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KoordinatorIn/ ProjekteinreicherIn:	Institut für Geographie, Universität Innsbruck Prof. Dr. Johann Stötter
Kontaktperson Name:	Dr. Rudolf Sailer
Kontaktperson Adresse:	Institut für Geographie, Innrain 52, A-6020 Innsbruck
Kontaktperson Telefon:	+42 512 507 5419
Kontaktperson E-Mail:	Rudolf.Sailer@uibk.ac.at
Projekt- und KooperationspartnerIn (inkl. Bundesland):	 P1 – Institut für Geologie und Paleontologie, Universität Innsbruck P2 - Institut für Photogrammetrie und Fernerkundung, TU Wien P3 - Institut für Meteorologie und Geophysik, Universität Innsbruck
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Project overview

Summary in German

Gebirgsräume und insbesondere die Kryosphärenelemente Gletscher und Permafrost reagieren besonders sensibel auf Änderungen des Klimasystems. Die in Folge der zunehmenden Erwärmung schrumpfenden Wasserspeicher der Kryosphäre resultieren in drastischen Veränderungen der Abflussregime sowie der Abflussmenge in den Gebirgsflüsse, aber vor allem auch in den angrenzenden Vorländern. Darüber hinaus wirkt das Abschmelzen der Gletscher und das Auftauen und Ausschmelzen des Permafrosts vorübergehend destabilisierend auf Lockermaterialköper bzw. Festgestein und führt somit zu einer erhöhten Gefährdung der vorwiegend in den Tälern liegenden Lebensräume. Während die offensichtlich wahrnehmbare Reaktion von Gletschern auf Klimaänderungen bereits gut erforscht ist, fehlen für den österreichischen Alpenraum detaillierte Aussagen zur Wechselbeziehung zwischen Klimaänderungen und die darauf folgende Reaktion des Permafrosts. Aus diesem Grund hat sich das Projekt C4AUSTRIA zum Ziel gesetzt, Airborne Laserscanning (ALS) basierte Methoden und Workflows zum Monitoring und zur Analyse von Oberflächenänderungen in Gletscher-, Toteisoder Permafrostgebieten zu entwickeln, anzupassen oder auch zu erweitern. Die im Projekt erfolgreich durchgeführte radiometrische Kalibrierung von gepulsten sowie sogenannten full-waveform Intensitätsdaten dient als Basis für eine ALS-basierte Klassifizierung von Oberflächen in Kryosphärengebieten der Alpen, die als Basis für weiterführende Modellrechnungen anzusehen sind. Noch bevor die Geometriedaten (ALS Punktdaten mit x,y,z-Koordinaten) für die Quantifizierung von Topographieveränderungen herangezogen wurden, erfolgte in C4AUSTRIA ein eingehende Qualitätsprüfung der ALS Daten. Die Qualtitätschecks bestätigten die positiven Erfahrungen aus vorangehenden Studien, so dass die im Projekt gewonnenen und nachfolgend dargestellten Ergebnisse als vertrauenswürdig anzusehen sind. Die Ergebnisse beziehen sich zum einen auf vertikale Höhenänderungen bzw. Volumenänderungen von Gletschern (inklusive Toteis) und Permafrostkörpern, zum anderen auf Oberflächengeschwindigkeiten von Blockgletschern. Massenbilanz Vergleichsmessungen mit Airborne Laserscanningdaten am Hintereisferner reichen zurück bis ins Jahr 2001. Mit den aktuellen Messungen in C4AUSTRIA konnten der weltweit einzigartige Datensatz erweitert und dabei entscheidende Fortschritte bei der Detektion und dem Ausschluss von methodenbedingten Fehlern erzielt werden. So weicht beispielsweise die kumulative ALS basierte Gesamtmassenbilanz des Hintereisferners von 2006 bis 2009 mit einem Wert von -28.62*10⁶ m³ nur geringfügig von der glaziologisch direkt ermittelten Bilanzsumme (-29.95*10⁶ m³) ab. Gute Ergebnisse konnten auch bei der Ermittlung der Oberflächengeschwindigkeiten von Blockgletschern erzielt werden. Die auf Basis von ALS Daten abgeleiteten Geschwindigkeitswerte liegen sehr nahe an den Werten, die aus differentiellen GPS (dGPS) Messungen ermittelt wurden. Die Differenzen bewegen sich im Rahmen von -0.12 m bis 0.06 m. Neben den Untersuchungen von Gletschern und Permafrostkörpern (Blockgletscher und flächenhafter Permafrost) konnten in C4AUSTRIA detaillierte Analysen von gravitativen und fluvialen Prozessfolgen im Periglazialbereich in einzigartiger Detailgenauigkeit über große Flächen durchgeführt werden. Im Projekt C4AUSTRIA wurden Versuche unternommen, den Klimaeinfluss auf Blockgletscheraktivitäten zu untersuchen. Zu diesem Zweck wurden bis in die 1950er Jahre reichende Luftbildeaufnahmen in die Analysen einbezogen. Die Auswertungen lassen den Schluss zu, dass erhöhte Blockgletscheraktivitäten (ausgedrückt durch hohe Bewegungsraten) mit einem Anstieg der Jahresmitteltemperatur korrelieren. Detaillierte Analysen, beispielsweise bezogen auf die Reaktionszeit von Permafrost im allgemeinen und Blockgletschern im speziellen auf Klimaänderungen, erfordern jedoch ein längerfristiges Monitoring (jährliche Messungen über einen Zeitraum von fünf bis zehn Jahren).

Zusammenfassend kann festgehalten werden, dass sich Airborne Laserscanning aufgrund der erreichten Präzision und hohen räumlichen Auflösung sehr gut dazu eignet, Oberflächenveränderungen im Hochgebirge zu detektieren, zu quantifizieren und zu analysieren. Die entsprechenden Methoden wurden im Projekt C4AUSTRIA entwickelt und in großem Umfang erfolgreich getestet. Für Prozesse, die hohe jährliche Änderungen nach sich ziehen, ist der zeitliche Abstand zwischen den ALS Befliegungen von untergeordneter Rolle. Je kleiner jedoch die zu erwartenden Veränderungsraten sind, desto länger sollte der zeitliche Abstand zwischen den ALS Aufnahmen und/oder die Anzahl der Einzelmessungen sein. Dies gilt insbesondere für die Erfassung von Degradationserscheinungen in Permafrostgebieten.



