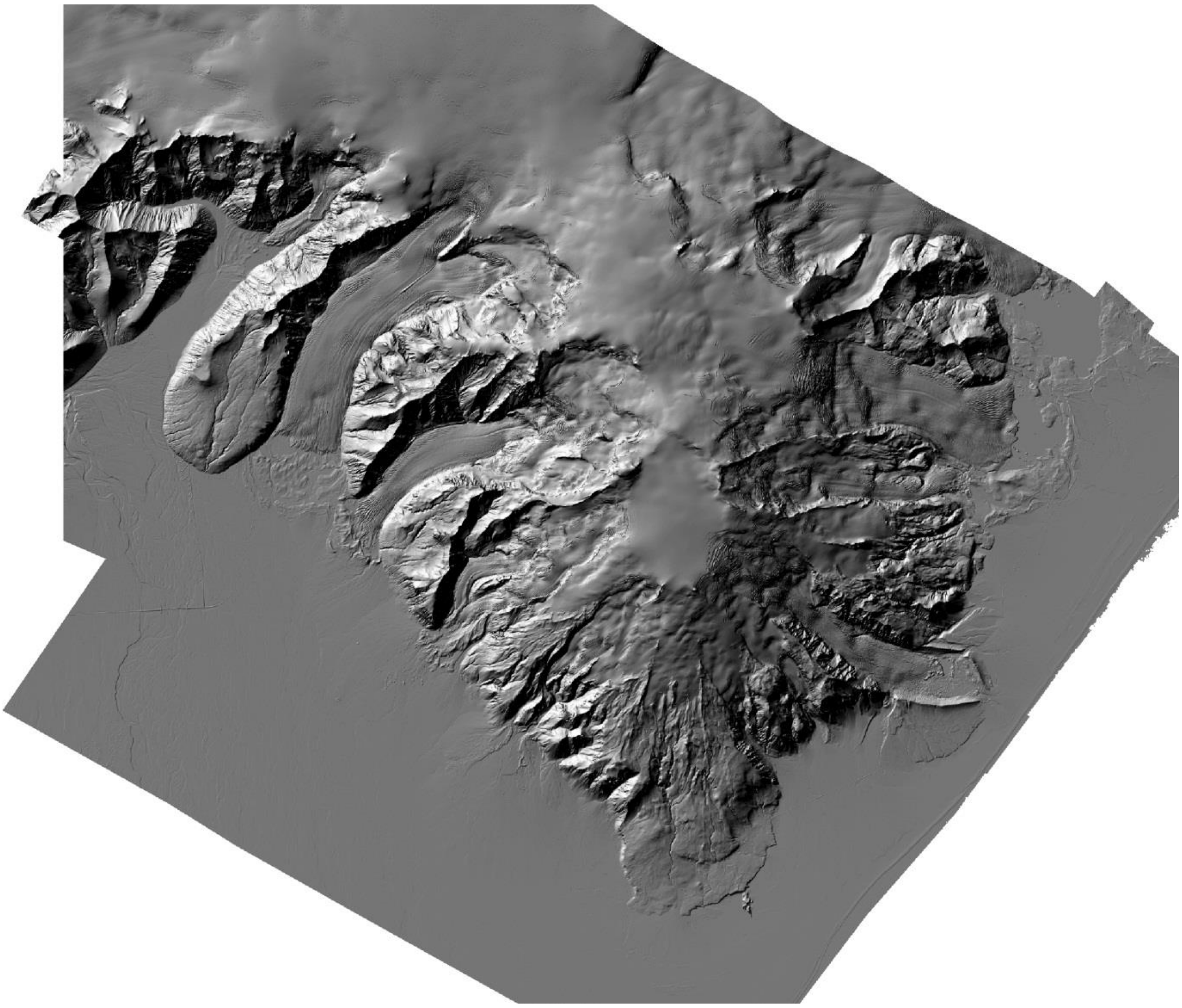
Lidar measurements of the cryosphere

Reykholt, Iceland, June 20–21, 2013

Abstract volume



Lidar map of the ice-covered stratovolcano Öræfajökull in S-Vatnajökull, S-Iceland, surveyed by TopScan GmbH in August 2011

Icelandic Met Office

SVALI

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Programme

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Norwegian Water Resources and Energy Directorate (NVE), Norway,
Lidar measurements of Norwegian glaciers – an overview

René Forsberg, Henriette Skourup and Sine M. Hvidegaard
DTU Space, Technical University of Denmark
A decade of lidar measurements for ice, ocean and land applications

Allen Pope, Ian C. Willis*, Finnur Pálsson Neil S. Arnold, W. Gareth Rees and Lauren Grey
Scott Polar Research Institute (SPRI), University of Cambridge, UK
Elevation change, mass balance, dynamics and surging of Langjökull, Iceland from 1997 to 2007

Johann Stötter, Rudolf Sailer and Erik Bollmann
Institute of Geography, University of Innsbruck, Austria
"–20% in 10 years" – Ten years of experience with laser scan applications on Austrian glaciers

