Selection of match points / point spacing (m)	Regular image grid, / ca. 2.7	Regular object grid, rotated / 10	Regular object grid / 10	Irregular points / ca. 2
Matching strategy	rugged	mountainous	Adaptive, modified steep_plus	NA

Table 2: Important parameters for automatic DTM generation.

In all cases we tried to optimise the matching strategy and parameters involved. Table 2 presents a short summary of the main matching parameters. With the DPW 770 version 1, each model was run seperately. In version 2 we used an adaptive matching, with a so called steep_plus strategy which we optimised. Adaptive matching can use more than two images, and computes the mean terrain inclination in small neighbourhoods. Based on this inclination, the two best ones out of all the available images are selected. Since the image overlap was considerable, many regions were visible in three or even 4 images. This selection generally led to better results in steep cliffs as occlusions and large perspective differences were reduced (visually controlled). The higher number of points with the first version (see Table 3) is due to the double measurements in the overlap region of the models. DPW 770 computes for each point a quality criterion (called Figure Of Merit, FOM). In the so called cleaned version, points having a FOM<32 (pressumably errors) were eliminated. The percentage of points with poor FOM for the two matching versions were 45.5% and 14.6% with the main rejection reasons being low correlation curvature (33.3%/8.3%) and low correlation coefficient (10.1%/3.6%), obviously mostly at areas with homogeneous texture.

With Match-T another version with an adaptive matching strategy (not be confused with the adaptive grid) led to almost no change (only about 100 points got different values). Increasing the smoothing weights from 1.5 to 3.5 led to extreme flatenning of the cliffs. Unfortunately, Match-T can not automatically self-tune these parameters based on the actual terrain form. With VirtuoZo apart from the rugged strategy also an undocumented so called “broken” one was used. Its results looked smoother on steep cliffs, but due to time constraints this version was not analysed further.

2.2 Comparison with manual Photogrammetry

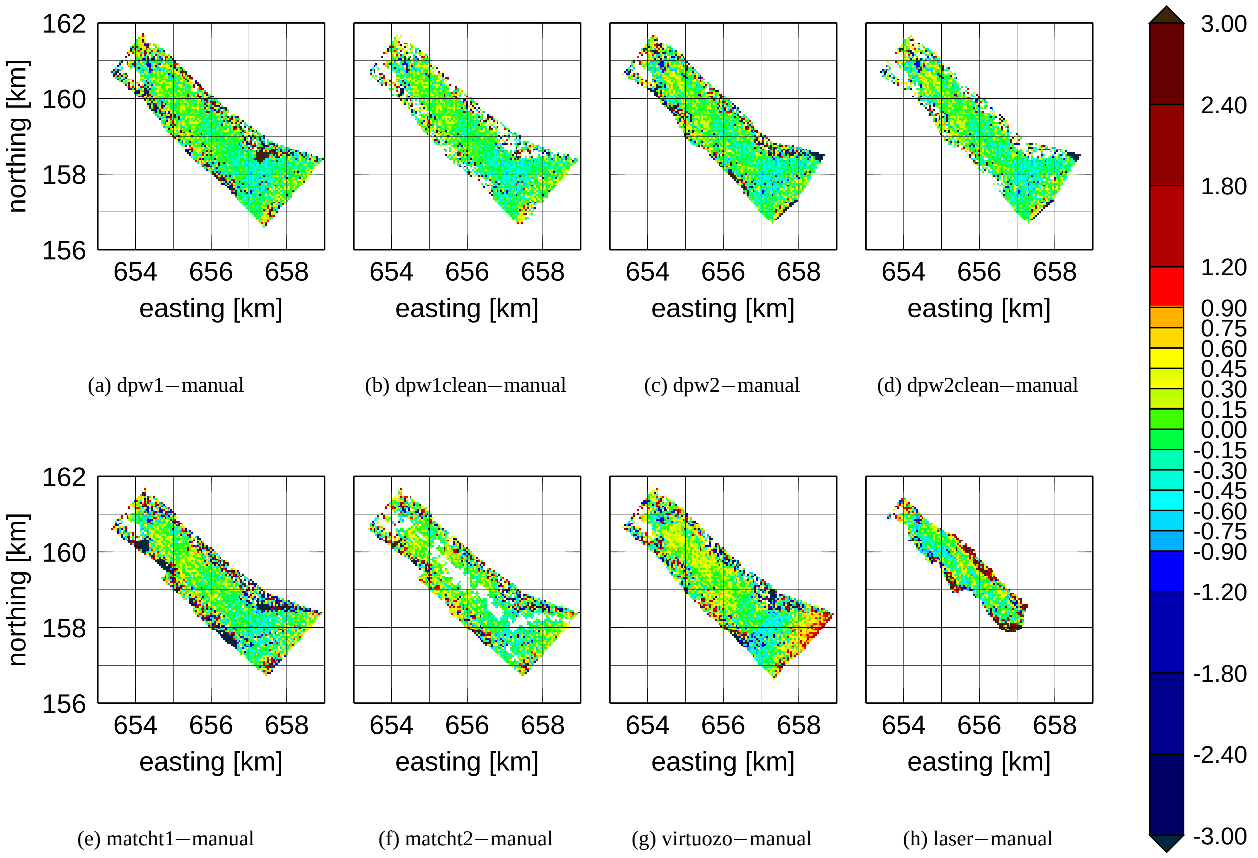
The results are presented in Table 3 and in graphical representation in Fig. 3. Much more detailed analysis than the one in this table was performed by checking in each model the accuracy for: (a) the whole area, (b) the glacier only, (c) the cliffs only, and (d) the breaklines only. We also checked the relative fit of the heights in the overlap region between neighbouring models for each matching version and all models. It was interesting to note that these relative differences were very high, and in all cases (except two inner models with VirtuoZo) higher than the differences of each individual model to the manual measurements. The relative differences are partly due to the not optimal orientation (no strong block geometry in the bundle adjustment) but also due to the matching differences because of other viewing and ray intersection angles, possibly different texture, varying perspective distortions of the images, differences in occlusions etc. This fact stresses the importance of using more than two images, either by choosing a priori the two best ones for each point to be matched, by comparison of heights in the overlap regions of neighbouring models and choice of the best one based on quality criteria, or even better by simultaneously matching all available images together.