1 Executive Summary

Glaciers and permafrost, both significant elements of the mountain cryosphere, are highly sensitive to climate change. While there is comprehensive knowledge about the link between climate and the immediate and clearly visible glacier dynamics, little is known about permafrost distribution and the effects of climate change on permafrost thaw in the Austrian Alps. To receive more detailed information about the permafrost distribution, several methods, including in-situ investigations, air- and space borne remote sensing as well as modelling approaches haven been carried out at different spatial and temporal scales within the last decade by different research groups. Over the years, LiDAR (Light Detection And Ranging) in general, and airborne laser scanning (ALS) in particular, have become a very valuable data sources for geomorphologic research studies. Regarding cryospheric research activities, several projects already applied ALS for glaciological investigations. Despite the glaciologic applications, the potential of multi-temporal ALS for the monitoring of permafrost phenomena, e.g. rockglaciers and ice-rich debris areas outside rockglaciers has not been evaluated yet. However, due to the high accuracy and precision of ALS, it is expected that multi-temporal ALS data will provide new possibilities to map permafrost areas (e.g. rockglaciers and ice-rich debris) and to quantify changes in the spatial distribution of permafrost caused by climate change. Regarding the fact, that at least bi-temporal area-wide ALS data of alpine areas will become more and more available in the near future, it is important to develop, apply and validate methods for an area-wide permafrost monitoring (e.g. surface classifications based on calibrated LiDAR intensity values, to determine the full information contained in LiDAR full-wave form data, and to determine melt and creep rates of rockglacier and glaciers), but also for glacier and dead-ice research, based on ALS data. The scientific community mainly agrees, that degradation of alpine permafrost and melting of glaciers can lead to an enhanced occurrence of rapid mass movements, e.g. rock falls and debris flows. Such mass movements cause a potential threat to infrastructure (e.g. mountain huts, skiing infrastructure, water reservoirs and hiking trails) and people in alpine areas. Thus, climate warming scenarios and following permafrost degradation and glacier melt in alpine areas will have socio-economic consequences. It is therefore important, to develop and validate methods for an area-wide long-term permafrost and glacier monitoring.

The main objective of C4AUSTRIA is the development of methods for the spatial monitoring and analysis of permafrost, dead ice and glacier changes as a result of climate change and is divided in five sub-objectives: 1. universal radiometric calibration of LiDAR intensities (wavelength of 1064 nm), 2. development of methodologies for the quantification of surface changes caused by permafrost and glacier activities based on LiDAR measurements, 3. extension of Hintereisferner LiDAR data record and subsequent multi-temporal analysis of permafrost, glacial and periglacial features, 4. assessing and expressing uncertainties in context of LiDAR measurements of permafrost, glacial and periglacial features and 5. analysis of the quantified topographical changes regarding climate interactions with permafrost (in general), rockglacier (in particular) and glacial features.

To reach the project objectives a workflow for the radiometric calibration of LiDAR intensities and the fullwaveform LiDAR processing were developed and adapted to the available datasets. For that purpose radiometric measurements (1064 nm laser device) were carried out in the field. The calibrated ALS intensity values are used for the classification of surface types in selected areas for permafrost modelling purposes for example. Prior to the quantification of topographical changes a sincere assessment of LiDAR uncertainties and uncertainties of subsequent LiDAR products were carried out in C4AUSTRIA. Based on the according promising results (including previous work of pre-projects) it can be stated that surface changes (vertical and/or horizontal displacements) on glaciers as well as rockglaciers can be detected with a high degree of accuracy. For that purpose point and raster based analysing tools were adapted and improved by the project consortium. Important progress was made for the calculation of surface velocities on rockglaciers based on multi-temporal Airborne Laserscanning data. For example, for the Hochebenkar rockglacier, one of the most famous rockglaciers in the Eastern Alps, area-averaged displacement rates of 0.85 ma⁻¹ were determined for the period from 2003 to 2009. The developed methods for the determination of rockglacier creep rates were successfully applied to the Innere Hochebenkar rockglacier, leading to area-averaged surface velocities this rockglacier of



0.58 ma⁻¹. Both values are good in agreement with in-situ observations. Thus, the transfer of the developed workflow to yet unmeasured rockglaciers was successful. The workflow was furthermore tested by incorporating an additional ALS data set from 2010 (alpS Centre for Climate Change Adaptation Technologies, MUSICALS Project). This allowed the calculation of creep and melt rates of 338 rockglaciers in the Ötztal Alps between 2006 and 2010. The achieved results provide a promising basis to determine the activity of rockglaciers based on bi-temporal ALS data and thus, to provide a reproducible standard method for an area-wide rockglacier monitoring. By incorporating photometrical analysis, creep rates of the rockglaciers (Hochebenkar, Reichenkar, Schrankar and Ölgrube) were calculated in different epochs between 1953 and 2009. Creep rates, respectively their temporal changes, were correlated to climatic changes. In summary, the calculated surface velocity rates correspond with the mean annual air temperatures. Temperature increase is assumed to lead to an increased rockglacier dynamic.

As planned, the 'Hintereisferner ALS data series' could be extended, contributing to the world-wide unique ALS data set of the high alpine, glacierised catchment of Hintereisferner, one of the largest glaciers in the Eastern Alps. Results on the comparison between the mass balance values derived from direct glaciological and the ALS-based method on an annual, as well as on a multi-annual scale, have already been published and show the value of a combined analysis of ALS and in-situ mass balance data. The cumulative total net balance between 2006 and 2009 derived from the direct glaciological method is -29.95 * 10⁶ m³ w.e., whereas the ALS based total net mass balance (volume change between 2006 and 2009 multiplied by an ice density of 0.9 g/cm³) is -28.62 * 10⁶ m³ water equivalent. As has to be expected, the two methods differ more significantly when investigating individual elevation bands due to the effect of ice dynamics (emergence and submergence) but also internal and basal melt.

Laserscanning and in particular Airborne Laserscanning do have the capability for an accurate, area-wide and reliable monitoring (quantification of process results as well as intensity based classification of surface characteristic) of elements of the Alpine cryosphere. Beside the wavelength (recommended wavelength between 900 and 1100 nm) the process dependent time span between the data acquisitions has to be kept in mind. Small process related rates of change, as observed for permafrost degradation processes (vertical displacement), suffer either longer time spans (> five years) and/or higher repetition rates (at least on measurement campaign per year). In contrast, for processes with expected large rates of change significant conclusions are to be expected using an ALS acquisition time lapse of one year or less. Whereas glaciers obviously react immediately on climatic changes a comparable behaviour can only be assumed for rockglaciers, although C4AUSTRIA findings prompt this conclusion. The (at the moment) available remote sensing and/or insitu rockglacier data do not allow the reconstruction of a continuous and long time series with a sufficient time resolution (at least annual data needed). A sincere statement on the response time of active rockglaciers on climate impacts will have to be based on long term (five to ten year) monitoring concepts, which will foresee high frequent data acquisitions (at least one measurement campaign per year).



2 Background and goals

Glaciers and permafrost, both significant elements of the mountain cryosphere, are highly sensitive to climate change. While there is a comprehensive knowledge about the link between climate and the immediate and clearly visible glacier dynamics, little is known about permafrost spatial distribution and the effects of climate change on permafrost thaw in the Austrian Alps. Increased thawing of permafrost bodies induces damages on buildings and infrastructure as well as increasing rock fall intensities. In Austria a considerable part of touristic infrastructure is situated in high alpine terrain and therefore exposed to permafrost changes, linked with direct (damages) and/or indirect (evacuations, decrease number of tourist and of overnight stands) consequences and costs. The thawing of permafrost and glacier ice has to be considered in the run off analysis of high alpine catchments. Particularly the management of storage lakes (hydro-power industry) and drinking water reservoirs is increasingly associated with climate change impact induced activity of permafrost layers. To receive more detailed information about the permafrost distribution, several methods, including in-situ investigations, air-and space borne remote sensing as well as modelling approaches haven been carried out at different spatial and temporal scales within the last decade by different research groups.