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Neil Arnold and Gareth Rees
Scott Polar Research Institute (SPRI), University of Cambridge, UK
Calculation of glacier velocity from repeat lidar survey

Tómas Jóhannesson
Icelandic Meteorological Office, Iceland
Flow paths of subglacial water detected by lidar measurements of changes in the ice surface elevation of glaciers

Jack Landy and David Barber
University of Manitoba, Canada
Using terrestrial lidar to understand the mechanisms driving melt pond evolution on sea ice in the Canadian Arctic

Hans-Gerd Maas and Ellen Schwalbe
TU Dresden, Institute of Photogrammetry and Remote Sensing, Germany
3D velocity fields at Jacobshavn Isbrae glacier from multi-temporal terrestrial laser scanner data

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Kjetil Melvold and Thomas Skaugen
Norwegian Water Resources and Energy Directorate (NVE), Norway
Spatial variability of snow depth determined from airborne laser scanning: implication for snow course design example from Hardangervidda southern Norway

Victoria H. Hamilton-Morris,
British Antarctic Survey (BAS), UK
Construction and analysis of lidar mosaics of sea ice floe elevations in the Weddell and Bellingshausen seas

Robert Ricker, Stefan Hendricks, Veit Helm, Sandra Schwegmann, Henriette Skourup and Rüdiger Gerdes
Alfred Wegener Institute for Polar and Marine Research, Germany
CryoSat-2 Arctic Sea-Ice Freeboard and Thickness Data Product and its Validation

Ciaran Robb, Ian Willis and Neil Arnold
Scott Polar Research Institute (SPRI), University of Cambridge, UK
Using airborne remote sensing to investigate glacier geomorphic processes

Rudolf Sailer, Erik Bollmann, Veronika Ebe, Anna Girstmair, Christoph Klug, Lorenzo Rieg, Maximilian Spross and Johann Stötter
Institute of Geography, University of Innsbruck, Austria
Potentials of ALS in the analysis of geomorphodynamic processes in high alpine regions

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Beata Csatho, Thorsten Markus and Thomas Neumann
University of Buffalo, USA
The ICESat-2 mission: design, applications and pre-launch performance assessments for monitoring cryopsheric changes

Toni Schenk and Beata Csatho
University of Buffalo, USA
Experimental Results from photon-counting laser altimetry system MABEL

Skype session

Michelle Hofton, B. Blair, D. Rabine and S. Luthcke
Dept of Geographical Sciences, University of Maryland, USA
Using NASA's LVIS wide-swath, full-waveform laser altimeter system to precisely and accurately image ice surfaces from high altitude

Michael Studinger
NASA Goddard Space Flight Center, USA
NASA's Operation IceBridge: using instrumented aircraft to bridge the observational gap between ICESat and ICESat-2 laser altimeter measurements

Another NASA persentation

Video discussion with input from NASA/USA

Thursday 18:30–20:00 – Workshop dinner

Thursday 20:00–21:00 – Evening session

Oddur Sigurðsson – Photographs of Icelandic glaciers

Finnur Pálsson – Langjökull ice cap

Friday, June 20, 09:00–10:30 – Lidar instruments and surveying

Peter Rieger
RIEGL Laser Measurement Systems GmbH, Austria
An airborne laser scanner utilizing novel multiple-time-around processing for efficient wide-area and high point density mapping of mixed-terrain, ice-sheets, and glaciers

Henriette Skourup, René Forsberg, Sine M. Hvidegaard, Indriði Einarsson, Arne V. Olesen, Stine K. Rose, Louise S. Sørensen, Veit Helm, Stefan Hendricks, Robert Ricker, Malcolm Davidson and Tânia Casal
DTU Space, Technical University of Denmark
Airborne Lidar measurements to support CryoSat-2 validation

Christian Wever
TopScan GmbH, Germany
Airborne laser scanning in Iceland

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Friday 11:00–12:30 – Poster session

Mauro Fischer, Matthias Huss and Martin Hoelzle
Department of Geosciences, University of Fribourg, Switzerland
Monitoring the geodetic mass balance of very small glaciers in the Swiss Alps with a long-range terrestrial lidar system

Snævarr Guðmundsson, Hrafnhildur Hannesdóttir and Helgi Björnsson
Institute of Earth Sciences, University of Iceland
Post-Little Ice Age (1891–2011 AD) volume loss of Kotárjökull glacier, southeastern Iceland, as established from historical photography and lidar

Sverrir Guðmundsson, Eyjólfur Magnússon, Helgi Björnsson, Finnur Pálsson, Tómas Jóhannesson and Etienne Berthier
Institute of Earth Sciences, University of Iceland
Mass balance and volume changes of Eyjafjallajökull ice cap, from 1984 to 2010, deduced by multi-temporal elevation maps