System Version	Test data # of pts	Reference data # comparison pts	RMS [m]	Mean with sign [m]	Max abs. [m]	% blunders[1]
VirtuoZo	Original	DTM / 4160	3.15	−0.14	78.28	13.73
	2 292 348	CLIF / 1409	5.32	−0.59	78.28	27.68
		GLAC / 2751	0.73	0.09	26.53	6.58
		BRKLIN / 538	3.04	−0.26	28.56	37.91
	10 m, inter-	DTM / 4158	5.25	−0.19	135.24	14.29
	polated	CLIF / 1404	8.98	−0.79	135.24	28.42
	regular grid	GLAC / 2754	0.74	0.11	26.04	7.08
	153 503	BRKLIN / 584	3.01	−0.12	30.94	51.20
Match-T	Original	DTM / 4091	3.40	0.08	76.87	13.62
version 2	351 283	CLIF / 1395	5.74	0.19	76.87	31.54
(adaptive		GLAC / 2696	0.72	0.02	26.25	4.34
grid 5,		BRKLIN / 549	9.27	−1.90	71.51	39.34
10, 20 m	10 m inter-	DTM / 4091	3.40	0.07	76.87	13.71
spacing)	polated	CLIF / 1395	5.74	0.18	76.87	31.83
	regular grid	GLAC / 2696	0.73	0.02	26.25	4.34
	95 174	BRKLIN / 549	9.35	−1.82	71.57	60.47
Match-T	Original	DTM / 4089	14.94	−2.30	215.82	21.99
version 1	112 000	CLIF / 1396	25.54	−6.80	215.82	50.21
(10 m		GLAC / 2693	0.83	0.03	24.8	7.35
spacing)		BRKLIN / 549	30.68	−6.97	232.91	64.66
DPW	Original	DTM / 3848	7.11	−0.66	102.55	16.42
version 2	87 454	CLIF / 1189	12.72	−1.98	102.55	39.95
(all images		GLAC / 2659	0.93	−0.06	26.32	5.90
matched		BRKLIN / 535	11.52	−2.21	84.62	45.61
together)	Cleaned[2]	DTM / 3285	5.02	−0.41	96.10	9.56
	76 021	CLIF / 701	10.79	−1.73	96.10	27.25
		GLAC / 2584	0.61	−0.06	6.39	4.76
		BRKLIN / 418	2.30	0.19	24.48	58.61
DPW	Original	DTM / 4195	7.72	0.42	158.13	22.31
version 1	114 874	CLIF / 1456	12.17	0.94	158.13	46.09
(matching		GLAC / 2739	3.55	0.14	136.20	9.68
per modell)		BRKLIN / 565	12.01	−0.08	123.82	67.96
	Cleaned[2]	DTM / 3637	1.37	0.03	26.68	10.5
	62 605	CLIF / 963	2.22	0.12	26.68	25.96
		GLAC / 2674	0.89	−0.00	23.88	4.94
		BRKLIN / 447	2.75	0.16	25.37	61.74
Laser	Original	DTM / 1784	1.89	0.47	13.83	23.71
	2 512 314	CLIF / 179	2.65	1.09	11.68	60.89
		GLAC / 1605	1.79	0.40	13.83	19.56
		BRKLIN / 77	3.72	0.01	13.21	72.73
		0099 DTM / 264	0.94	0.03	7.30	18.94
		9997 DTM / 490	1.25	0.10	11.68	16.53
		9795 DTM / 495	1.59	0.55	7.26	24.85
		9593 DTM / 455	2.16	0.67	12.80	27.25
		9392 DTM / 73	5.26	2.79	13.83	55.56
		0099 GLAC / 241	0.73	0.07	4.00	17.43
		9997 GLAC / 427	0.84	−0.02	7.01	10.77
		9795 GLAC / 446	1.42	0.42	7.26	19.51
		9593 GLAC / 421	2.08	0.58	12.80	23.99
		9392 GLAC / 71	5.31	2.78	13.83	54.29