Over the years, Light Detection And Ranging (LiDAR) in general, and airborne laser scanning (ALS) in particular, have become a very valuable data sources for geomorphologic research. Regarding research activities on the cryosphere, several projects already applied ALS for glaciological investigations. Despite the glaciologic applications, the potential of multi-temporal ALS for the monitoring of permafrost phenomena, e.g. rockglaciers and ice-rich debris areas outside rockglaciers has not been evaluated yet. However, due to the high accuracy and precision of ALS, it is expected that multi-temporal ALS data will provide new possibilities to map permafrost areas (e.g. rockglaciers and ice-rich debris) and to quantify changes in the spatial distribution of permafrost caused by climate change. Regarding the fact that at least bi-temporal area-wide ALS data of alpine areas will become more and more available in the near future, it is important to develop, apply and validate methods for an area-wide permafrost monitoring (e.g. surface classifications based on calibrated LiDAR intensity values, to determine the full information contained in LiDAR full-wave form data, and to determine melt and creep rates of rockglacier and glaciers), but also for glacier and dead-ice research, based on ALS data.

The scientific community mainly agrees that degradation of alpine permafrost and melting of glaciers can lead to an enhanced occurrence of rapid mass movements, e.g. rock falls and debris flows. Such mass movements cause a potential threat to infrastructure (e.g. mountain huts, skiing infrastructure, water reservoirs and hiking trails) and people in alpine areas. Thus, climate warming scenarios and following permafrost degradation and glacier melt in alpine areas will have socio-economic consequences. It is therefore important, to develop and validate methods for an area-wide long-term permafrost and glacier monitoring. The main objective of C4AUSTRIA is the development of methods for the spatial monitoring and analysis of permafrost, dead ice and glacier changes as a result of climate change.

Sub-objectives are:

- 1. universal radiometric calibration of LiDAR intensities (wavelength of 1064 nm)
- 2. development of methodologies for the quantification of surface changes caused by permafrost and glacier activities based on LiDAR measurements
- 3. extension of Hintereisferner LiDAR data record and subsequent multi-temporal analysis of permafrost, glacial and periglacial features
- 4. assessing and expressing uncertainties in context of LiDAR measurements of permafrost, glacial and periglacial features
- 5. analysis of the quantified topographical changes regarding climate interactions with permafrost (in general), rockglaciers (in particular) and glacial features



As the project primarily aims at the development of methods to monitor and quantify climate change impact on i) permafrost, ii) dead ice and iii) glacier retreats/advances, various measurement techniques will be applied. Airborne laser scanning measurements will be used to derive spatial distributed, geometric information about permafrost features as well as glacial and periglacial melt processes. This will provide significant information on volume changes of these cryospheric elements, which will be linked to controlling meteorological characteristics. The validation of the ALS based results will be done by incorporating results from in-situ measurements. The most relevant in-situ measurements encompass dGPS measurements on the Hochebenkar rockglacier, glacier mass balance studies and radiometric measurements at Hintereisferner, geophysical investigations and BTS measurements at Rofenberg (Ötztal Alps, Austria).

Besides the geometric information contained in ALS data, the backscattered laser intensity (amplitude) will be analysed and interpreted to distinguish between different surface types (e.g. ice, firn, snow and debris). Until now a radiometric calibration has not been performed for laser scanners operating in the wavelength of 1064 nm. The 1064nm wavelength was used for the majority of the available ALS data (e.g. 18 campaigns at Hintereisferner) and has also been used for the ALS flight campaigns carried out in C4AUSTRIA. Therefore, a high priority is given to the radiometric calibration of existing ALS data sets as well as for new data sets. Up to now, the majority of available ALS data are so-called pulsed data, which are derived from the original full-wave form data. The extraction of individual pulses from the full-wave form can be considered as a loss of information. Therefore, one important part of the project focuses on the development of a work flow for the full-wave form data processing and the evaluation of the overall information contained in the full-wave form ALS data.

3 Project content and results

Study sites

Six study sites have been designated for the analysis performed within the C4AUSTRIA project. An overview on the location of the C4AUSTRIA study sites is given in *Figure 1*.



Figure 1. Location of study sites. HEF = Hintereisferner, ROF = Rofenberg, OEL = Oelgruben rockglacier, IHKR = Innerer Hochebenkar rockglacier, RKR = Reichenenkar rockglacier, SKR =Schrankar rockglacier.



Besides the rockglacier in the Innere Hochebenkar, all selected study sites have been intensively investigated in the past using a variety of methods:

- 1. Hintereisferner (Ötztal): situated in the back of the Rofental and one of the best investigated glaciers in the Alps; since 2001 ALS measurements have been carried out regularly, leading to a worldwide unique LiDAR data record.
- 2. Äußeres Hochebenkar (Ötztal Alps): probably the best investigated rockglacier site in the Austrian Alps. Since 1938 velocities are measured on Hochebenkar rockglacier near Obergurgl has been measured every year. Furthermore, geophysical investigations and remote sensing analysis have been carried out on the rockglacier.
- 3. Inneres Reichenkar (Ötztal Alps): in recent years intensively investigated rockglacier (velocity, temperature, ice content, water chemistry).
- 4. Innere Ölgrube (Kaunergrat): in recent years intensively rockglacier is also deeply investigated (velocity, temperature, ice content).
- 5. Schrankar (Stubai Alps): recently instrumented research area with several rockglaciers, research funded by the Austrian Academy of Sciences
- 6. Inneres Hochebenkar (Ötztal Alps): situated close to Äußeres Hochebenkar; no surface change measurements or velocity measurements have been carried out until now although this is a large active rockglacier with well-developed surface morphology and a steep front.

Installation of LiDAR specific data base (LIS) and automatic weather station

An important task at an early stage of the project (WP2) was the installation of the LIS database system for ALS data storage, management and analysis. The installation was realized at the beginning of the project in cooperation with the subcontractor LASERDATA GmbH. Thereafter, pulsed ALS data of 2006 (F1) obtained from the Tiroler Landesregierung were imported into the LIS database.

To obtain climatological data from the Hochebenkar study site, an automatic weather station (AWS) was installed near the Hochebenkar rockglacier on the 12th of October 2010 (*Figure 2*). Data scans take place every minute and get stored as ten minutes mean, minimum, maximum, sum or vector depending on each measured parameter. The AWS records wind speed and direction, precipitation, short and long wave radiation, barometric pressure, air temperature and humidity, soil and snowpack temperature, as well as snow depth.



Figure 2. Installed weather station at Hochebenkar rockglacier.



ALS data acquisition campaign in 2009 (F2) and 2011 (F3) and data quality check

In WP3, the first ALS data acquisition campaign (F2) was carried out in 2009 and time-synchronous in-situ measurements were planned and conducted at the different study sites. All pulsed ALS data were imported to the project LIS data base. To determine the vertical accuracy of the ALS data, individual ALS point height values (n=6433) were compared to known height values of a control area. The arithmetic average (HeightLaser - HeightControll area) is found to be -0.7 cm with a standard deviation of 5.5 cm. The ALS point densities varied slightly between 2.7 points per m² at Hintereisferner and 3.2 points per m² at rockglaciers in Schrankar. Thus, the pulsed ALS data of F2 were suitable for all planned analysis of the subsequent WPs. The F3 ALS data acquisition (2011) and time-synchronous in-situ measurements were planned and conducted on the 03.10.2011 (Hintereisferner) and 04.10.2011 (rockglaciers) as part of WP5. Adapted LIS routines were used for data management and analysis of the pulsed ALS data. To determine the vertical accuracy of the Hintereisferner ALS data acquisition, individual ALS point measurements (n=8311) were compared to known height values of a control area. The arithmetic average (HeightLaser - HeightControll area) is 0.7 cm with a standard deviation of 4.2 cm. For the 04.10.2011 ALS flight campaign, the arithmetic average (HeightLaser - HeightControll area) is 0.0 cm with a standard deviation of 4.9 cm (n=10.887). The ALS point densities varied slightly between 2.4 points per m² at Reichenkar and 2.9 points per m² at Hintereisferner.