Tómas Jóhannesson, Helgi Björnsson, Sverrir Guðmundsson, Eyjólfur Magnússon, Finnur Pálsson, Oddur Sigurðsson, Árni Snorrason and Þorsteinn Þorsteinsson
Icelandic Meteorological Office, Iceland
Measurements of the ice surface elevation of glaciers in Iceland with lidar

Hrafnhildur Hannesdóttir, Helgi Björnsson, Finnur Pálsson and Snævarr Guðmundsson
Institute of Earth Sciences, University of Iceland
Glacier surface elevation changes in the accumulation area of Vatnajökull ice cap since the end of the Little Ice Age – from lidar DEMs, aerial images and historical photographs

Anne Le-Brocq, Neil Ross and Martin Siegert
College of Life and Environmental Sciences, University of Exeter, UK
SURFMAP? – integrating lidar measurements into an Antarctic surface DEM

Joaquín Muñoz-Cobo Belart, Eyjólfur Magnússon and Finnur Pálsson
University of Iceland, Iceland
Mass balance analysis of Drangajökull ice cap from historical photogrammetry and lidar

Gary M. Llewellyn
Airborne Research and Survey Facility, Natural Environment Research Council (NERC), UK
An overview of past and future surveys of Iceland conducted by the NERC ARSF

Eric Lutz, Bob Hawley, Michelle Hofton, John Sonntag, Kelly Brunt and Roseanne Dominguez
Department of Earth Sciences, Dartmouth College, USA
Validation of NASA laser altimeters at Summit, Greenland

Finnur Pálsson, Eyjólfur Magnússon, Sverrir Guðmundsson, Helgi Björnsson, Hannes H. Haraldsson, and Tómas Jóhannesson
Institute of Earth Sciences, University of Iceland
The mass balance of Brúarjökull, outlet of N-Vatnajökull Ice cap Iceland, in the 20th and 21st century

Chris Polashenski
USACE Cold Regions Research and Engineering Laboratory (USACE-CRREL)
Applications of terrestrial lidar in sea-ice and snow research

Lunch 12:30–13:30

Friday 14:00–18:00 – Excursion on Langjökull

List of participants

	Name	Institute
1	Liss Marie Andreassen	Norwegian Water Resources and Energy Directorate (NVE)
2	Neil Arnold	Scott Polar Res. Inst. (SPRI), Univ. of Cambridge, UK
3	Joaquín Muñoz-Cobo Belart	University of Iceland
4	Beata Csatho	University of Buffalo, USA
5	Mauro Fischer	Department of Geosciences, University of Fribourg, Switzerland
6	René Forsberg	DTU-Space, Technical University of Denmark
7	Snævarr Guðmundsson	Institute of Earth Sciences (IES), University of Iceland
8	Sverrir Guðmundsson	Institute of Earth Sciences (IES), University of Iceland
9	Brian C. Gunter	Delft University of Technology, The Netherlands
10	Victoria H. Hamilton-Morris	British Antarctic Survey (BAS), UK
11	Hrafnhildur Hannesdóttir	Institute of Earth Sciences (IES), University of Iceland
12	Jóhann Helgason	National Land Survey of Iceland
13	Michelle Hofton*	Dept. of Geographical Sciences, University of Maryland
14	Sine Munk Hvidegaard	DTU Space, Technical University of Denmark
15	Tómas Jóhannesson	Icelandic Meteorological Office (IMO)
16	Jack Landy	University of Manitoba, Canada
17	Anne Le-Brocq	College of Life and Environm. Sci., University of Exeter, UK
18	Gary M. Llewellyn	Natural Environment Research Council (NERC), UK
19	Eric Lutz	Department of Earth Sciences, Dartmouth College, USA
20	Hans-Gerd Maas	Inst. of Photogrammetry and Remote Sens., TU Dresden, Germany
21	Eyjólfur Magnússon	Institute of Earth Sciences (IES), University of Iceland
22	Ingvar Matthíasson	National Land Survey of Iceland
23	Kjetil Melvold	Norwegian Water Resources and Energy Directorate (NVE)
24	Finnur Pálsson	Institute of Earth Sciences (IES), University of Iceland
25	Gro Birkefeldt Møller Pedersen	Nordic Volcanological Center, IES, University of Iceland
26	Chris Polashenski	USACE Cold Regions Res. and Eng. Lab. (USACE-CRREL)
27	Robert Ricker	Alfred Wegener Institute for Polar and Marine Research, Germany
28	Peter Rieger	RIEGL Laser Measurement Systems GmbH, Austria
29	Ciaran Robb	Scott Polar Res. Inst. (SPRI), Univ. of Cambridge, UK
30	Rudolf Sailer	Institute for Geography, University of Innsbruck, Austria
31	Toni Schenk	University of Buffalo, USA
32	Ellen Schwalbe	Inst. of Photogrammetry and Remote Sens., TU Dresden, Germany
33	Oddur Sigurðsson	Icelandic Meteorological Office (IMO)
34	Henriette Skourup	DTU-Space, Technical University of Denmark
35	Johann Stötter,	Institute for Geography, University of Innsbruck, Austria
36	Michael Studinger*	NASA Goddard Space Flight Center, USA
37	Guðmundur Valsson	National Land Survey of Iceland
38	Christian Wever	TopScan GmbH, Germany
39	Ian Willis	Scott Polar Res. Inst. (SPRI), Univ. of Cambridge, UK