[1] Threshold for blunders is 0.9 m. This threshold is calculated as 3 RMS, where RMS is computed based on the assumption of one pixel error in matching corresponding to ca. 0.3 m for the three inner models (60% overlap) and ca. 0.6 m for the two outer ones (80% overlap).

[2] Cleaned means without points with a poor quality label, i.e. Figure Of Merit (FOM) less than 33, as assigned automatically by the matching algorithm.

Table 3: Error statistics of automatically generated DTMs—reference data for whole area (DTM), glacier only (GLAC), mountain cliffs only (CLIF) and breaklines (BRKLIN).



(a) dpw1−manual (b) dpw1clean−manual (c) dpw2−manual (d) dpw2clean−manual

(e) matcht1−manual (f) matcht2−manual (g) virtuozo−manual (h) laser−manual

Figure 3: Differences in [m] of respective digital solution minus manual photogrammetric measurements.

2.2.1 Some conclusions from the comparison of systems and versions. The results at the cliffs were by far worse than on the glacier. Particularly cliffs with shadows and sudden height changes were problematic. The results on the glacier varied, with the exception of the raw DPW 770 version 1, from 0.6 to 0.9 m, so it was higher than the expected accuracy for the inner models but quite close to the expected one for the border ones. Still, the performance was surprisingly good even in the upper glacier models with very little texture (to a large extent due to Wallis filtering). In addition, the higher than expected RMS in the inner models is strongly influenced by large blunders, even if their number is low. Through elimination of these blunders, the expected accuracy can be achieved or even slightly exceeded.

The results for the breaklines were generally similar or better than those of the cliffs, with the exception of Match-T which shows a poor performance there. The reason for that is probably the robust filtering of the raw measurements in each grid mesh, leading to a removal of these terrain “outliers”. Also the adaptive grid spacing is computed for each matching unit (13$\times$13 grid meshes), which is too coarse for fine linear discontinuities in a neighbourhood which is mainly planar. VirtuoZo (and DPW 770 after cleaning) performs the best and also adapts better to rough terrain. In all cases, the breaklines were 3–38 times worse than the flat glacier. Thus, in practical production it may be better to first measure the breaklines manually and then fix them during matching and also use them for a better approximate terrain modelling.

We were expecting the two border models 0099 and 9392 to have lower accuracy due to poorer orientation (strip borders), larger overlap (which however makes matching easier), lower texture (0099) and smaller image scale (9392, lowest glacier part). However, the results (comparison with manual measurements and relative differences in overlap regions) were not much worse than those of the inner models. The reason is obviously that the accuracy influence of these factors is lower that the inherent errors of matching.

In all systems and versions big blunders remain in the results. With the exception of one case, the maximum absolute error was never below 24 m, reaching to 233 m. Their percentage on easy terrain (glacier) is not very high but even there their magnitude is several times the RMS. To solve this problem, efficient postprocessing tools are needed or even better sophisticated methods for automatic blunder detection. Both cleaned versions of DPW 770 showed a dramatic improvement over the raw data (especially for version 1). Still many blunders, especially in cliffs and breaklines remain undetected. The cleaned versions also show gaps in problematic areas, but for practical postprocessing work it is preferable to manually measure points in such gaps, than search for more blunders in a dense point field over the whole terrain area. In all versions, the bias (mean with sign) is small, except some cases where big blunders totally distort the error statistics.