In-situ measurements for validation of ALS-based results and radiometric calibration

Field campaigns were conducted to document the state of the Hintereisferner glacier surface during the F2 and F3 ALS flight campaign (*Figure 3*). The snow cover retreat was recorded daily at Hintereisferner over the full project period and since 23.08.2012 on Äusseres Hochebenkar rockglacier. Several field campaigns have been carried out to map snow cover, record flow velocities of Hintereisferner and monitor glacier mass balance. Maps of firn-, and snow cover, as well as bare ice areas, have been derived from the time lapse cam images and used as validation of the radiometrically calibrated LiDAR images.



Figure 3. dGPS measurements at the Äußere Hochebenkar rockglacier.





Figure 4. Reflectometer measurements for radiometric calibration of ALS data carried out in the fore-field of Hintereisferner and on the glacier.

Radiometric measurements using a 1064 nm laser device were carried out on Hintereisferner and its surrounding (*Figure 4*). The data is used for calibration of the ALS intensity values and subsequent change detection studies.

Full-waveform LiDAR data processing and radiometric calibration

During the F2 ALS campaign full-waveform (FWF) LiDAR data were recorded. A substantial part of WP3 encompassed full-waveform LiDAR processing and radiometric calibration. For full-waveform data analysis and interpretation, the file standards and the processing chain suggested by the scanner manufacturer were implemented and originally tested using the F2 data. Unfortunately, the recorded FWF data were corrupt and could not be used for testing the developed FWF data processing chain. The implantation of full-waveform processing was instead tested using data acquired for the MUSICALS project provided by the alpS Centre for Climate Change Adaptation. For a successful processing, several Matlab routines had to be implemented additionally to the C++ source codes. This routines were necessary for data integrity checking and, if necessary, correction. The outputs of the full-waveform processing are 3D point clouds with calibrated radiometric information. The data are given flightstripwise and geometrically aligned to each other. The radiometric information is given as diffuse reflectance according to an assumed Lambertian scattering process at the surface. As already mentioned, the full-waveform data of F2 were not accessible. Thus, the planned radiometric calibration was carried out using the intensity information of the pulsed LiDAR point cloud and in-situ measurements, accompanied by a geometric strip adjustment using a least-squares approach. Both tasks were performed using the LiDAR software suite Opals, which is developed by partner 2. The workflow for the processing of F3 data followed the same principle as F2. For absolute radiometric calibration, in-situ reflectometer measurements were taken synchronously to the ALS campaign on October 3, 2011. The results of the radiometric calibration of intensity values at Hochebenkar rockglacier are given in Figure 5. Instead of F3, fullwaveform processing was carried out on the data set acquired on April 20, 2011.





Figure 5. Result of radiomatric calibration of intensity values at Hochebenkar rockglacier. Left panel: Amplitude image before calibration. Right panel after calibration.

Method development for multi-temporal analysis of ALS data and results

Creep velocities of rockglaciers

The main focus of WP4 was the development of tools for multi-temporal analysis of ALS data with the goal to quantify volume, respectively mass changes, of glaciers, dead-ice bodies, rockglaciers and ice-rich permafrost outside rockglaciers and to determine the data and method inherent accuracy. Furthermore, a software processing chain was developed to calculate rockglacier creep rates based on ALS data. Rockglacier creep rates were determined for each study rockglacier. As one example, out of all study rockglaciers, the determined displacement field as well as thickness change of Hochebenkar rockglacier is visualised in *Figure 6*. The accuracy of the ALS-based results at the Hochebenkar rockglacier is given in *Table 1*.

Imcorr - dGPS	Mean [m]	STDV [m]	Max. [m]	Min. [m]	R
2006-2009	0.06	0.42	0.77	-1.16	0.96
2006-2010	-0.08	0.3	0.52	-0.91	0.94
2009-2010	-0.12	0.5	1.27	-1.15	0.98

Table 1: Comparison between horizontal displacements determined from ALS and dGPS data. Mean: arithmetic mean; STDV: Standard deviation; Max.: maximum deviation; Min. minimum deviation between dGPS and corresponding ALS based displacement.

The accuracy assessment indicates that area-averaged displacement rates of rockglaciers can be determined with a high degree of accuracy from multi-temporal ALS data. However, the relation between the time span of the ALS data acquisitions, the ALS data accuracy, and rockglacier creep rates have to be kept in mind: The higher the rockglacier creep rate and the longer the time-span between the ALS flight campaigns, the more significant are the ALS based creep results in relation to the measurement errors.





Figure 6. Results from ALS analysis. Left panel shows displacement field of Hochebenkar rockglacier between 2006 and 2010. Right panel shows the thickness change. The red and black dots indicate the location of dGPS measurements used for validation.

At Hochebenkar rockglacier, individual surface velocity fields were detected for the time period 2006 to 2010. In general, the mean annual velocity increases gradually from < 0.2 ma⁻¹ at the root zone to a maximum of > 2 ma¹ in the middle part of the rockglacier and at its orographic right side at about 2600 m. Maximum velocities correspond well with an increase of terrain steepness below 2640 m. Between the period 2006/2009 and 2009/2010 a general velocity increase is detected. The absolute increase of surface velocity is highest in areas that initially showed high mean annual velocities. The most significant acceleration in the order of 1.0 - 1.5 ma⁻¹ occurs in the steepest part of the rockglacier.

Thickness change of rockglaciers, glaciers, dead-ice and ice-rich permafrost

Multi-temporal ALS data was also used calculate the thickness change of the investigated rockglaciers. The vertical accuracy of the DTMs of Hochebenkar was first validated using the acquired dGPS data. We found a mean deviation of -0.02 m (STDV 0.15 m) for the 2006 DTM and 0.04 m (STDV 0.09 m) for the 2009 DTM. Thickness change rates > 0.5m are identified in several areas of Hochebenkar rockglacier. At the orographic right margin of the rockglacier values > 0.5 m are caused by creep processes that resulted in a downward transport of mass and expansion of the rockglacier between 2006 and 2010. Distinct elongate-shaped alterations of positive and negative values occur on the main part of the rockglacier, especially between 2730 m and 2820 m at the orographic right side. They clearly result from advancing ridges and furrows. Thickness changes, respectively surface subsidence, were quantified for two dead ice bodies at the orographic right side of Hintereisferner, for rockglaciers in the Hochebenkar (HKR), Reichenkar (RKR) and Ölgrube (OEL), as well as for three ice-rich permafrost areas (PF1, PF2, PF3) at Rofenberg in the Hintereisferner (HEF) study region. *Table 2* gives a summary about the thickness change rates caused by ice melt and following surface subsidence of four components of the alpine cryosphere (glacier, dead-ice, rockglacier, ice-rich permafrost outside rockglaciers) between 2006 and 2009.