* Video conference

Lidar measurements of Norwegian glaciers – an overview

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ABSTRACT

The current glacier monitoring programme in mainland Norway includes direct mass balance investigations on 14 glaciers. Accurate maps are essential for the surveys. Previously, glaciers maps were typically constructed from aerial photographs. Poor optical contrast of snow-covered parts of the glacier surfaces cause larger uncertainties in derived elevations. Data derived from laser scanning (lidar) is very accurate, particularly on snow covered surfaces with low roughness. The first laser scanning campaigns of Norwegian glaciers were conducted in 2001–2003 when Engabreen were mapped repeatedly. Over the period 2007–2011 new lidar campaigns have been conducted on numerous glaciers in Norway. In most of the campaigns simultaneous air photos have been taken. The objectives of the surveys are to produce high quality digital elevation models (DEMs) and orthophotos to document the present state of the glaciers and assess mass changes of the glaciers since the previous mappings. Furthermore, the DEMs and orthophotos provide an accurate baseline for future repeated mapping and glacier change detection.

The surveys cover ~800 km^2, more than 30 % of the glacier area in Norway. All current mass balance glaciers are now mapped with lidar. The surveys and raw data processing were done by commercial companies, whereas NVE has carried out the further processing. The collected data are used to calculate geodetic mass balance and are compared with mass balance measured by the direct method where available. The new laser data combined with old surveys are thus important for an independent validation of the direct field method. Here we present the methods used for assessing the geodetic mass balance and its uncertainty.

Calculation of glacier velocity from repeat lidar surveys

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ABSTRACT
Remotely-sensed imagery is being increasingly used as a method to calculate glacier and ice sheet velocity. The two most common techniques revolve around radar interferometry, and feature tracking using radar or visible imagery. Velocity calculations from spaceborne platforms, particularly for slower and/or smaller ice masses, are limited by the spatial resolution and repeat interval of such imagery, however. In this paper, we evaluate the potential of high resolution airborne lidar imagery as a method to derive glacier velocity for slower moving, smaller ice masses, using surveys of Midre Lovenbreen, NW Svalbard, from 2003 and 2005. These data were used by Rees and Arnold (2007) to calculate preliminary estimates of the glacier velocity. We use three methods; manual delineation of visible features (e.g. supraglacial streams, crevasse fields); automated feature tracking (using the VISICORR software (Dowdeswell and Benham, 2003)); and a semi-automated Fourier-transform based cross-correlation technique. In this paper, we extend this analysis to investigate the impact of various pre-processing steps (such as slope shading of the surface derived from the point cloud); the impact of the window size used to calculate the Fourier transforms; and also the use of lidar return intensity measurements as well as the elevation data itself.

Mass balance analysis of Drangajökull ice cap from historical photogrammetry and lidar

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[2]*University of Jaén, Spain*
[3]*Institute of Earth Sciences, University of Iceland*
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ABSTRACT

We present work in progress, applying lidar observation and photogrammetric processing of aerial photographs with the aim of deducing volume changes of Drangajökull ice cap in Northwest Iceland. Drangajökull was surveyed with an airborne lidar in the summer 2011. The density of observations allows creation of a Digital Elevation Model (DEM) with 2x2m cell size and accuracy <0.5 m in both elevation and horizontal positioning (Jóhannesson et al., 2011). Aerial photographs allowing photogrammetric processing cover large parts of Drangajökull in 1946, 1975, 1985 and 1994. We view the lidar DEM as hillshade image and compare it with the aerial photographs to extract locations of Ground Control Points (GCP) for the orientation of aerial photographs. The elevation of the GCPs is extracted directly from the lidar DEM. For orientation of the 1994 photographs we reach a RMS error in planimetry below the meter-level for 40 GCPs obtained from the lidar. The vertical component shows even better results, with a RMS error below 0.5 meters. The difference between the lidar DEM and the 1994 photogrammetric DEM in 10x10m resolution indicates a bias of 0.34 m for the 1994 DEM. The standard deviation of the difference between the DEMs is 1.26 m for stable areas outside the glacier. The above parameters of accuracy in orientation and DEM extraction indicate that by using lidar data as a single support it is possible to get highly accurate results in photogrammetric processing of historical photographs.

REFERENCE

Jóhannesson, T., H. Björnsson, F. Pálsson, O. Sigurðsson and Þ. Þorsteinsson. 2011. Lidar mapping of the Snæfellsjökull ice cap, western Iceland, *Jökull*, **61**,19–32.