The computation time is the longest for Match-T and the shortest for VirtuoZo (more than an order of magnitude faster than both other systems). Although the differences between the systems in some cases seem small, our analysis (and additional visual controls) showed that generally VirtuoZo performs the best, especially at breaklines and steep, rugged terrain. However, when matching fails, the errors there can be very large (no gracious deterioration). The cleaned DPW 770 versions are also good, with the exception of the cliffs of version 2, but at the cost of lower point density and gaps. For this type of variable rugged terrain, it is always better (as well for automatic blunder detection, if supported by the systems) to match very densely and then thin-out the results by an intelligent interpolation method. Matching should be locally adaptive (within a very small area), depending on terrain relief and image texture, especially for important parameters like patch size, number of pyramid levels used, density of matched points and resulting regular grid (latter applicable only for Match-T). An appropriate combination of more than 2 images is also beneficial, especially for rough terrain.

2.2.2 Conclusions for individual systems. With DPW 770 although some visual comparisons in some steep cliffs showed that versions 2 performs better, the global statistics of Table 3 do not support this for the cliffs, especially for the cleaned versions. Version 2 was expected, based also on experience reports of photogrammetric firms, to perform better especially in the cliffs. This contradiction can be due to poor algorithms in the choice of the best 2 images and also because the mean terrain inclination seems to be computed in a neighbourhood than is too large (25×25 grid meshes) for the rapidly varying Alpine terrain. Another reason for this worse performance of version 2, is that in the cleaned version much less points than in version 1 had poor FOM, so it seems that many blunders remained undetected. This is also an indication that with the current algorithms of the system it is probably better to have independent measurements of the same region from 2 stereomodells, combine the results and then clean them, than trying to select the best 2 images out of the 3, match only once and then clean. Comparing the two Match-T versions shows that the adaptive grid performs much better, especially at cliffs and breaklines, and produces less points (smaller datasets, faster processing).

3 RESULTS OF LASER SCANNING

3.1 Preprocessing

The laser scanning data was preprocessed by the calibration technique described in Thiel and Wehr (1999) to estimate misalignment angles between the laser coordinate frame and the aircraft body frame. No further preprocessing, such as filtering or classifying objects, was applied to the raw laser ground points. As the laser scanning requires low flying height above ground (max. 750 m) to achieve reasonable results and obtain enough ground reflection, flight planning in the mountaineous terrain posed tough challenges. For security reasons, and because the focus of applying the laser scanning technique was put on the firn areas of the glacier, flight lines lower than an altitude of 3400 m were ommitted. This led to a height over ground of 600 m and 1100 m in the stereo models 0099 and 9392 respectively. The received laser signal power at 1100 m flying height over ground was at the limit of S/N ratio and thus is expected to result in a high RMS, when compared to photogrammetry. This holds for all data with flying height >750 m

The laser flight trajectory was estimated with differential GPS using double frequency carrier phase measurements. The accuracy of positioning and attitude measurements is assumed to be about 0.05 m and better than 0.05° respectively, based on previous investigations of the same system setup flown over a runway as known terrain (Favey et al., 1999a). To be able to compare the heights derived from laser measurements with photogrammetry, the raw laser data were transformed to the Swiss geodetic datum and projection system. Geoid undulations of centimeter accuracy (Marti, 1997) were applied. As the coordinates of the GCPs used for the photogrammetric measurements were known in the previous Swiss reference system only (not using true orthometric heights), local 3D translation parameters were estimated using static DGPS measurements on a control point in the glacier area.

Version	# of comparison pts	RMS [m]	Mean with sign [m]	Max abs. [m]
laser line west − laser line center	187092	1.27	−0.36	32.09
laser line center − laser line east	321778	1.29	0.13	68.93

Table 4: Statistics of differences of laser swath overlaps.

Over the Lauteraargletscher, 3 laser lines (west, center, and east) were flown for airborne laser scanning. The results of a comparison of the overlap region is given in Table 4. The two overlapping regions of adjacent laser swath lines show a RMS of about 1.28 m. This is mainly due to unmodelled errors in attitude angles, which appear to be worse than the results obtained over the runway due to bad flying conditions during this flight (strong winds and vibration). As parts of the glacier contain many deep crevasses, maximal differences in the order of ten meters are easily possible.