	HEF	DI1	DI2	HKR	RKR	OEL	PF1	PF2	PF3
Area-averaged thickness									
change between 2006 and	-4.22	-6.64	-1.12	-0.02	-0.08	-0.05	-0.15	-0.11	-0.15
2009 [m]									

Table 2: Area-averaged thickness change determined from DTM-differencing between 2006 and 2009 of four cryospheric components. Glacier: HEF = Hintereisferner; Dead-ice: DI1 and DI2 = dead ice body 1 and 2 at the orographic right side of HEF; Rockglacier: HKR = Hochebenkar, RKR = Reichenkar, OEL = Oelgrube; Ice-rich permafrost: PF1 - PF3 at Rofenbergköpfe.

Obviously, the thickness change rates between 2006 and 2009 of Hintereisferner with -4.22 m and the two dead ice bodies (-6.64 m and -1.12 m) are significantly higher than the determined accuracy of the ALS data. Thus, on time-spans of four or more years, reliable monitoring results can be obtained. In contrast, the area-averaged thickness change of the three rockglaciers are close the error range of the DTMs derived from ALS data. This has to be considered when interpreting the thickness changes of the investigaed rockglaciers and probably also other rockglaciers. However, the rather small area-averaged thickness change values result from significantly higher positive as well as negative values occurring at spatially distinct parts of the rockglaciers. The area-averaged thickness change can therefore not directly be used as quality measure in relation to the ALS data accuracy. Interestingly, ice-rich permafrost areas (PF1 – PF3) outside rockglaciers show greater thickness changes than active rockglaciers. On the one hand, a thick rock cover on top of rockglaciers might act as a good isolation layer to protect internal ice melt, on the other hand the differences might be explained by different methods used to determine the thickness change (cf. Bollmann et al. 2012 and Sailer et al. 2012).

The mass balance of Hintereisferner derived from in-situ measurements and ALS

Besides the presented results on thickness change rates of rockglaciers, dead-ice and ice-rich permafrost, a comparison between the direct-glaciological method and ALS based glacier mass balance was an important task of WP4. The comparison between the direct glaciological method and the ALS based mass balance indicates no big deviation between the two methods for the period 2006 to 2009. The cumulative total net balance between 2006 and 2009 derived from the direct glaciological method is -29.95 * 106 m³ w.e., whereas the ALS based total net mass balance (volume change between 2006 and 2009 multiplied by an ice density of 0.9 g/cm³) is -28.62 * 106 m³ w.e.. As expected, the two methods differ more significantly when investigating individual elevation bands due to the effect of ice dynamics (emergence and submergence) but also internal and basal melt. The mass balance methods were also compared over a time span of 8 years at Hintereisferner and Kesselwandferner. The geodetic mass balance was calculated from the volume change using detailed maps of the firn cover and applying corrections for the seasonal snow cover. The maximum snow height at the time of the elevation data flight was 0.5m averaged over the glacier surface. The volume change data was compared to in situ mass balance data for the total area and at the stakes. As the ALS data set of Hintereisferner could be extended by the C4AUSTRIA project, a longer time period could be analysed. For the total period of 8 years, the difference between the geodetic and the direct mass balance is 2.4 m w.e. on Hintereisferner and 1.4 m w.e. on Kesselwandferner, corresponding to about two times the mean annual mass balance. The vertical ice flow velocity was measured and found to be on the same order of magnitude as the mass balance at KWF. This is an indicator that volume change data does not allow the calculation of ablation or accumulation rates without detailed measurements or models of the vertical ice flow velocity. Therefore, only direct mass balance data allow process studies or investigation of the climatic controls of the resulting mass changes. Figure 7 shows the thickness change at the lower tongue of Hintereisferner and two dead-ice bodies (DI1 and DI2) at the orographic right side between 2009 and 2010 derived from ALS data. The different cryospheric components can be clearly identified by individual melt rates.

Figure 7. Thickness change of Hintereisferner and two dead-ice bodies (DI1 and DI2).

Figure 8 also indicates the erosion and deposition area of a debris flow that occurred in summer 2010. The debris accumulation on Hintereisferner strongly alters the ice ablation rate in that as can be seen in *Figure 8*.

Figure 8. Debris flow that run onto Hintereisferner.

Geophysical and temperature measurements (BTS) at Rofenberg area (PF1 – PF3)

To confirm the hypothesis that degradation (surface subsidence) of ice-rich permafrost can be detected and quantified by means of multi-temporal ALS data analysis, geophysical surveys were conducted at those areas

where ice-rich permafrost degradation had to be expected based on the ALS data analysis. Furthermore, temperature measurements below the winter snow cover (BTS and temperature loggers) were conducted. The geophysical survey as well as the temperature measurements confirmed the existence of ice-rich permafrost at these locations (location shown in *Figure 9*).

Figure 9. Location of the geophysical profiles and results from the temperature measurements at Rofenberg. Green areas indicate areas where degradation (subsidence) of ice-rich permafrost was detected by means of DTM differencing.

Combing photogrammetry and ALS to determine rockglacier creep rates and temporarily extending the data set

By incorporating photometrical analysis into the analysis of ALS data, creep rates of Hochebenkar, Reichenkar and Ölgruben rockglacier were calculated in different epochs between 1953 and 201. The change of surface velocity of Hochenebkar rockglacier is given in *Table 3*.

	1953	1969	1971	1977	1990	1997	2003
Time period	to						
	1969	1971	1977	1990	1997	2003	2009
Area-averaged annual	0.84	0.64	0.42	0.54	0.63	0.77	0.85
displacement rate [m]				0.54	0.05	0.77	

Table 3: Area-averaged annual displacement of Hochebenkar rockglacier determined from photogrammetric analysis.

Linking temperature and rockglacier velocity

Creep rates, respectively their temporal changes, were correlated to climatic changes (see *Figure 10* and *Figure 11*). Mean annual air temperature data have been taken from the literature for the period 1953 / 54 to 1998. The period from 1999 to 2009 has been taken from the annual reports of the Zentralanstalt für Meteorologie (ZAMG). Temperature correlated in some periods with changing displacement rates. On Hochebenkar rockglacier the datasets correlate over the investigated periods. Only in the period 1969–1971, where high movement rates have been caused by topography, the curves show contrary trends. From the 1970s the displacement rates seem to follow temperature again. Although on RK the velocity seems to correlate well with temperature data, the extremely high movement rates from 1990s on cannot be attributed to climatic influences alone. Possible causes could be topography, basal sliding.

Figure 10. Correlation between rockglacier velocity and temperature at Hochebenkar rockglacier.

Figure 11. Correlation between rockglacier velocity and temperature at Reichenkar rockglacier.

Application of tools to unmeasured rockglaciers

The developed methods for the determination of rockglacier creep rates were successfully applied to the Innere Hochebenkar (IHKR) rockglacier. For IHKR, an area-averaged creep rate of 0.58 m with a standard deviation of 0.42 m was calculated. The area-averaged thickness change of IHKR is very small with -0.01 m and a standard deviation of 0.41. Thus, the transfer of the developed workflow to yet unmeasured rockglaciers was successful. The developed workflow was further more applied to a large bi-temporal ALS data set covering about 870 km² of the Ötztal Alps, Austria. This allowed the calculation of creep and melt rates of 338 rockglaciers in the Ötztal Alps between 2006 and 2010. The achieved results provide a promising basis to determine the activity of

rockglaciers based on bi-temporal ALS data and thus, to provide a reproducible standard method for an areawide rockglacier monitoring. However, from our analysis we conclude that a crucial point is the rather small thickness change rates of intact rockglaciers with respect to the ALS data accuracy.