The ICESat-2 mission: design, applications and pre-launch performance assessments for monitoring cryopsheric changes

Beata Csatho*[1], Thorsten Markus[2] and Thomas Neumann[2]

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ABSTRACT
NASA's Ice, Cloud, and land Elevation Satellite-2 (ICESat-2) is a 2nd-generation orbiting laser altimeter, a follow-on to the ICESat mission, which operated between 2003 and 2009. Its primary aim is to monitor sea-ice thickness and ice sheet elevation change at scales from outlet glaciers to the entire ice sheet as established by ICESat. ICESat-2 is now in phase-C (Design and Development). It is scheduled to launch in July 2016 on a Delta II rocket from Vandenberg Air Force Base in California.

ICESat-2 will carry the Advanced Topographic Laser Altimeter System (ATLAS) and collect data to a latitudinal limit of 88 degrees. In contrast to Geoscience Laser Altimeter System (GLAS) on ICESat, ATLAS employs a 6-beam micro-pulse laser photon-counting approach. It uses a high repetition rate (10 kHz; 70 cm on the ground along the direction of travel) low-power laser in conjunction with single-photon sensitive detectors to measure ranges using ~532 nm (green) light. In the polar regions, the 91-day repeat orbit pattern with a roughly monthly sub-cycle is designed to monitor seasonal and interannual variations of Greenland and Antarctic ice sheet elevations and monthly sea ice thickness changes. Dense ground-tracks over the rest of the globe (appr. 2 km ground-track spacing at the equator after two years) will enable measurements of land topography and vegetation canopy heights, allowing estimates of biomass and carbon in above ground vegetation. While the ICESat-2 mission was optimized for cryospheric science, vast amount of accurate elevation measurements will be taken over land and oceans as well as of the atmosphere. These observations will provide a wealth of opportunities, ranging from the retrieval of cloud properties, to river stages, to snow cover, to land use changes and ocean surface topography and more.

This talk will provide an overview of the ICESat-2 mission and elaborates on its expected performance for ice sheet monitoring and change detection.

Monitoring the geodetic mass balance of very small glaciers in the Swiss Alps with a long-range terrestrial lidar system

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ABSTRACT

More than 80% of all Swiss glaciers are smaller than 0.5 km^2 and hence belong to the size class of very small glaciers, occuring mostly in cirques, niches and below headwalls where topoclimatical factors and snow accumulation patterns are favourable for the persistence of snow and ice. However, very small glaciers have hardly been studied and empirical field measurements are sparse. Thus, the response of very small glaciers in the Swiss Alps to climate change is being investigated based on an integrated approach including field evidence, modeling and remote sensing.

Measuring glacier mass balance is important as it directly reflects the climatic forcing on the glacier. Since 2012, both seasonal and annual mass balance of seven very small glaciers in Switzerland is measured using the glaciological method (snow soundings and density measurements at the end of the accumulation season, measuring melt at ablation stakes at the end of the ablation period). Mass balance can also be reconstructed by means of the geodetic method, which is based on the comparison of two different Digital Elevation Models (DEMs). So far, the accuracy of such DEMs mostly derived from airborne or terrestrial laserscanning, photogrammetry or topographic maps limited the time resolution of reliable mass balance measurements resulting from the geodetic method to a decadal scale. Most recently, a new generation of long-range terrestrial laserscanners especially designed for surveying snowy and icy terrain entered the market of laserscanning devices. This is highly promising for future accurate determination of annual and even seasonal mass balance of Alpine glaciers. It may have the potential to circumvent laborious and time consuming glaciological mass balance measurements. Furthermore and because ice flow is reduced for very small glaciers, it may help to improve our understanding of the spatial and temporal component of accumulation and melt processes on Alpine glaciers.

Here we present first expericences and experiments from working with the new Riegl VZ-6000 long-range terrestrial laserscanner (TLS). Furthermore, we set up a strategy for an efficient and high-quality future monitoring of the geodetic mass balance of very small glaciers in the Swiss Alps.

A decade of lidar measurements for ice, ocean and land applications

René Forsberg*, Henriette Skourup and Sine M. Hvidegaard

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ABSTRACT

Starting from laser altimeter experiments for ocean dynamic topography experiments in the North Sea, DTU-Space has over the years developed various affordable airborne lidar system setups, mainly for land and sea ice applications. Riegl scanning laser units have been the core instruments of this in-house development, which has also included development of software for IMU altitude determination and calibration. In the talk, the background on the software and methodology development is outlined, and examples shown for results of various campaigns over the Greenland ice sheet, the Arctic and Atlantic Oceans and elsewhere, including a test in paragliders by an upstart company. Generally, accuracies of the system are at the 5–10 cm level, and mainly limited by GPS accuracies. The most recent 2012 airborne campaign included overflights over Iceland and East Greenland glaciers for change detection, with our typically used Norlandair DHC-6 Twin-Otter as survey aircraft.

