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

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Abstract

This research is part of a Swiss National Science Foundation project on "Mass Balance Determination of Glaciers with the Use of State-of-the-art Remote Sensing Methods and a Numerical Flow Model". Remote sensing involves automated processing of aerial images and laser scanning and aims at producing glacier surface models with an accuracy of about 0·5-1 m in time periods of 1-5 years. The Unteraar glacier, Switzerland, has been chosen to test both methods, as it has been extensively studied by glaciologists. The results of laser and digital photogrammetry were evaluated using accurate manual measurements at an analytical plotter. Regarding laser data processing, different aspects like system description, position and attitude determination, transformation to the Swiss map co-ordinate system, fit of overlapping laser strips and problems encountered are presented. Three digital photogrammetric systems (Match-T, LHS DPW770 and VirtuoZo) were used for surface model generation using image matching. 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 is presented.

KEYWORDS: glacier monitoring, change detection, DSM, multi-sensor integration, laser scanning, digital photogrammetric stations, image matching

INTRODUCTION

Glacier Development, Status and Monitoring Word-Wide

Glaciers and generally ice and snow surfaces presently cover about 10 per cent of the land area and store about 75 per cent of the world's freshwater. Glaciers are monitored world-wide, since 1986 by the World Glacier Monitoring Service (WGMS, 2000), and are considered one of the most reliable and easily understandable indicators of climate change, termed three-star indicators according to IPCC (1996). They are related among other to global warming, sea-level rise, natural hazards, fresh water supply, hydrological and geological systems, delicate ecosystems (especially high latitude and/or altitude ones) and are part of our natural heritage. Arctic temperature trends in the period 1966-1995 showed a warming in the great majority of the observed regions reaching up to 4 ^{o} increase in central Siberia. On a global scale, an increase of 0·7 ^{o} compared to the end of 19th century was observed, while the last 20 years were continuously warmer than the average of the last hundred years. The average sea-level rise in the last 100 years was 1.8 mm/y (about 1/6 of it from Greenland and 1/6 from mountain glaciers which may account up to 1/2 in high mass-loss years); note that 400 km^3 melting results in 1 mm sea-level rise and if all land ice melted, the sea-level would rise about 80 m. An increased glacier mass loss has been observed since the mid 80s and an acceleration since the late 80s. Natural hazards include outburst floods, surging glaciers, iceberg discharge, debris flows/landslides and ice avalanches and may cause severe damage to humans and artificial and natural objects. Fresh water supply is important, depending on the region, for drinking water, agriculture and electricity (the latter being of importance for Switzerland). Glaciers should be seen not just as part of the cryosphere but also the hydrological (glaciers are the second largest water reservoir with 2.15 per cent after oceans with 97.2 per cent) and geological systems.

Currently, glacier monitoring has the following characteristics:

(a) methods are slow, cumbersome and costly
(b) measurement density and/or accuracy are insufficient
(c) many regions (central Asia, Patagonia) and glaciers are poorly or not monitored
(d) measurement repetition cycle is too long
(e) observation records are too short (thus, often extrapolation is used)

As an example, mass balance is measured by WGMS only for 52 glaciers. This is a point where modern remote sensing methods could make a contribution.

Analysis of glaciers is highly complicated due to various reasons. There are many different glacier types depending on latitude, altitude, area, length, slope, thickness, type, glacier bed, composition and adjacency to sea. The observed parameters are influenced by climate (temperature, precipitation, etc.), interactions with other components of the cryosphere system, interactions with the atmosphere and oceans, etc. To model all these components, sophisticated integrated models are needed, which involve many parameters often with insufficient observations and complicated and poorly known interactions.

Regarding glacier development, generally reduction of their volume, mass and length has been observed since 1850, although in the upper glacier parts the mass/volume may increase. The ablation glacier areas, as well as low altitude/latitude and humid/maritime glaciers are more sensitive to climate and exhibit more changes in mass balance. The glacier reaction to climate also depends strongly on length and slope. Long/flat glaciers show a slow reaction to climate and mass balance changes, while short/steep ones react fast. Regarding ice sheets, there are varying developments but generally ice thinning and disintegration predominates (for example in West Antarctica ice shelves have occasionally lost over 1000 km^2 in one event, and icebergs with an area of over 10000 km^2 have been calved). Sometimes, as in Greenland for example, scientific results are contradictory, not comparable or difficult to interpret. Useful information on glaciers, including most of the above mentioned data, can be found at USGS (2000a), WGMS (2000), NSIDC (2000), Williams (1986) and a bibliographic collection at USGS (2000b).

Glaciers in Switzerland

Glaciers are important for Switzerland and this is one of the reasons why it contributes significantly to WGMS (with headquarters in Zurich) through financial and logistics support. In 1998, there were 2164 glaciers with 1300 km^2 area and 74 km^3 volume (third largest volume in Europe, excluding Russia). 53 (2.4 per cent) were tongue-form, valley ones, with 51.2 per cent of the total area and 75.8 per cent of the volume. In Switzerland, glacier reports exist since 1880. There are long time series (> 100 years) for some glaciers. Swiss glaciers are together with the Scandinavian ones the best known world-wide. In spite of these facts, out of the 2164 glaciers, only 121 (6 per cent) are observed, representing 60 per cent of the area and 85 per cent of the volume. They are divided in 4 classes according to length. Yearly length measurements (tongue retreat) are performed for 80 - 100 glaciers. About 12 of them are observed photogrammetrically, while direct mass balance measurements are made only for 4. Mass balance changes measured indirectly from cumulative length changes and glacier response time for 68 glaciers (1850 - 1996) showed a mass balance change of -0·17 m w.e. / year (w.e. ...water equivalent). The larger the glacier, the higher the mass loss was. These results were verified by glaciologic and photogrammetric measurements. From 1850 to 1998 and for all glaciers, a 27 per cent area loss was observed, while the length was decreased for the 4 glacier classes as follows: 0-1 km, 43 per cent ; 1-5 km, 32 per cent ; 5-10 km, 22 per cent ; > 10 km, 16 per cent. From 1973 to 1998 and for the 121 observed glaciers, results showed retreat for 77 per cent, advance for 15 per cent and stability for 8 per cent. The larger the glacier, the higher the retreat absolutely, and the lower the retreat relatively (in per cent). An inventory of all glaciers was made in 1973 and there are plans for a new inventory in the near future using various remote sensing sensors, especially NASA's ASTER. The detailed yearly reports on the development of Swiss glaciers and other related publications can be found in GCSAS (2000).