3.2 Comparison with Photogrammetry

3.2.1 Comparison with Manual Photogrammetry. A comparison with manual photogrammetric measurements was made both, on a per model basis as well as all points together (Table 3). The "dark" parts for the laser wavelength of 810 nm pose problems to the laser scanning technique, as the reflecion there is much weaker than on snow and ice. This is mainly the case in the cliff regions and on debris-covered parts of the glacier. In the region of model 9392, the laser technique reaches its limits with a slant range of over 1200 m (system performance is guaranteed by the system provider up to 750 m, which is the case only in models 0099 and 9997) and almost no received signal, which results in an expectedly high RMS. On the top models 0099 and 9997, where the slant range is around 600 m, the RMS of still more than 0.7 m is probably due to the attitude measurement problems discussed in the previous section. Nevertheless, the project target of achieving a DTM accuracy of 0.5–1 m is achieved in this upper region, at which the flight planning was targeted. The digital model points compared on the glacier only show just a slightly lower RMS than when including the cliff parts. This is because much blunder of the laser data is on the glacier-parts where the glacier is covered with debris, (see Fig. 3(h)) and thus only a weak S/N ratio could be obtained.

The signed mean values of the difference to the single models show some sort of bias which increases with the increasing flying height towards the south-east. This is a known effect of this laser scanning system, which is due to a yet uncorrected bias of the raw distance measurement with increasing height above ground. This also distorts the overall statistics with a "mean" bias.

3.2.2 Comparison with Digital Photogrammetry. Photogrammetry, as shown by the VirtuoZo example, can measure with equal or even higher density than laser. Flight time is shorter, flight planning is simpler, and sensitivity of the results to variations of the flying height over ground is much less. The visual quality of the images is much better than the reflectivity images that the used laser scanner produces. For the laser scanner, system calibration is much more complicated and has a much stronger influence on the accuracy. On the other hand with photogrammetry, processing of the data takes more time, is more complicated and needs more specialised hardware (film development, scanner, digital photogrammetric system). Since photogrammetric film cameras usually do not have INS, ground control points, which are difficult and costly to establish and maintain, especially in mountaineous regions, are needed. Most of the previously mentioned disadvantages will however disappear with digital photogrammetric cameras that are expected this year, yet system calibration will then show similar complications and influences as with laser scanning.

Based on Table 3, the laser's accuracy is, unexpectedly, lower than photogrammetry on the glacier due especially to the lower three models, which show problems in the debris-covered and cliff areas, but also due to attitude errors as explained above. This could be addressed by eliminating the laser points with a received signal power lower than a threshold and by flying lower lines with a maximum height over ground of 750 m. Where laser clearly beats photogrammetry is the size of the large errors. As Table 3 shows, the maximum absolute error with laser is similar for all datasets and bounded (not exceeding 14 m). With photogrammetry the blunders are larger, especially at the cliffs and breaklines. With improvements in attitude determination, the laser may be able to reach the expected accuracy of 10–20 cm. In such a case, photogrammetry can compete only by increasing the image scale to about 1:6 500.

4 CONCLUSION

The project target of achieving a DTM accuracy of 0.5–1 m for the glacier was achieved by all, except one, matching versions. However, big blunders remain in the results making manual postprocessing necessary. Of the three digital photogrammetric systems DPW 770 provides the best tools for such editing. Thus, a possibility to employ digital photogrammetry for measuring surfaces was proven to be possible even in glacier regions with very little texture. Matching performance in rugged, steep terrain and at breaklines on the other hand is much less accurate and the blunders more and larger, requiring much pre- and post-editing. Thus, in such terrain, when the accuracy requirements are high, it may be faster to measure the whole DTM manually.

Out of the 3 photogrammetric systems, the best concerning accuracy, speed, price (at least in our case) and ease-of-use is VirtuoZo. However, it is also the closest system, with the poorest documentation and explanation of the underlying algorithms. Very few matching parameters can be set, which is an advantage for production environments but a disadvantage for sophisticated and knowledgeable users who wish to experiment or improve the results by fine-tuning of some parameters. Finally, its pre- and post-editing capabilities are not that extensive as with DPW 770.

Airborne laser scanning performs as well as digital photogrammetry as long as the flying height above ground does not exceed the system's ranging limits of 750 m. It performs well on white snow and ice area, but blunders are likely in debris-covered or cliff regions. By using laser scanning, 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 because no locations suited for GCPs can be found. With improvements in attitude determination and calibration, the laser may be able to reach the expected accuracy of 10–20 cm.