Post-Little Ice Age (1891–2011 AD) volume loss of Kotárjökull glacier, southeastern Iceland, as established from historical photography and lidar

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ABSTRACT

Kotárjökull is one of several outlet glaciers draining the ice-covered central volcano Öræfajökull in SE-Iceland. We estimate the average annual specific mass loss of the glacier, to be 0.22 m (water equivalent) per year over the post Little Ice Age period 1891–2011. The glacial recession corresponds to an areal decrease of 2.7 km^2 (20%) and a volume loss of 0.4 km^3 (30%). A surface lowering of 180 m is observed near the snout decreasing to negligible amounts above 1700 m elevation. This minimal surface lowering at high altitudes is supported by a comparison of the elevation of trigonometrical points on the plateau of Öræfajökull from the Danish General Staff map of 1904 and a recent lidar-based digital elevation model. Our estimates are derived from a) three pairs of photographs from 1891 and 2011, b) geomorphological field evidence delineating the maximum glacier extent at the end of the Little Ice Age, and c) the high-resolution digital elevation model from 2010–2011. The historical photographs of Frederick W.W. Howell from 1891 were taken at the end of the Little Ice Age in Iceland, thus providing a reference of the maximum glacier extent.

Mass balance and volume changes of Eyjafjallajökull ice cap, from 1984 to 2010, deduced by multi-temporal elevation maps

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ABSTRACT
We assess the mass balance changes of the ~81 km^2 Eyjafjallajökull ice cap in South Iceland, over three distinct periods, 1984 to 1998, 1998 to 2004, and 2004 to 2010 (influenced by the 2010 Eyjafjallajökull eruption), by comparing digital elevation models (DEMs) covering the entire glacier. The DEMs were compiled by using i) aerial photographs taken in August 1984 by the U.S. Defense Map Agency (DMA) and the National Land Survey of Iceland, ii) airborne EMISAR radar images obtained in August 1998 by the Electromagnetic system (EMI) of the Technical University of Denmark, iii) two image pairs from the SPOT 5 high resolution stereoscopic (HRS) instrument from August 2004 and iv) airborne lidar from August 2010 (after the Eyjafjallajökull eruption from 14 April to 22 May 2010). The average specific mass balance was estimated as the mean elevation difference between glaciated areas of the DEMs. The glacier mass balance declined significantly between the first two periods: from +0.2 m yr^{-1} w. eq. during first period 1984–1998 to –1.5 m yr^{-1} w. eq. for the period 1998 to 2004. This declining mass balance takes place at the same time as the average regional temperatures increased by ~1 °C from the first to the second period (1980–1998 to 1998 to 2004). The mass balance during the third period (2004–2010) was –0.9 m yr^{-1} w. eq. This increase in the mass balance from the second to the third period (–1.5 to –0.9 yr^{-1} w. eq.) is explained by the deposition of a thick insulating tephra layer spread over the ice cap, that did prevent melting during the summer 2010. Assuming a mass balance of –1.5 m yr^{-1} w. eq. from 2004 to 2009 (the same as that for 1998 to 2004, at similar average temperature), yields a mass balance of around +2 m for the glaciological year 2009 to 2010, or a gain of ~0.18 km^3 (mixture of ice and tephra).

Construction and analysis of lidar mosaics of sea ice floe elevations in the Weddell and Bellingshausen seas

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ABSTRACT

Satellite altimeters, such as CryoSat-2 and ICESat, have the potential to monitor trends in Antarctic ice thickness and extent. The Ice Characterisation Experiment in the Bellingshausen and Weddell seas (ICEBell) aims to provide improved algorithms for extracting Antarctic sea ice thickness from altimeter measurements. As part of a simultaneous underwater, on-ice and airborne campaign, airborne lidar measurements were obtained over sea ice floes in a grid pattern. This lidar data were then combined into large scale mosaics by minimising the elevation differences in the gridline overlaps. These sea ice elevation mosaics are being used in conjunction with snow thickness and ice draft measurements to develop freeboard to ice thickness algorithms, as well as furthering our understanding of elevation and morphology statistics over larger regions of sea ice. These data will provide excellent satellite altimeter validation datasets. I will present the most recent results from the analysis of these mosaics, including comparison of the elevation distributions from single gridlines versus the full mosaics, validation of construction from independent data and the benefit of generating large scale floe mosaics to help validate and put into context local and remote sensing observations.