Glacier Monitoring and Mass Balance

According to the WGMS monitoring strategy, mass balance is an important indicator as it reacts fast to weather (temperature, precipitation), contrary to length changes (reaction in few years to centuries depending on glacier length/slope). Monitoring volume changes of small alpine glaciers in particular is important, as alpine glaciers are sensitive to changes in local climate (Orlemans, 1994) and may contribute significantly to sea-level variations (Meier, 1984). The monitoring procedure tries to invert the real physical processes and goes from observations on glacier advance/retreat to glacier geometry and temperature to mass and energy balances to climate and possible anthropogenic influence on the climate (greenhouse forcing). Remote sensing could be used for mass balance estimation (using measurements or assumptions about the density of snow, firn and ice[1]), estimation of surface topography, area, length, motion and time variation of these parameters, while airborne radar sounding can also measure thickness for cold glaciers.

Net mass balance is usually calculated based on traditional glaciologic methods using stakes and pits. Other methods for mass balance determination include the hydrological method, which is not reliable and accurate, and indirect methods from cumulative length change and glacier response time, which are not always feasible as the necessary data do not exist. An alternative to the time consuming glaciologic method is the photogrammetric/remote sensing method, which has been adopted by the Glaciology group of ETH (Guðmundsson and Bauder, 1999). Thereby, the glacier DSM can be measured from aerial images, let's say every 5-10 years, volume changes are converted to mass change and the results are input into full 3-D non-linear flow numerical models, which can output various parameters, like distribution, strains and stresses. Furthermore, this remote sensing approach, and volume changes in particular, can be used for validation/calibration of the glaciologic method (Funk *et al.*, 1997), and to test theoretical concepts about the response of glaciers to changes in climate (Jóhannesson *et al.*, 1989).

Use of Remote Sensing for Glaciers, Snow and Ice

Various spaceborne sensors have been used for such studies including: Landsat (RBV, MSS, TM, ETM+), SPOT (PAN, XS), AVHRR, RESURS-01, declassified Argon (Corona programme), DMSP, Radarsat, ERS-1/2 (SAR, RA (radar altimeter)), J-ERS (SAR), SIR-C/X-SAR, QuikScat (radar, launched in 1999), Shuttle's SLA-1/2 (laser launched in 1996/97), Seasat and Geosat (altimeter), while recent sensors are slowly also used (Terra/ASTER, MODIS etc.). Airborne sensors include aerial imagery, laser especially from NASA (ATM, SLICER, profilers), SAR (Topsar), radar altimeter and ice penetrating radar. Planned missions of relevance include the ICESAT satellite with the GLAS laser (planned for 2001) and to a lesser extent the MBLA satellite with the VCL laser (planned for the near future).

The applications of these remote sensing studies were mapping (glacier detection, line maps, orthoimage-maps, mosaics, measurement of DSMs and discrete points, estimation of temperature, melting and transient snow line, classification of glacier zones and snow/ice classes), monitoring (hazards, changes of parameters such as tongue retreat, area, length, volume, velocity etc.) and mass balance determination.

Some of the milestones of the above remote sensing applications include:

(a) Use of Landsat for a glacier atlas, which is expected to be completed in 2001 (Williams and Ferrigno, 1999)
(b) ATM laser scanner flights over Greenland (NASA) and ice thinning studies since 1993 (see references below)
(c) Iceberg tracking (especially with ERS)
(d) Radarsat mosaic of Antarctica, with mapping performed in just 3+ weeks (second mapping expected to start in autumn 2000) (Choi, 1999; Jezek, 1999)
(e) Monitoring of various hazards

Other expected highlights are the use of SRTM SAR data to study glacier topography and motion, exploiting one-pass interferometry and multiple orbits over the same area, and exploitation of ASTER for global land ice monitoring (GLIMS project).

The importance of remote sensing is underlined by a concluding statement in a USGS sponsored international workshop on glaciers in 1996 („Satellite RS is the only feasible way of measuring/monitoring changes of global large glaciers but selected ground-based data are necessary for validation") and a conclusion of the WGMS monitoring strategy („Systematic application of advanced remote sensing and modelling techniques appears to be the main challenge for world-wide glacier monitoring in the 21st century"). More information on the use of remote sensing for ice and snow can be found in Hall and Martinec (1985) and Williams and Hall (1998). Below, some relevant references on the techniques used in this project (photogrammetry, laser scanning) but also on the use of spaceborne microwave and optical sensors for derivation of geometric information (DTMs/DSMs, motion) and studies for mass balance estimation are given. In general and regarding spaceborne sensors, use of microwave sensors is increasing due to their wider availability compared to the past, but mainly due to weather/cloud and illumination independence and also due to interferometric/ differential interferometric capabilities to measure surfaces and surface changes/motion, as well as the potential of radar regarding moisture content and snow/ice classification. Optical spaceborne sensors have been used more for mapping of glaciers and snow/ice/glacier classification based on reflectance properties.

Digital photogrammetry for glaciers, especially surface modelling, has been used for example by Etzelmüller *et al.* (1993), Wrobel and Schlüter (1997) who used object-based image matching for surface models in Antarctica and Bacher *et al.* (1999) using the DPW700 for surface modelling. Traditional photogrammetric techniques have been used since decades and surveying and mapping of glaciers has been performed already in the 19th century. Recent examples of traditional photogrammetric techniques are found in Fox and Nuttall (1997) for DTM generation, Wright and Dahl (1995) who used 35 mm or similar cameras over a theodolite for surveying mountain and polar glaciers and

[1] Volume changes can be transformed to mass using the density of snow (< 0.1 gr/cm^3), firn (about 0.4 gr/cm^3) and ice (about 0.9 gr/cm^3). Firn is snow which has survived one year.

Fox (1995) who used multiple input sources (including satellite images) to enhance and support mapping from aerial imagery in Antarctica.

Airborne laser altimetry has been used for glaciology since the early 90s. Extensive work has been performed by NASA in Greenland for DTM measurement (with an accuracy of 10-20 cm), ice velocity and thickness, surface roughness and mass balance estimation (Garvin and Williams, 1993; Krabill *et al.*, 1995, 2000; Thomas *et al.*, 2000; van der Veen *et al.*, 1998; Abdalati and Krabill, 1999). Other studies in Greenland include Bamber *et al.* (1998) who made a comparison between airborne laser and ERS-1 RA data and Ekholm (1996) who used airborne/spaceborne radar altimeter and airborne laser data, photogrammetry and scanned maps to generate a DTM of whole Greenland. Further studies of airborne laser scanning are given by Kennett and Eiken (1997) who achieved a height accuracy of 10-20 cm, Adalgeirsdótir *et al.* (1998) and Conway *et al.* (1999). Tests with laser profiling on glaciers has been performed for example by Echelmeyer *et al.* (1996) and Bindschadler *et al.* (1999) who compared it with airborne SAR (TOPSAR).