Both digital photogrammetric systems and airborne laser scanners are expected to improve in the future and have their advantages and disadvantages. The choice of one of these measurement techniques over the other requires careful analysis of the requirements of the application at hand and consideration of additional boundary conditions.

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REFERENCES

Baltsavias, E. P., 1991. Multiphoto Geometrically Constrained Matching. Technical report, Institute of Geodesy and Photogrammetry, ETH Zürich. Mitteilungen, Nr. 49, 221 p.

Baltsavias, E. P., Li, H., Mason, S., Stefanidis, A. and Sinning, M., 1996. Comparison of Two Digital Photogrammetric Systems with Emphasis on DTM Generation: Case Study Glacier Measurement. In: IAPRS, Vol. 31, Part B4, Paper presented at the 18th ISPRS Congress, 9–14 July, Vienna, Austria, pp. 104–109.

Echelmeyer, K. A., Harrison, W. D., Larsen, C. F., Sapiano, J., Mitchell, J. E., DeMallie, J., Rabus, B., Aðalgeirsdóttir, G. and Sombardier, L., 1996. Airborne surface profiling of glaciers: a case-study in Alaska. J. Glaciol. 42(142), pp. 538–547.

Favey, E., Cerniar, M., Cocard, M. and Geiger, A., 1999a. Sensor Attitude Determination Using GPS Antenna Array and INS. In: ISPRS WG III/1 Workshop: Direct Versus Indirect Methods of Sensor Orientation, Barcelona, Nov. 25–26, pp. 28–38.

Favey, E., Geiger, A., Guðmundsson, G. H. and Wehr, A., 1999b. Evaluating the potential of an airborne laser scanning system for measuring volume changes of glaciers. Geografiska Annaler 81A(4), pp. 555–561.

Funk, M., Morelli, R. and Stahel, W., 1997. Mass balance of Griesgletscher 1961-1994: different methods of determination. Zeitschrift für Gletscherkunde und Glazialgeologie 33(1), pp. 41–55.

Garvin, J. B. and Williams, R. S., 1993. Geodetic airborne laser altimetry of Breidamerkurjökull and Skeidarárjökull, Iceland, and Jakobshavns Isbræ, West Greenland. Ann. Glaciol. 17, pp. 379–385.

Geiger, A., Cocard, M., Peter, Y. and Kahle, H.-G., 1994. Precise DGPS and Self Calibrating Laser Altimetry for Airborne Marine Geoid Determination and Detection of Glacial Fluctuation. In: Proceedings of ION GPS-94, 7th International Technical Meeting of The Satellite Division of The Institute of Navigation, Part 1, Salt Lake City, Utah, September 20–23, pp. 471–476.

Guðmundsson, G. H. and Bauder, A., 1999. Towards an indirect determination of the mass-balance distribution of glaciers using the kinematic boundary condition. Geogr. Ann. 81A(4), pp. 575–584.

Jóhannesson, T., Raymond, C. F. and Waddington, E. W., 1989. Time-scale for adjustment of glaciers to changes in mass balance. J. Glaciol. 35(121), pp. 355–369.

Kennett, M. and Eiken, T., 1997. Airborne measurement of glacier surface elevation by scanning laser altimeter. Ann. Glaciol. 24, pp. 293–296.

Marti, U., 1997. Integrierte Geoidbestimmung in der Schweiz: wissenschaftliche Basis zur Höhenbestimmung in der Schweizerischen Landesvermessung mit Hilfe von satellitengestützen Verfahren. PhD thesis, ETH Zürich, Nr. 12015, 140 p.

Meier, M. F., 1984. Contribution of small glaciers to global sea level. Science 226(4681), pp. 1418–21.

Oerlemans, J., 1994. Quantifying global warming from the retreat of glaciers. Science 264(5156), pp. 243–245.

Thiel, K.-H. and Wehr, A., 1999. Calibration Procedures of the Imaging Laser Altimeter and Data Processing. In: Joint Workshop of ISPRS WGs I/1,I/3, and IV/4: Sensors and Mapping from Space, Univ. Hannover, Vol. 18. on CD-Rom.

Thomas, R., Krabill, W., Frederick, E. and Jezek, K., 1995. Thickening of Jakobshavns Isbræ, West Greenland, measured by airborne laser altimetry. Ann. Glaciol. 21, pp. 259–262.

Wehr, A. and Lohr, U., 1999. Airborne laser scanning—an introduction and overview. ISPRS Journal of Photogrammetry & Remote Sensing 54(2–3), pp. 68–82.