Glacier surface elevation changes in the accumulation area of Vatnajökull ice cap since the end of the Little Ice Age – from lidar DEMs, aerial images and historical photographs

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ABSTRACT

The southeastern outlet glaciers of Vatnajökull ice cap have lost 15–40% of their volume since the end of the Little Ice Age around 1890. The average annual specific mass loss of the glaciers during the last 120 years is between 0.23–0.57 $m_{w.eq.}$ The mass loss is concentrated in the ablation areas, where lateral moraines, trimlines, and glacier erratics clearly outline the glaciers´ maximum extent. Surface lowering on the order of 150–250 m is observed close to the glacier snouts in the narrow alpine-like valleys of S-Vatnajökull. Geomorphological field evidence is more limited in the accumulation area. However, from aerial images of Loftmyndir ehf., it is possible to determine whether the slopes and nunataks have been covered by ice. The high-resolution lidar DEMs (2x2 m cell size, accuracy <0.5 m in horizontal and vertical positioning, Jóhannesson et al., 2011, 2013) provide an accurate baseline for estimating surface elevation changes in the accumulation area by comparing the size of numerous nunataks at different times during the 20th century, from the lidar DEMs, aerial images and historical photographs. In the post Little Ice Age period, a surface lowering of 10–15 m is estimated on Breiðabunga dome, and negligible changes are observed above 1700 m on Öræfajökull ice cap (Guðmundsson et al., 2012). The minimal surface lowering close to the ice divides on Breiðabunga is supported by DGPS measurements of the last 20 years. The detailed lidar DEMs also provide basic topographical data for the peripheral areas of the glaciers, aiding in the reconstruction of the 1890 glacier.

REFERENCES

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Jóhannesson, T., H. Björnsson, F. Pálsson, O. Sigurðsson and Þ. Þorsteinsson. 2011. Lidar mapping of the Snæfellsjökull ice cap, western Iceland, *Jökull*, **61**, 19–32.

Jóhannesson T., Björnsson H., Magnússon E., Guðmundsson S., Pálsson F., Sigurðsson O., Thorsteinsson T., and Berthier E. 2013. Ice-volume changes, bias estimation of mass-balance measurements and changes in subglacial lakes derived by lidar mapping of the surface of Icelandic glaciers, *Annals of Glaciology*, **54**, 63–74, 10.3189/2013AoG63-A422.

Using NASA's LVIS wide-swath, full-waveform laser altimeter system to precisely and accurately image ice surfaces from high altitude

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ABSTRACT
NASA's Land, Vegetation, and Ice Sensor (LVIS) is a high-altitude, imaging lidar system that measures surface elevation and surface structure across a 2km-wide swath from a nominal altitude of 10 km. Since, 2009 it has been used to image large areas of the Greenland and Antarctica ice sheets as part of NASA's Operation Icebridge. Most recently LVIS has operated from dedicated, high-altitude aircraft to enable more efficient and extensive mapping of the ice surfaces than are possible from low altitude, typically mapping areas 10X larger than what is possible from lower altitudes. We present latest results using the sensor, including an assessment of ICESat-1's inter-campaign elevation biases, determined using data from LVIS flights at latitude 86S (the southernmost extent of the ICESat-1 orbit) in 2009 and 2010. A new version of the LVIS sensor is currently being readied for deployment on the NASA's UAV Global Hawk aircraft. This version of the sensor utilizes a 4km-wide swath comprised of 10 m wide footprints from a flight altitude of 65,000'. Details of the instrument and initial results from the sensor tests will be presented. Testing of the LVIS-GH instrument demonstrated sub-centimeter range precision and the high dynamic range needed to support precise elevation data collections over the wide range of surface reflectances experienced over sea ice and ice sheets.

Flow paths of subglacial water detected by lidar measurements of changes in the ice surface elevation of glaciers

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ABSTRACT
Interest in the dynamics of subglacial water flow has increased greatly in recent years with the realisation that large variations in ice flow velocity in space and time on the ice sheets of Greenland and Antarctica appear to be driven by changes in basal sliding that are most likely caused by variations in the amount and pressure of basal water. As a part of lidar mapping of the surface of glaciers and ice caps in Iceland 2008–2012, some source areas for jökulhlaups (glacier outburst floods) have been surveyed more than once. These include the Skaftá cauldrons in western Vatnajökull and several cauldrons in the Katla caldera in the Mýrdalsjökull ice cap where the lidar measurements have been used to estimate floodwater volumes and the hypsometry of the subglacial water bodies. The outflow locations from the cauldrons are visible as several km long elongated depressions in the ice surface along the inferred subglacial flood paths that are ~10 m deeper shortly after than shortly before jökulhlaups. For the Skaftá cauldrons, these depressions are thought to be formed by subglacial melting driven by the initial heat of the flood water in repeated jökulhlaups and the difference in the depth of the depressions before and after jökulhlaups is interpreted as the consequence of melting that takes place in a single flood. For cauldrons in Mýrdalsjökull, similar depressions surveyed in 2011 were formed in a single flood and may be partly created by erosion of loose bed material by the flood. The length of the depression is related to the efficiency of heat transfer in the subglacial water flow to the surrounding ice walls. The inferred efficiency of the heat transfer is many times greater than assumed in traditional theories of jökulhlaups. This is consistent with measurements of flood water temperature at the glacier margin during jökulhlaups that show the water to be within a few thousandths of a degree from the freezing point.