Rott et al. (1988) present a study on applicability of SAR for snow and glacier monitoring. Goldstein *et al.* (1993) used SAR interferometry to detect ice motion in Antarctica. Joughin *et al.* (1996) used SAR interferometry to measure ice sheet topography. Rignot *et al.* (1996) and Forster *et al.* (1999) used SIR-C's L-band and interferometry for glacier surface modelling and ice motion. Kelly *et al.* (1997) used ERS-1/2 data to monitor the transient snow line. Münzer *et al.* (1998) used ERS-1/2 and other remote sensing systems to monitor surface changes and subglacial volcanic eruptions. Mohr *et al.* (1998) measured glacier elevation and flow with interferometry. Wingham *et al.* (1998) used ERS-1/2 RA to determine elevation changes in the Antarctic. Dowdeswell *et al.* (1999) estimated velocity structure, flow instability and mass flux using radar interferometry. Joughin *et al.* (1999) have detected new ice streams in Antarctica by RADARSAT interferometry. Michel and Rignot (1999) compared phase correlation and interferometry for glacier flow estimation. Davis *et al.* (2000) used Seasat and Geosat radar altimetry for estimation of elevation changes in southern Greenland. Stenoien and Bentley (2000) combined ERS-1/2 interferometry and altimetry to study the catchment area of an Antarctic glacier by estimating DTM and motion. Smith *et al.* (2000) used SAR interferometry to estimate changes in erosion, deposition and volume, caused by outburst floods.

Li *et al.* (1998) measured glacier variations in Tibet using Landsat data. Bindschadler and Vornberger (2000) detected ice-sheet topography with AVHRR, RESURS-01, and Landsat TM imagery.

Investigations on remote sensing for mass balance estimation include for example Østrem (1975) using Landsat-1, Hall et al. (1989) using Landsat TM, Etzelmüller *et al.* (1993) using DSMs from digital photogrammetry and radio-echo soundings, Conway *et al.* (1999) using laser altimetry and maps from aerial imagery, Demuth and Pietroniro (1999) using RADARSAT and Engeset (1999) using ERS-1 SAR.

Aim of this work

The Glaciology groups of ETH and University of Zurich have previously used photogrammetry, among other for mass balance (Kääb and Funk, 1999; Guðmundsson and Bauder, 1999), surface displacement using analytical or digital photogrammetry and multitemporal monoplotting (Kääb, 1996), early hazard recognition (Kääb, 1996, 2000) and surface deformation of permafrost (Kääb *et al.*, 1997). Until recently, DSMs for mass balance estimation were derived manually by analytical photogrammetry using multi-temporal images in scale 1:10000-1:15000 flown in August or September. Thus, a project on "Mass Balance Determination of Glaciers with the Use of State-of-the-art Remote Sensing Methods and a Numerical Flow Model" was formulated and financed by the Swiss National Science Foundation. The here presented research is part of this project with aim to automate and speed-up the DSM generation process and improve the spatio-temporal density and accuracy of the measurements by using automated remote sensing techniques. Specific goals were:

(a) measurement of surface topography with an accuracy of about 0·5-1 m accuracy and a 10 m grid
(b) multitemporal tracking of discrete points (not realised due to project´s reduced funding)
(c) increase of automation and reliability
(d) use of a test area with many data (reference, multitemporal, glaciologic ground one)

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 snow/firn parts of the glacier, matching was expected to be problematic.

Spaceborne sensors were not appropriate at that time (insufficient accuracy, clouds for optical sensors). Airborne SAR was also excluded as there were (and still are) few such systems, their cost would be high, mountains create problems with shadows and layover and there was an uncertainty as to whether the results would be satisfactory. On the other hand, airborne laser altimetry (ALA) was a promising method for DSM generation of snow-covered areas as proven by previous investigations, especially from NASA, while the Geodesy and Geodynamics Group of ETH had experience with airborne laser profiling for marine geoid determination (Geiger *et al.*, 1994). In addition to that, through a co-operation with the Institute of Navigation, University of Stuttgart, their airborne laser system, having favourable spectral properties for high snow/ice reflectivity, could be used at no cost and mounted on an aircraft of the Swiss Federal Office of Topography that was also available gratis. Furthermore, ALA is independent of surface texture and external light sources, it was expected to give generally denser and more accurate measurements than photogrammetry for the given conditions, plus the cumbersome task of establishing and maintaining GCPs for photogrammetry is avoided, 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 parts were measured by the two methods, so that an optimal operational procedure for glacier monitoring could be chosen. Three flight campaigns, all with similar systems and aims took place in 1997, 1998 and 1999, from middle of August to beginning of September. In 1997, there were hardware problems with the time synchronisation and crosstalk between intensity and range data (both of which are registered by the given laser system) leading to Moiré effects and thus this data will not be treated further (Favey *et al.*, 1999b). The 1998 data were acceptable and their processing will be presented here. The time difference between the laser and imagery flights was two weeks, with no snowfall in between. Simultaneous acquisition of laser and image data was not possible because each system requires different flying height, which could not be realised due to cloud coverage change. In addition, very strong winds and sudden wind direction changes have influenced the laser scanner performance and resulted in very undulating laser strips. The 1999 data has not been analysed as detailed as the 1998 one. First results show that the DSM change from 1998 to 1999 is similar for both measurement techniques (laser and digital image matching).

TEST REGION, USED SYSTEMS AND AVAILABLE DATASETS

Test Region

The glacier used in these investigations was the Unteraar and in particular its tributary Lauteraar (see Fig. 1). Unteraar has a length of 12·4 km (1998) and an area of 29·5 km^2 (1973), ranking 4th on these parameters among the Swiss glaciers. Its length decrease since 1850 is 2·1 km and the last period: 27·6m (95/96), 30·8 m (96/97) and 94 m (97/98). In the 95/96 period, there was a volume loss of 24·5 million m^3, a mass loss of 21·7 million m^3, a mean surface lowering of 1·8 m and a slight increase of surface velocities. Its thickness change in 1924-1997 was - 80 m. It is one of the best investigated in the Alps, with first observations in 1830 and the first topographic map of a glacier with scientific value generated by J. Wild in 1847 (1:10000, no contours). Since 1924, surveying of the tongue, as well as velocity and thickness changes in selected profiles have been performed. Since 1969, aerial images have been taken every year. Since the early 90s, DSMs have been measured and spatio-temporal height and volume changes have been estimated. Since 1997, the DSM measurements became denser, and since 1996 orthoimages and mosaics have been generated. Geophysical methods (seismic, direct current geo-electricity, radar echo depth sounding) have been used to determine topography and characteristics of the glacier bed. Study of the flow (motion measurements on surface using GPS and photogrammetry), borehole measurements up to the glacier bed (200-300 m below surface) together with surface and bed topography have been used as input in numerical flow models. Mass balance measurements using the glaciologic method have also been performed.