Figure 12. Rockglacier creep rates determined from bi-temporal ALS data between 2006 and 2010 in the Oetztal Alps.

Figure 12 shows area-averaged creep rates of 338 rockglaciers in the Oetztal Alps calculated by the developed workflow. In general, the results agree with the activity classification of Tyrolean rockglacier Inventory (Krainer and Ribis 2012¹). Furthermore, the results suggest that the activity of rockglaciers, as given in the inventory have to be corrected, e.g. from inactive to active. It has to be state, that due to the short time between the two ALS campaigns (2006 and 2010) in combination with the ALS point spacing and accuracy, the developed workflow comes to its limits when calculating creep rates of very slow creeping rockglaciers.

4 Conclusion and recommendations

Two ALS flight campaigns were carried out within C4AUSTRIA, accompanied by time-synchronous in-situ measurements in different study sites. Pulsed as well as FWF ALS data were acquired and subsequently stored in a Laser Information System (LIS). This system is integrated in an open Source Geographical Information System, which allows the seamless integration into operational spatial data processing and analysis workflows. Details of the data handling and data base storage concept can be found in Rieg et al. (submitted). It has to be emphasized that the storage of ALS data in a data base system like LIS is mandatory for an efficient processing of ALS data.

¹ Krainer, K., Ribis, M., 2012. A Rock Glacier Inventory of the Tyrolean Alps (Austria). Austrian Journal of Earth Sciences 150, 32–47.

For example, a seamless access to data of different flight campaigns for comparison purposes cannot be realized without an adequate data management.

Furthermore, specific data handling routines are necessary to draw reliable conclusions concerning the process activity in high alpine regions. Within C4AUSTRIA those routines were improved, tested and applied. One focus was laid on the FWF data processing and radiometric calibration of FWF data (cf. *Figure 5* and *Figure 13*). The radiometric calibration was carried out using the intensity information of the pulsed LiDAR point cloud and insitu measurements, accompanied by a geometric strip adjustment using a least-squares approach. Both tasks were performed using the LiDAR software suite Opals, which is developed at the IPF (P2) and was adapted for the specific Optech FWF data format. In particular the processing of the Optech FWF data is hard to realize. Details can be found in Roncat et al. (2012) and Briese et al. (2012). A radiometric calibration as well as a correction of pulsed intensity values is mandatory for a reliable interpretation of surface characteristics, which is based on radiometric ALS information.

Figure 13: Reflectance at the tongue of Hintereisferner. Black: 0% reflectance, White: 100% reflectance.

For the usage of ALS data for glacier mass balance purposes, the Applicant and P3 have a broad experience. The Applicant performed a detailed error analysis (e.g. Bollmann et al., 2011) of ALS data, showing that the already available and in C4AUSTRIA acquired ALS data fulfill the accuracy requirements for a sincere quantification of geomorphologic processes in high alpine terrains. In C4AUSTRIA, the ALS based mass balance of Hintereisferner was extended, contributing to the world-wide unique ALS data set of the high alpine catchment. Results on the comparison between the mass balance values derived from direct glaciological and the ALS-based method on an annual, as well as on a multi-annual scale, have already been published (e.g. Fischer, 2011; Sailer et al., 2012; Bollmann et al., in prep.) and show the value of a combined analysis of ALS and in-situ mass balance data. Furthermore, at least two dead ice bodies have been identified, spatially separated from each other and analysed based on ALS data. Remarkable melting rates are determined for these dead ice bodies (cf. Bollmann et al., 2011; Sailer et al., 2012). The dead ice degradation rates are clearly linked with the time of the dead ice formation. The younger dead ice body is characterized by larger melting rates (DI1, -2.2 ma⁻¹) than older dead ice bodies (DI1, -0.4 ma⁻¹). A detailed re-/analysis of the Hintereisferner mass balances based on ALS data processing (including derivative products) is currently in progress. Bollmann et al. (in prep.) show that ALS data leads to a reliable total mass balance and can be used for the reanalysis of geodetic mass balances. The results of C4AUSTRIA show that not only the glacier itself but also its surroundings (periglacial terrain) are affected by

remarkable changes of the surface. Based on the ALS data and the adjacent workflows, various non-glacial processes were detected, quantified and analysed (Sailer et al., 2012), notably gravitational (e.g. rock fall) and fluvial (fluvial erosion, reallocation or deposition; e.g. *Figure 7*) processes or permafrost degradation.

It can be stated that ALS-based quantification fulfils the requirements for the analysis of a variety of geomorphological processes in high alpine terrain and at a perennial timescale. In particular for permafrost degradation induced surface changes the problem of low process related magnitudes in combination with short measurement time spans is evident. The multi-temporal analysis of ALS data In the vicinity of Hintereisferner lead to the hypothesis that height changes (surface subsidence) can be attributed to permafrost degradation. Geophysical measurements (Mössinger, 2012; Ott, 2012) confirm the evidence of ice rich permafrost in this area (Rofenberg; *Figure 9* and *Figure 14*).

Figure 14: Model of the underground at Rofenberg area ,Mulde' (Hintereisferner region, Ötztal Alps), derived from Ground Penetrating Radar and Electrical Resistivity Tomography measurements; layer boundaries are the mean of both measurements (Ott, 2012)

C4AUSTRIA focused on clearly defined and separated processes. To get a deeper understanding of mass budgets in alpine terrain, further investigations will have to concentrate on complex process chains and cascading effects (Sailer et al., 2012).

Beyond glacial and periglacial processes around Hintereisferner, C4AUSTRIA focused on the multi-temporal analysis of vertical and horizontal displacements on rockglaciers. It can be shown clearly that ALS data can be used for the quantification of vertical and horizontal displacement rates with a sufficient degree of accuracy. For details on the quantification of rockglacier creep see Bollmann et al. (2012) and Klug et al. (2012). Although the thermal induced surface subsidence of rockglaciers is relatively small (about 0.05 ma⁻¹), the average over the entire rockglacier areas gives an idea on the ongoing climate induced melt processes. The ALS based multitemporal calculations of the surface velocity of the investigated rockglaciers are more significant and show areaaveraged values of about 1.0 ma⁻¹. To get an impression on the rockglacier surface velocities over the last decades, a photogrammetric analysis was conducted. The analysis of 'historic' orthophotos shows that during the last decades a slight increase of the surface velocities is evident. The surface velocities were correlated with air temperatures as shown in Figure 10 and Figure 11 (cf. also Klug, 2012; Schümberg, 2012). Because of the low subsidence rates (0.05 ma⁻¹), which are close to the measurement error, it has to be stated that for the calculation of height changes on rockglaciers a time span between the ALS observations of several year (in minimum five) is required. In contrast, due to the large rates of change annual or even monthly ALS observations are recommended for velocity analysis of (active) rockglaciers. In both cases the significance of the conclusions to be drawn will increase with the repetition rate of the ALS or combined (orthophotos, ground based systems) measurements (cf. Sailer et al., 2012). High repetition rates in combination with extended observation periods (longer than five years) are necessary to analyze the response of rockglacier dynamics to climate signals in detail.