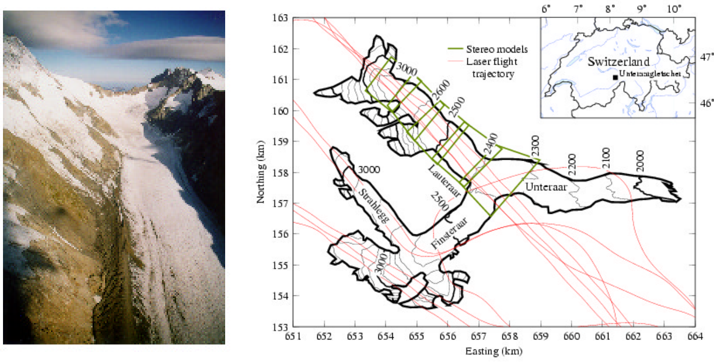

FIG. 1. Left photograph of Lauteraar glacier and right map of Unteraar glacier and its tributaries Lauteraar, Strahlegg and Finsteraar showing the location of the test site. The laser scanning flight trajectory, as well as the approximate boundaries of the stereo models are drawn in red and olive, respectively. The stereo models shown are labelled in the following text from north-west to south-east as 0099, 9997, 9795, 9593, 9392. The contour interval is 100 m.

Used Systems

The aircraft used for the laser as well as the photogrammetric flights was a De Havilland Twin Otter of the Swiss Federal Office of Topography, equipped with GPS and IMU (Inertial Measurement Unit). The flight lines for the laser and the image stereopairs are shown in Fig. 1. For the laser, three overlapping lines were flown over the Lauteraar glacier.

The laser employed was the ScaLars II of the Institute of Navigation, University of Stuttgart (Hug, 1996). The characteristics of this semiconductor laser diode transmitter are given in Table I. The laser unit uses the multi-frequency CW (continuous wave) ranging method (for more details on pulse versus CW laser and a general introduction to airborne laser scanning see Wehr and Lohr, 1999). The low frequency is used to solve ambiguities of less than 150 m range, while the high frequency provides high measurement accuracy. When sudden terrain discontinuities exceed 150 m, gross errors can and did occur, although there are methods (similar to phase unwrapping in interferometric SAR processing or by easy manual editing) to correct for these. The swath width for the 1998 flight was about 290-530 m at 600-1100 m height above ground.

TABLE I. Technical specifications of ScaLars II (hg ...flying height over ground)

Modulation CW-sinusoidal 1 MHz, 150 m range ambiguity 10 MHz, 15 m range ambiguity	Scanning angles in flight +/- 9.7 ^{o} across flight +/- 13.6 ^{o}
Wavelength 810 nm good reflectivity (ρ) for ice and snow	Scan pattern ca. elliptical (Palmer scan), nutating mirror
Measures ground reflectivity (intensity images)	Point spacing ca. 2 m
Range (for ρ = 20%) 750 m	Swath width 340 m for 700 m hg
Measurement rate 7.5 KHz	Range resolution 0.1 cm
Scan rate = 20 Hz, variable	Range accuracy 0.1 m (1 sigma) for ρ = 30%
Beam divergence 2 mrad	Elevation accuracy < 20 cm, open area, 700 m hg
Footprint ca. 1.4 m for 700 m hg	Horizontal accuracy 1 m , open area, 700 m hg

GPS measurements for positioning were acquired at a rate of 2 Hz using two double frequency Trimble 4000 SSI receivers measuring code and phase, 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. One Leica GPS receiver on the aircraft was used for navigation. Additionally, a GPS antenna array of four Novatel single frequency receivers measuring code and phase at 4 Hz 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 latter four receivers are not necessary for airborne sensor positioning but were used within the frame of investigations to show that an array of cheap single frequency receivers together with a cheap, not highly accurate IMU can lead to similar accuracies, as a combination of double frequency GPS and an expensive accurate IMU, at lower cost.

For attitude determination, the DIS-FP strapdown IMU with three fibre-optic gyros of iMAR GmbH, Germany (IMAR, 2000) was used. It had a resolution of 0.001 ^{o}/s, 0.001 ^{o} and 0.05 mg (for rotation rates, attitude and heading and acceleration, respectively), a sampling rate of 100 Hz, a gyro bias stability of < 3 ^{o}/h, and a linearity error of < 0.05 per cent (rate and acceleration). ScaLars II was at a later stage equipped with a more accurate Applanix DG 310 IMU, which was not available for our test flights due to Canadian Government export restrictions.

The different offsets and misalignments between GPS, INS and laser were geodetically measured on the ground before the flight. First tests of the laser system with the given laser/GPS/IMU configuration over a runway using ground GPS reference data showed height differences between laser and GPS with a bias of 2 dm and a RMS of 1-2 dm (Favey *et al.*, 1999a). Other investigations (Favey *et al.*, 1999b) showed that systematic offsets of the gyro system (partially caused by misalignment with the aircraft and laser frame) for the pitch and roll were close to 1 ^{o}. Thus, calibration flights over a runway were used also before the 1998 laser flight.

For DSM generation with image matching, three digital photogrammetric systems were compared, using in some cases multiple matching strategies and error post-processing: INPHO/Match-T (also used in Z/I Imaging and DAT/EM digital photogrammetric systems) on SGI (Version 2.2.1), LHS DPW770 on Windows NT (Versions SocetSet 4.2.1 and ORIMA 1.0), and VirtuoZo on Windows NT (Version 3.0). A SGI version of VirtuoZo was also tried but could not work with the 14 μm images; it seems that the system has an internal image size limit corresponding to a minimum scan pixel size of about 25 μm.

Aerial Imagery and Initial Processing

Image Characteristics. The six B/W images, forming a strip and covering the Lauteraar glacier, were acquired with a RC 30 camera with a focal length of 152 mm and an average scale of 1:13000. The overlap was about 60 per cent for the three inner models and 80 per cent for the two outer ones (0099 and 9392). The images were scanned with 14 μm at a Zeiss SCAI. The expected height accuracy based on the assumption of 1 pixel mean error for matching was 0·3 m and 0·6 m for the inner and outer models, respectively. Table II shows the characteristics of the terrain, with large height range and steep slopes for most models. Models 0099 and 9997 were at the upper glacier part where more textureless snow and firn areas exist.

Image Orientation. The control and tie points were measured with ORIMA at the DPW770 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. Since ORIMA was always changing the given camera constant and principal point (apparently due to use of additional parameters which could not be switched off), the bundle adjustment was finally performed with an own programme. The a posteriori standard deviation of the adjustment was 5 µm, and as expected the residuals were higher at the border models (especially 9392, which had the smallest image scale). The image co-ordinates 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 have a more objective comparison for the DSMs, the image orientation was imported and used in all digital photogrammetric systems except VirtuoZo (at this stage we had not figured out how to perform this; thus, a separate orientation was performed which, however, led to similar results as the ones from the bundle adjustment). Import of orientation is in most systems cumbersome, often with inconsistencies between menu-input and project-file orientation data and insufficient to no documentation.

Image Preprocessing. The images were pre-processed with a Wallis filter (Baltsavias, 1991) for radiometric equalisation of the images and especially contrast enhancement which helps matching, particularly for feature-based methods as Match-T. Contrast enhancement was necessary especially for the quite homogeneous snow and ice areas and the shadowed steep cliffs (see Fig. 2). A first visual test with DPW770 showed that the Wallis-filtered images were better than the original ones, so they were used with all three digital photogrammetric systems.

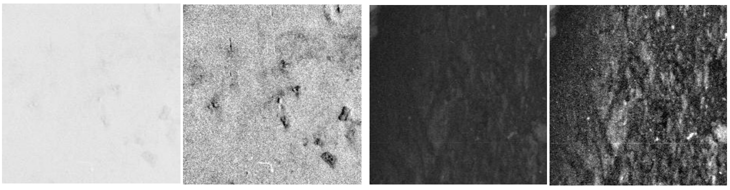

FIG. 2. Left image pair: snow area, right image pair: shadowed cliff. In each image pair left the original, right after Wallis filtering. The original image of the shadowed cliff has been stretched since originally it was appearing totally black.

TABLE II. Some data about the reference dataset.

Stereopair or dataset[a]	*Mean ÑZ*[b] *[°]*	*Max ÑZ*[b] *[°]*	*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

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

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

Acquisition of Reference DSM Data

To check the accuracy of matching, a reference dataset (see Table II) 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.

RESULTS OF IMAGE MATCHING AND QUALITY EVALUATION

Matching Parameters and Versions for each System

For reasons of objectivity, apart from using the same exterior orientation, 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 in many cases not possible. With DPW770 a North-East oriented DTM grid with 10 m spacing was defined. The system does not allow rotation of the grid so that it could be aligned with the manual measurements in nearly-rectangular NW/SE oriented 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 IV) were very similar). However, with Match-T the raw measurements from which a regular grid is interpolated through robust filtering are very dense (for example 2·07 million raw points for 75000 grid nodes). In a second version of Match-T, an adaptive grid strategy with densification factor 1 was used; the grid spacing was adapted automatically to 5 m in steep areas and 20 m in flat areas, while at the rest it remained 10 m. VirtuoZo uses an image grid. We tried to use a spacing of 55 pixels, corresponding to about 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 divided the overlap area in 9 blocks (horizontal strips) covering the overlap area from top to bottom). It seems that VirtuoZo needs an image grid pixel spacing that is similar to the patch size used for matching (15x15 pixels, corresponding to about 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.

In all cases, we tried to optimise the matching strategy and parameters involved. Table III presents a short summary of the main matching parameters. With the DPW770 version 1, each model was run separately with a so-called steep_plus strategy which we optimised. In version 2 we used an adaptive matching, with the same strategy. Adaptive matching can use more than two images, can generate regular grids or triangulated irregular networks (TINs), changes some of the strategy parameters based on an “inference” engine, and computes the mean terrain inclination in small neighbourhoods. Based on this inclination and image exterior orientation (this is our assumption; no documentation on AATE (Adaptive Automatic Terrain Extraction) exists), 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 (visually controlled) in steep cliffs as problems due to occlusions and large perspective differences can be reduced by appropriate stereopair choice. The higher number of points with the first version (see Table IV) is due to the double measurements in the overlap region of the models. DPW770 computes for each point a quality criterion (called Figure Of Merit, FOM). In the so-called cleaned version, points having a FOM less than 33 (presumably errors, according to the system) were eliminated. The percentage of points with poor FOM for the two matching versions were 45.5 per cent and 14·6 per cent with the main failure reasons being low correlation curvature (33·3 per cent / 8·3 per cent) and low correlation coefficient (10·1 per cent / 3·6 per cent), obviously mostly at areas with homogeneous texture for the first failure reason and wrong matching/occlusions/unmodelled perspective differences for the second one.

TABLE III. Important image matching parameters for automatic DSM generation.

	VirtuoZo	*Match-T / Version 1*	*DPW Versions 1/2*	*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 about 2 m
# of pyramid levels, incl. original image	4	9	6	NA
Selection of match points / point spacing (m)	Regular image grid / about 2·7	Regular object grid, rotated / 10	Regular object grid / 10	Irregular points / about 2
Matching strategy	rugged	mountainous	Modified steep_plus, Adaptive (version 2)	NA

With Match-T, an additional version with an adaptive matching strategy (which should increase the number of matched points in poorly textured areas at increased computational cost ; not to be confused with the adaptive grid strategy) led to almost no change (only about 100 points got different values) and will not be treated in the sequel. In another Match-T test, increasing the surface smoothing weights[2] from 1·5 to 3·5 led to total flattening of the cliffs, although this value should actually lead to only medium smoothing. 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] These weights vary from 1 to 10 in Match-T with values of 1·5, 3 and 5 for low, medium and high smoothing, respectively.

TABLE IV. Error statistics of automatically generated DTMs minus reference data for the whole area (DTM), glacier (GLAC), mountain cliffs (CLIF) and breaklines (BRKLIN).