In C4AUSTRIA, ALS point data as well as rasterized data were used. Whereas the point based calculations of geomorphologic process results demand more complex workflows and need more computing time, raster based quantifications result, as a consequence of the point to raster conversion, in a loss of accuracy and level of detail. Due to the higher degree of complexity, point based quantifications are currently restricted to single geomorphologic entities like single rockglaciers. The extended and already mentioned MUSICALS dataset permitted the analysis of the influence of increasing cell sizes on the representativeness of the process result quantifications in alpine regions (Sailer et al., submitted). A distinct dependency on the slope and roughness of the process terrain on the quality of process quantifications can be confirmed. In summary, it can be stated that the larger the slope and/or roughness as well as the cell size, the higher the relative height differences have to be to assure a reliable interpretation of the process results. Exceptionally small surface differences are measured within permafrost areas (including rockglaciers). Although these areas are characterized by relatively small slope and roughness values, a raster and even point based differencing is only advisable over large time spans (in minimum 5 years) or with repeat cycles of at least one ALS campaign per year. As mentioned, rockglacier surface velocity calculations demand less time spans or repeat cycles. Dead ice as well as glacier melt commonly results in large height differences. Furthermore, dead ice areas and glaciers are relatively flat, comparable smooth and homogenous. Hence, assuming constant climatic situations, reliable information of the surface changes on glaciers and dead ice bodies can be derived from raster analysis based on large cell sizes of about 5 to 10 m (Sailer et al., in review).

In summary, it can be stated that Laserscanning, and in particular Airborne Laserscanning, has the capability for an accurate, area-wide and reliable monitoring (quantification of process results as well as intensity based classification of surface characteristic) of elements of the Alpine cryosphere. Beside the wavelength (recommended wavelength between 900 and 1100 nm) the process dependent time span between the data acquisitions has to be kept in mind. Small process related changing rates, as observed for permafrost degradation processes (vertical displacement), require either longer time spans (> five years) and/or higher repetition rates (at least one measurement campaign per year). In contrast, for processes with large changing rates, significant conclusions are to be expected using an ALS acquisition time lapse of one year or less. Whereas glaciers obviously react immediately on climatic changes, a comparable behaviour can only be assumed for rockglaciers, although C4AUSTRIA findings prompt this conclusion. The (at the moment) available remote sensing and/or in-situ rockglacier data do not allow the reconstruction of a continuous and long time series with a sufficient time resolution (at least annual data needed). A sincere statement on the response time of active rockglaciers on climate impacts will have to be based on long term (five to ten year) monitoring concepts, which will foresee high frequent data acquisitions (at least one measurement campaign per year).

B) Project details

5 Methods

Present permafrost studies are mainly based on traditional in-situ point measurements. Hence, permafrost distribution models have been adapted to permafrost distribution maps which are based on those in-situ point measurements and geomorphologic mapping of surface features. The C4AUSTRIA project aimed at the measurement of the spatial distribution of permafrost, dead ice as well as glacier and rockglacier changes most likely caused by climate impacts. Airborne LiDAR allows observing large areas within an appropriate time and with a high degree of accuracy. The observed permafrost related altitude changes of about ≥ 0.1 m per year as well as the rockglaciers velocities in the range of 0.5 m to 2.0 per year are much larger than the LiDAR technique uncertainties. Therefore, an important part of C4AUSTRIA was the development of a methodology to collect, analyse and verify the relevant changes of the topography in glacial, permafrost and other periglacial terrain caused by climate change impacts.

In the C4AUSTRIA project, the acquired LiDAR data were partly measured in full-waveform, to evaluate the potential of the FWF data for cryospheric applications. This requires a full-waveform data processing workflow and quality control. For this workflow, it was important to select natural radiometric reference targets and to conduct in-situ reflectometer measurements during the flight time. Such a comprehensive procedure covering waveform analysis, data quality control and improvement (e.g. strip adjustment) and final radiometric calibration has not been implemented by any scientific nor commercial group so far. Hence, the definition of methodological standards was of great importance for following multi-temporal investigation and interpretation of the LiDAR products (e.g. digital elevation models and backscatter images).

The scientific novelties regarding the methodology are:

- 1. evaluation of LiDAR intensity values using natural radiometric reference targets in a high mountain environment combined with in-situ reflectometer measurements for calibration of traditional and full-waveform LiDAR data in the near-infrared wavelength of 1064 nm,
- 2. definition and assessment of the quality of radiometric calibration of natural surfaces, in order to enable the retrieval of universal LiDAR signatures for different surface classes (e.g. snow, ice, debris)
- 3. investigation of the improvement in accuracy by using full-waveform echo detection and digital terrain model generation supported by full-waveform information (i.e. echo width)

The implemented procedure was then also applied in the second LiDAR flight campaign (F3). This allowed to assess the robustness and quality of the developed processing methods and their qualification for monitoring changes in the cryosphere. Ground truth data was used for the radiometric calibration of the LiDAR data. After quality control and radiometric calibration, the derived calibrated point cloud data was also stored in the LIS database. The LIS method package allowed the processing of the data in its original and pre-processed point format as well as in common raster formats. This includes an operative input routine, pre-processing and export of the LiDAR data. Hence, LIS is the computational framework for the analysis of the LiDAR data within C4AUSTRIA (inventory and new collected) and provides raw as well as pre-processed point and raster data to the project partners for subsequent analysis.

The major tasks of C4AUSTRIA were related to the multi-temporal analysis of airborne LiDAR data. In particular difference models of the ALS derived DTMs were used to analyse surface elevation changes beyond the system inherent noise level of the data. At the Institute of Geography, University of Innsbruck, the error analysis of ALS data in a high alpine environment was carried out prior C4AUSTRIA (ALS-X, 2009). This study shows that i) under exclusion of ice, snow and gravitational slope processes and ii) under the assumption that the time difference between the ALS campaigns ensures surface changes with larger magnitudes than the system inherent errors, surface elevation changes might be attributed to permafrost thawing in High Alpine terrain. According to that study, a period of at last three years from one flight to the other is required. As the C4AUSTRIA campaigns were

carried out in 2009 and 2011 respectively, and ALS data from 2006 obtained from the Tyrolean government were included in the analysis, this requirement was fulfilled.

For the generation of the DTMs and subsequent difference models from ALS data standard routines developed at the Institute of Geography, University of Innsbruck, were used and improved. These LiDAR tools especially for glacier analysis, were adapted to permafrost relevant problems. In certain cases specific tools were developed. The results of the ALS data analysis had to be cross crosschecked with the ground truth data (e.g. GPS data, geodetic measurements). Six test sites in the Tyrolean Alps (Austria) have been designated for the method adaption, improvement or development.

- 1. Hintereisferner (Ötztal Alps): situated in the back of the Rofental and one of the best investigated glaciers in the Alps. Since 2001, ALS measurements have been carried out regularly, leading to a worldwide unique LiDAR data record.
- 2. Äußeres Hochebenkar (Ötztal Alps): probably the best investigated rockglacier site in the Austrian Alps. Since 1938, velocities are measured on Hochebenkar rockglacier near Obergurgl has been measured every. Furthermore, geophysical investigations and remote sensing analysis have been carried out on the rockglacier.
- 3. Inneres Reichenkar (Ötztal Alps): in recent years intensively investigated rockglacier (velocity, temperature, ice content, water chemistry).
- 4. Innere Ölgrube (Kaunergrat): in recent years intensively rockglacier is also deeply investigated (velocity, temperature, ice content).
- 5. Schrankar (Stubai Alps): recently instrumented research area with several rockglaciers
- 6. Inneres Hochebenkar (Ötztal Alps): situated close to Äußeres Hochebenkar; no surface change measurements or velocity measurements have been carried out until now although this is a large, active rockglacier with well-developed surface morphology and a steep front.