System Version	*Test data / # of points*	*Reference data / # of comparison points*	*RMS [m]*	*Mean with sign [m]*	*Max abs. [m]*	*% blunders*[a]
VirtuoZo	Original 2,292,348	DTM / 4160	3·15	-0·14	78·28	13·73
		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-polated regular grid 153,503	DTM / 4158	5·25	-0·19	135·24	14·29
		CLIF / 1404	8·98	-0·79	135·24	28·42
		GLAC / 2754	0·74	0·11	26·04	7·08
		BRKLIN / 584	3·01	-0·12	30·94	51·20
Match-T version 2 (adaptive grid 5, 10, 20 m spacing)	Original 351,283	DTM / 4091	3·40	0·08	76·87	13·62
		CLIF / 1395	5·74	0·19	76·87	31·54
		GLAC / 2696	0·72	0·02	26·25	4·34
		BRKLIN / 549	9·27	-1·90	71·51	39·34
	10 m inter-polated regular grid 95,174	DTM / 4091	3·40	0·07	76·87	13·71
		CLIF / 1395	5·74	0·18	76·87	31·83
		GLAC / 2696	0·73	0·02	26·25	4·34
		BRKLIN / 549	9·35	-1·82	71·57	60·47
Match-T version 1 (10 m spacing)	Original 112,000	DTM / 4089	14·94	-2·30	215·82	21·99
		CLIF / 1396	25·54	-6·80	215·82	50·21
		GLAC / 2693	0·83	0·03	24·8	7·35
		BRKLIN / 549	30·68	-6·97	232·91	64·66
DPW version 2 (all images matched together)	Original 87,454	DTM / 3848	7·11	-0·66	102·55	16·42
		CLIF / 1189	12·72	-1·98	102·55	39·95
		GLAC / 2659	0·93	-0·06	26·32	5·90
		BRKLIN / 535	11·52	-2·21	84·62	45·61
	Cleaned[b] 76,021	DTM / 3285	5·02	-0·41	96·10	9·56
		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 version 1 (matching per model)	Original 114,874	DTM / 4195	7·72	0·42	158·13	22·31
		CLIF / 1456	12·17	0·94	158·13	46·09
		GLAC / 2739	3·55	0·14	136·20	9·68
		BRKLIN / 565	12·01	-0·08	123·82	67·96
	Cleaned[b] 62,605	DTM / 3637	1·37	0·03	26·68	10·5
		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 2,512,314	DTM / 1784	1·89	0·47	13·83	23·71
		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

[a] 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 about 0·3 m for the three inner models (60 per cent overlap) and about 0·6 m for the two outer ones (80 per cent overlap).

[b] Cleaned means without possible blunders with a FOM less than 33.

Comparison with Reference Data

Overview of relative and absolute accuracy. The results are presented in Table IV and 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 large, and in all cases (except two inner models with VirtuoZo) larger than the differences of each individual model to the manual measurements. The large relative differences are partly due to the not optimal orientation (no strong block geometry in the bundle adjustment) but mainly due to matching differences caused by other viewing and ray intersection angles, possibly different texture, varying perspective distortions of the images, differences regarding occlusions etc. This fact stresses the importance of using more than two images, either by: (a) choosing a priori the two best ones for each point to be matched; or (b) a posteriori combination of heights in the overlap regions of neighbouring models and weighted averaging or choice of the best one, both based on quality criteria; or (c), even better, simultaneous matching of all available images.

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 original DPW770 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 (probably to a large extent due to Wallis filtering). The higher than expected RMS in the inner models is strongly influenced by large blunders which were visually detected, even if their number is low. Through elimination of these blunders, the expected accuracy could 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 (13x13 grid meshes), which is too coarse for fine linear discontinuities in a neighbourhood which is mainly planar. VirtuoZo (and DPW770 after "cleaning") performs the best and also adapts better to rough terrain. In all cases, the results for the breaklines were 3-38 times worse than those for the 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 better initial approximation of the terrain.

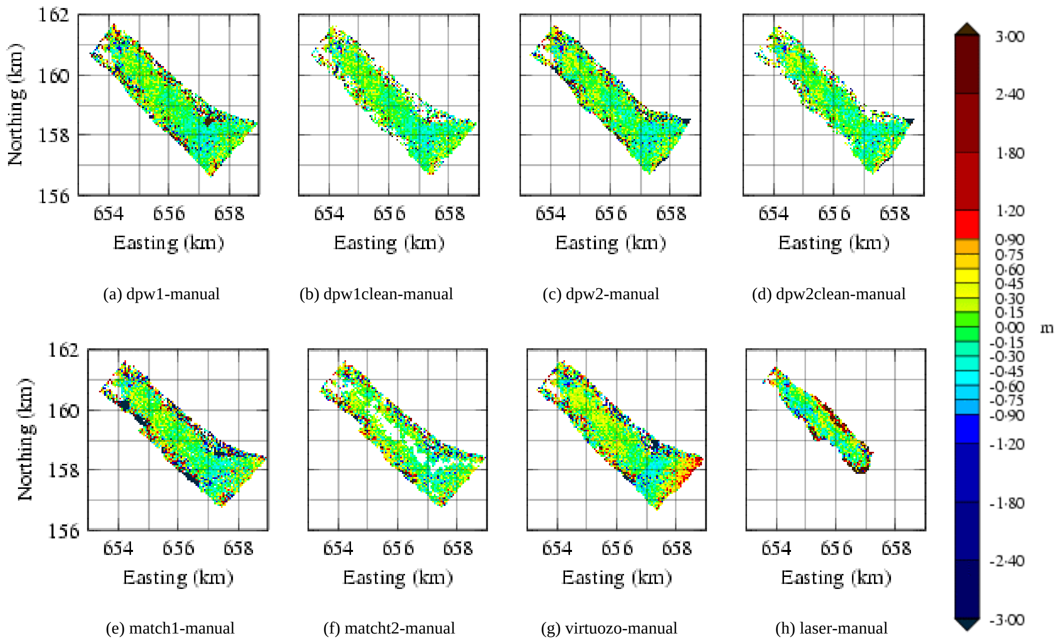

FIG. 3. Differences in [m] of respective automated DTM minus manual photogrammetric measurements. The gaps that occur in some plots only are because of the use of a maximum interpolation distance (when automatically measured points were further than this maximum distance away from a manual measurement, no height interpolation in the automatically generated DTM occurred; this happened in principle with the cleaned versions and version match2 (adaptive grid) where data gaps existed).

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). 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 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 post-processing tools are needed or, even better, sophisticated methods for automatic blunder detection. Both cleaned versions of DPW770 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 post-processing work it is preferable to manually measure points in such gaps (if they are not too large), 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 in cases where big blunders totally distort the error statistics, typically at cliffs and breaklines.

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, with VirtuoZo when matching fails, then errors can be very large (no gracious deterioration). The cleaned DPW770 versions are also good, with the exception of the cliffs of version 2, but at the cost of lower point density and gaps compared to VirtuoZo. For this type of variable rugged terrain, it is always better (as well as 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 two images is also beneficial, especially for rough terrain.

Conclusions for Individual Systems. With DPW770, although some visual comparisons in some steep cliffs showed that version 2 performs better, the global statistics of Table IV do not support this for the cliffs, especially for the cleaned versions. Version 2 was expected, based also on experience reports of Swiss photogrammetric firms, to perform better in mountainous areas and similarly or slightly worse (according to the previous reports) in flat areas. This contradiction can be due to poor algorithms in the choice of the best two images and also because the mean terrain inclination seems to be computed in a neighbourhood that is too large (25x25 grid meshes) for the rapidly varying Alpine terrain. Use of the AATE in other ETH projects has shown severe errors (total flattening of the terrain) at image borders when simultaneously using more than two images (similar problems are mentioned by Bacher *et al.*, 1999), but not so when using only two images. 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 DPW770, it is probably better to have independent measurements of the same region from two stereomodells, combine the results and then “clean” them, than trying to select the best two images, match only once and then “clean” the results. 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).

RESULTS OF LASER SCANNING

Preprocessing

The laser scanning data was pre-processed by the calibration technique described in Thiel and Wehr (1999) to estimate misalignment angles between the laser co-ordinate 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 (range should be smaller than 750 m; due to the small scanning angle, this threshold refers approximately to flying height too) to achieve reasonable results and obtain enough object reflection, flight planning in the mountainous steep terrain posed tough challenges, due to small swath width and very limited tolerances for flight plan deviations, which were made bigger due to the strong winds, leading in rare cases in small data gaps. For flying security reasons (steep mountains), and because the focus of applying the laser scanning technique was put on the upper areas of the glacier, flight lines lower than an altitude of 3400 m were avoided. 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 was expected to result in a high RMS. This holds for all data with flying height above ground more than about 750 m.

The laser flight trajectory was estimated with differential GPS using double frequency carrier phase measurements. Positioning and attitude measurements were estimated at 100 Hz and their accuracy is assumed to be about 0·05 m and better than 0·05°, respectively, based on previous investigations of the same laser/GPS/IMU flown over a runway with known terrain heights (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 cm accuracy (Marti, 1997) were applied. As the co-ordinates of the GCPs used for the photogrammetric measurements were known in the previous Swiss reference system only which has changed recently, local 3D translation parameters between the old and the new reference systems were estimated using static DGPS measurements on three control points in the glacier area.

The results of a comparison in the overlap region between neighbouring laser swaths is given in Table V. The two overlapping regions of adjacent laser swaths show a RMS of about 1·28 m. This is partially due to unmodelled errors in the attitude angles, which are expected to be less accurate than the results obtained over the runway due to strong winds during the glacier flight. As parts of the glacier contain many deep crevasses, maximum differences in the order of tens of meters are easily possible. Other sources of laser measurement errors, not only for the overlapping regions, include:

(a) Poor reflectivity of dark targets, e.g. debris. The recorded intensities can be used to identify possible problematic areas and derive quality criteria for the range measurements. Poor reflectivity results in a decrease of the signal to noise ratio, i.e. the phase measurement has a higher uncertainty. If the uncertainty in the phase measurement of the 150 m wavelength exceeds the 15 m wavelength of the higher laser frequency, this shorter wavelength is attributed a wrong ambiguity (wrong ambiguity fixes). The percentage of wrong ambiguity fixes of the shorter 15 m wavelength increases, the poorer the reflectivity is. In the regions of weak reflectivity (lower lying models 9392, 9593 and 9795), this percentage ranges from 10 per cent in general, up to 50 per cent at the debris-covered areas and the cliffs. A method to automatically detect and correct or remove wrong ambiguity fixes is under development.
(b) Large distance from target ; the received power is inversely proportional to the square of the range and measurements with an intensity value lower than a certain threshold should not be taken into account.
(c) Remaining errors in attitude determination, with increasing effect with the flying height over ground.
(d) Poor planimetric accuracy ; this is typical of laser systems and contrary to photogrammetry where planimetry is better than height estimation. Errors in planimetry translate increasingly into height errors with increasing surface slope, which was the case especially with the mountain cliffs.
(e) Wrong corrections due to refraction were applied, leading to an estimated range error of ca. 30 cm.

TABLE V. Statistics of differences of laser swath overlaps.

Version	*# of comparison points*	*RMS [m]*	*Mean with sign [m]*	*Max abs. [m]*
laser line west - laser line centre	187092	1·27	-0·36	32·09
laser line centre - laser line east	321778	1·29	0·13	68·93

Comparison of Laser Scanning with Photogrammetry

Comparison with Manual Photogrammetry. A comparison with manual photogrammetric measurements was made both on a per model basis, as well as for all points together (Table IV). The “dark” parts for the given laser wavelength (810 nm) pose problems to the laser scanning technique, as the reflection there is much weaker than on snow and ice. This is mainly the case at the cliff regions and the debris-covered parts of the glacier. In the region of model 9392, the laser technique reaches its limits with a range of over 1200 m (system performance is guaranteed by the system provider up to 750 m range, which is the case only in models 0099 and 9997) and almost no received signal, which results in an expectedly high RMS. On the higher lying models 0099 and 9997, where the range is around 600 m, the RMS of still more than 0·7 m is probably due to missing elimination/correction of wrong short-wavelength ambiguity fixes and to a minor extent due to the attitude measurement problems discussed above. Nevertheless, the project target of DTM accuracy of 0·5-1 m was achieved in this upper glacier region, for which the flying height was planned. Points on the glacier show only a slightly lower RMS than when including the cliff parts. This is because many blunders of the laser data are on the glacier parts covered with debris (see Fig. 3(h)), where only a weak S/N ratio could be obtained, plus range for glacier is longer than for the cliffs.

The mean values of the signed differences for single models show some sort of bias, which increases with the increasing flying height towards the south-east. This is due to the wrong refraction correction mentioned above and distorts also the statistics for the whole area with a “mean” bias.