While test sites 1 to 5 were used to develop new methods, test site 6 - as a scientifically rather unknown rockglacier - was used solely for method verification purposes. Beside the difference models which are based on ALS DTMs, the velocity information of glaciers or rockglaciers are of interest in climate impact research. The calculation of the surface velocities was done by feature tracking routines. These routines have been applied to calculate glacier surface velocities and were applied to calculate the surface velocities of rockglaciers. Traditional velocity information (geodetic measurements, GPS data) were used to verify the velocities gained from ALS data. Test site 2 was equipped with an Automatic Weather Station (AWS) to monitor the micro climate at the rockglacier surfaces who meteorological data. At the test site 1 (Hintereisfern region), two AWS are already installed. The according meteorological data were connected with glacier retreats of the Hintereisferner and derived mass balance calculations. The Hintereisferner test site is characterized by spatial distributed permafrost bodies, which are posed to climate change impact induces thawing. By usage of the above mentioned methods, and under consideration of the results of the error analysis (ALS-X, 2009), the evidence of the spatially distributed melt water loss could be shown.

6 Workplan and Schedule

Figure 15: Gannt chart showing the project progress of individual workpackages and tasks.

7 Publication and Dissemination

Peer-reviewed journal articles:

- Abermann, J.; Kuhn, M.; Fischer, A. (2011): Climatic controls of glacier distribution and changes in Austria. Annals of Glaciology, 52/59, pp. 83 - 90.
- Bollmann, E., Sailer, R., Briese, C., Stötter, J., Fritzmann, P. (2011). Potential of airborne laser scanning for geomorphologic feature and process detection and quantifications in high alpine mountains. In: Zeitschrift für Geomorphologie / Annals of Geomorphology / Annales de Geomorphologie 55/Suppl. 2, S. 83 – 104.
- Fischer, A., H. Schneider, G. Merkel, R. Sailer: Comparison of direct and geodetic mass balances on annual time scale, The Cryosphere Discuss., 5, 565-604, 2011 www.the-cryosphere-discuss.net/5/565/2011/doi:10.5194/tcd-5-565-2011
- Fischer, A., (accepted). Long term monitoring of glacier mass balance and length changes in Tyrol as a base for glacier foreland succession studies, Plant Ecology and Diversity.
- Fischer, A, (2011), Comparison of direct and geodetic mass balances on a multi-annual time scale, The Cryosphere, 5, 107-124, http://www.the-cryosphere.net/5/107/2011/tc-5-107-2011.pdf doi:10.5194/tc-5- 107-2011
- Fischer, A. (2010): Glaciers and climate change: Interpretation of 50 years of direct mass balance of Hintereisferner, Global and Planetary Change, Volume 71, Issues 1-2, Pages 13-26, ISSN 0921-8181, DOI: 10.1016/j.gloplacha.2009.11.014.
- Fritzmann, P., Höfle, B., Vetter, M., Sailer, R., Stötter, J., Bollmann, E. (2011): Surface classification based on multitemporal airborne LiDAR intensity data in high mountain environments, A case study from Hintereisferner, Austria.
 In: Zeitschrift für Geomorphologie / Annals of Geomorphology / Annales de Geomorphologie 55/Suppl. 2, S. 105 -126.
- Sailer, R., Bollmann, E., Hoinkes, S., Rieg, L., Sproß, M., and Stötter, J. (2012): Quantification of geomorphodynamic processes in glaciated and recently deglaciated terrain based on airborne laser scanning data. Geografiska Annaler: Series A, Physical Geography, 94(1), 17–32.

Planned publications in peer-reviewed journals:

- Bollmann, E., Fischer, A., Markl, G., Sailer, R., Stötter, J., Kaser, G. (in preparation). Comparing the Hintereisferner massderived from ALS and the direct glaciological method on an annual time scale. The Cryosphere.
- Bollmann, E., Girstmaier, A., Mitterer, S., Krainer, K., Sailer, R., Stötter J. (in preparation). A new rockglacier activity index based on thickness change and creep rates derived from ALS data. Permafrost and perigalcial processes.
- Sailer, R., Rieg, L., Rutzinger, M. and Wichmann, V. (submitted): Digital elevation models derived from airborne laser scanning point clouds: appropriate spatial resolutions for multi-temporal characterisation and quantication of geomorphologic processes. Submitted to: Earth Surface Processes and Landforms, Special Issue 'Innovative analysis and use of high resolution DTMs for understanding earth surface processes'.
- Rieg, L., Wichmann, V., Rutzinger, M., Sailer, R., Stötter, J. and Geist, T. (submitted): Data infrastructure for multitemporal airborne LiDAR point cloud analysis - research examples from physical geography at Hintereisferner. Computers, Environment and Urban Systems Special Issue. 3D Laser Scanning, Spatial Data and Analysis Infrastructure.
- Klug, C., Mössinger, M., Ott, P., Rieg, L., Sailer, R., Sass, O. (in preparation), Mountain permafrost detection inferred by a combined remote sensing, geomorphological and geophysical approach.

Reviewed articles:

- Bollmann, E., Abermann, J., Klug, C., Sailer, R., Stötter, J. (2012). Quantifying rockglacier creep using airborne laserscanning

 a case study from two rockglaciers in the Austrian Alps. In: Hinkel, K. M. Proceedings of the 10th International Conference on Permafrost, Salekhard, Russia, 2012, p.49-54.
- Briese, C., Pfennigbauer, M., Lehner, H., Ullrich, A., Wagner, W., Pfeifer, N., (2012). Radiometric Calibration of Multi-Wavelength Airborne Laser Scanning Data; XXII ISPRS Congress, Melbourne, Australia; 25.08.2012 01.09.2012; in: "ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences (ISPRS Annals)", 37 (2012), ISSN: 1682-1750; pp. 335-340.

- Klug, C., Bollmann, E., Kääb, A., Krainer, K., Sailer, R., Stötter, J. (2012). Monitoring of permafrost creep on two rock glaciers in the Austrian eastern Alps: Combination of aerophotogrammetry and airborne laser scanning. In: Hinkel, K. M. Proceedings of the 10th International Conference on Permafrost, Salekhard, Russia, 2012, p.215-220.
- Lehner, H., Briese, C. (2010). Radiometric calibration of Full-Waveform Airborne Laser Scanning Data based on natural surfaces. ISPRS Technical Commission VII Symposium, Vienna; 05.07.2010 - 07.07.2010; in: "100 Years ISPRS Advancing Remote Sensing Science", XXXVIII/7B (2010), ISSN: 1682-1777; pp. 360-365.
- Roncat, A., Pfeifer, N., Briese, C. (2012). A linear approach for radiometric calibration of full-waveform Lidar data. Proc. SPIE 8537, Image and Signal Processing for Remote Sensing XVIII, Edinburgh, United Kingdom, September 24, 2012. doi:10.1117/12.970305

Other scientific articles:

- Bender O., A. Borsdorf, A. Fischer and J. Stötter, Mountains Under Climate and Global Change Conditions Research Results in the Alps, InTech, September 2011, ISBN 978-953-307-419-1
- Fischer, A. 2010, Homogenization of 50 years of mass balance data at Hintereisferner, Austria. Journal of Alpine Geology, 52, Pangeo 2010, Extended Abstracts, 110.
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