Comparison with Digital Photogrammetry. Photogrammetry, as shown by the VirtuoZo example, can measure with equal or even higher density than laser. Flight time for imagery is shorter, flight planning is simpler, and sensitivity of the results to variations of the flying height over ground or wind conditions 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, needs more processing steps and specialised hardware (film development, scanner). Since photogrammetric film cameras are usually not equipped with INS, ground control points, which are difficult and costly to establish and maintain, especially in mountainous regions, are needed. Most of the previously mentioned disadvantages will however disappear with digital photogrammetric cameras that are expected to be produced serially from 2001, yet system calibration will then show similar complications and influences as with laser scanning, albeit with simpler imaging geometry (line or frame as compared to point one).

Based on Table IV, the laser 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 measurement error sources 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 range of 750 m. Where laser clearly beats photogrammetry is the size of the large errors. As Table IV shows, the maximum absolute error with laser is similar for all datasets and bounded (not exceeding 14 m). With photogrammetry 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 1:6500. A detailed more general comparison between photogrammetry and airborne laser scanning is given in Baltsavias (1999).

CONCLUSIONS

The project target of achieving DTM accuracy of 0·5-1 m for the glacier was achieved by all, except one, image matching versions. Thus, a possibility to employ digital photogrammetry for measuring surfaces was proven to be possible even in glacier regions with very little texture. However, big blunders remain in the results making necessary development of reliable automatic blunder detection algorithms or manual post-processing. Matching performance in rugged, steep terrain and at breaklines is much less accurate than on the glacier 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. Of the three tested digital photogrammetric systems, DPW770 provides the best tools for pre- and post-editing.

No significant improvements in matching have been achieved the last period. Commercial systems still have several serious weak points and need improvement regarding adaptivity of matching parameters (patch size, pyramid levels, raw point density, etc.), adaptation based on surface roughness/discontinuities and image texture, intelligent reduction/interpolation of raw dense points, simultaneous use of more than two images, better documentation and more openness.

Out of the three photogrammetric systems, the best concerning accuracy, speed, price (at least in this 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 rather limited.

In this test, airborne laser scanning performs as well as digital photogrammetry as long as the flying height above ground does not exceed the system's range limit of 750 m. It performs well on textureless snow and ice areas, but blunders are likely in poor reflectivity regions (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 upper snow/firn areas, which may not be measurable by photogrammetric means either because of total lack of texture or because of no natural objects suited for GCPs. It should be noted though that a part of the laser “errors” is due to the different orientation used for laser and manual photogrammetric measurements, while manual and automated photogrammetric measurements used the same orientation. With improvements in attitude determination and calibration, the laser may be able to reach the expected accuracy of 10-20 cm.

These accuracy tests should be treated with some caution. The reference data also had substantial errors and were definitely not much more accurate than the other measurements (ideally, reference data should be an order of magnitude more accurate than the tested measurements). Furthermore, while laser and matching (at least the area-based methods) essentially measure height within an area (1.4 m laser footprint, 2·7 m x 2·7 m patch) giving an average height for a surface that can have substantial roughness (as often observed at glaciers), manual observations measure height at a much smaller region, leading thus to local non-averaged results.

Aerial imagery and airborne laser scanners partly compete but also complement each other. Both are expected to improve in the near 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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Zusammenfassung

Diese Forschungsarbeit ist Teil eines schweizerischen Nationalfonds Projektes „Massenbilanzbestimmung von Gletschern durch Fernerkundungsmethoden und einem numerischen Fliessmodell.“ Fernerkundung beinhaltet das automatische Prozessieren von Luftbildern und Laserscanning mit dem Ziel, Gletscher-Oberflächenmodelle mit einer Genauigkeit von ca. 0.5–1 m in Zeitabständen von 1-5 Jahren zu produzieren. Der Unteraargletscher in der Schweiz wurde zum Testen beider Methoden ausgewählt, da er von Glaziologen schon als Ort intensiver Studien verwendet wurde. Die Ergebnisse von Laserscanning und digitaler Photogrammetrie wurden mit Hilfe von genauen, manuellen Messungen an einem analytischen Plotter evaluiert. In bezug auf die Laserdatenprozessierung werden verschiedene Aspekte beleuchtet: Systembeschreibung, Bestimmung von Position und Lage, Transformation in das schweizerische Projektionssystem, Übereinstimmung von sich überlappenden Laserstreifen, sowie andere aufgetretene Probleme. Drei digitale photogrammetrische Systeme (Match-T, LHS DPW 770 und VirtuoZo) wurden zur Oberflächenmodellgenerierung mittels Bildzuordnung benutzt. Es werden die unterschiedlichen Zuordnungsalgorithmen und -strategien, aufgetretene Zuordnungsprobleme aufgrund von schwacher Textur, von Schattenwurf, oder von steilen Hängen, sowie eine quantitative und qualitative Evaluation der Ergebnisse besprochen. Ebenfalls wird ein Vergleich zwischen Photogrammetrie und Laserscanning bezüglich Genauigkeit und Punktdichte präsentiert.

Résumé

Ce travail de recherche a été initié dans le cadre d'un projet du Fonds National Suisse de la Recherche Scientifique, concernant «la détermination de la masse des glaciers par utilisation de la télédétection et d'un modèle numérique de flux». L'étude des glaciers par la télédétection suppose le traitement conjoint des informations issues d'images aériennes et celles fournies par un altimètre laser. Le but est d'en déduire des modèles de la topographie des glaciers avec une précision compris entre 0.5 et 1 mètre, et ce sur des périodes de temps de 1 à 5 ans. C'est le glacier Unteraar, situé en Suisse, qui a été choisi pour tester les deux méthodes, car déjà largement étudié par les glaciologues. La précision des résultats de l'altimétrie laser et de la photogrammétrie numérique, a été estimée par comparison avec des mesures classiques réputées de très bonne qualité. En ce qui concerne le traitement des données de l'altimètre laser, différents aspects, tels que le fonctionnement de l'instrument, la détermination de la position et l'attitude de l'avion, la réduction des données dans le système cartographique Suisse, ainsi que l'estimation de la qualité des mesures grâce aux zones de chevauchement des bandes du laser, sont abordés et commentés. Au total, 3 systèmes numériques de photogrammétrie (Match-T, LHS DPW 770 et VirtuoZo) ont été utilisés pour générer des modèles de surfaces. Les différents algorithmes et stratégies, utilisés pour résoudre les problèmes de manque de contraste, de zones d'ombre, des pentes abruptes etc. sont également présentés, ainsi qu'une évaluation quantitative et qualitative de leurs résultats. Ce travail s'achève par une comparison de la photogrammétrie et de l'altimétrie laser du point de vue de leur précision et de la densité de points de mesure qu'elles permettent.