Measurements of the ice surface elevation of glaciers in Iceland with lidar

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ABSTRACT

Detailed mapping of the surface of glaciers and ice caps in Iceland was initiated during the International Polar Year 2007–2009 and essentially completed in the summer of 2012. An airborne laser scanning method (lidar) has been employed, covering the entire surface of each glacier/ice cap surveyed and thus yielding accurate maps of crevassed areas and other regions that are hard to access in ground-based surveys. The vertical accuracy of the surveys is better than 0.5 m and Digital Elevation Models (DEMs) with a resolution of 5x5m are produced. All glaciers in Iceland >10 km² in area have now been mapped with lidar, in total ~11000 km² of ice-covered areas. The total surveyed area is >15000 km², including proglacial areas and repeated mapping of some areas with rapid changes due to subglacial eruptions and emptying of subglacial water bodies. These new surface maps/DEMs will serve as a benchmark for future evaluation of changes in the areal extent and volume of all major glaciers and ice caps in Iceland.

The glaciers and ice caps surveyed are of different sizes and types: Vatnajökull is the largest ice mass by volume in Europe, with sea-level equivalent of 0.85 cm, or 85% of the total volume of glacier ice in Iceland. The Langjökull and Hofsjökull ice caps have both lost ~10% of their total volume since 1995 and the lidar maps have enabled accurate estimates of drastic elevation changes on these ice caps near their periphery when compared to other surface DTMs. Drangajökull is a 150 km^2 ice cap in NW-Iceland that survives below 900 m elevation under cool conditions close to the Arctic Circle; the lidar results are now yielding the first accurate estimates of its mass balance since ~1990. Airborne lidar scanning of the surface of the glacier-capped volcano Eyjafjallajökull revealed the morphology of channels formed in the ice surface, when meltwater floods and lahars (volcanic debris flows) descended down-slope during the eruption in 2010. In addition, measurements of the surface of the Mýrdals-jökull ice cap, carried out in the summer of 2010 and repeated over the subglacial Katla caldera in 2011, allowed estimation of the volume of floodwater released from a subglacial lake in July 2011, which swept away a bridge on the main road around Iceland. This cauldron is one of several located within the caldera where a large eruption could occur in the near future.

The project is an Icelandic contribution to ongoing research on the effects of global warming on Arctic/Sub-Arctic ice caps and mountain glaciers worldwide. The maps will be useful for research on glacier surges and on isostatic uplift due to decreasing lithospheric load. They can also be useful for comparison with satellite-based measurements of glacial surfaces. Mapping of glaciers in the vicinity of subglacial lakes (like Grímsvötn and Skaftárkatlar in Vatnajökull) and marginal lakes (f.ex. Grænalón) is of importance for the study of jökulhlaups (glacier outburst floods) and for investigations of changes in the courses of glacier rivers. The project

has already produced results on the volume decrease of some ice caps in Iceland over the past few decades, by comparison with older maps and satellite data. The lidar maps will be in the public domain, open for use in map production and scientific research.

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Using terrestrial lidar to understand the mechanisms driving melt pond evolution on sea ice in the Canadian Arctic

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ABSTRACT
In situ data were collected over landfast first-year sea ice (FYI) in Resolute Passage, Nunavut (Canada) between May and July in 2011 and 2012, as part of the Arctic-ICE field program, to examine the mechanisms driving melt pond formation and evolution at the ice surface. Changes in the surface morphology of snow- then melt pond-covered ice were measured quantitatively with a terrestrial laser scanner (lidar) and, in combination with physical measurements taken along a geostatistical transect adjacent to the laser scanning site, were used to calculate mass and meltwater balance at the ice surface. We present our methods for collecting terrestrial lidar measurements on sea ice and the many challenges associated with using such technology in an extreme Arctic environment. Low temperatures, high winds and regular precipitation affected the operational capabilities of the instrument and the quality of the data collected. Continuous ice movement in three dimensions also proved problematic for registering lidar scans and georeferencing to a fixed geographic datum. We discuss the steps taken to overcome these difficulties and produce an accurate, high-quality time-series of digital surface models (DSMs) of the ice throughout the melt season. And we briefly review the results of our field studies, which demonstrate that melt pond coverage varied substantially between the two years, owing to spatio-temporal variations in the dynamic and thermodynamic processes controlling meltwater production and drainage at the ice surface.

SURFMAP? – integrating lidar measurements into an Antarctic surface DEM

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ABSTRACT

Recent major geophysical campaigns in Antarctica have acquired airborne surface elevation measurements alongside ice thickness measurements from radar. BEDMAP2 has brought together the radar ice thickness measurements to create Antarctic-wide grids of ice thicknesses and bed topography. In contrast, however, the airborne surface elevation measurements have been little used in the production of Antarctic-wide digital elevation models of the ice sheet surface, with the exception of for error assessment purposes (e.g. Bamber et al., 2009). An accurate ice surface elevation product is essential for the accurate prediction of regional subglacial hydrological systems, however, because the ice surface slope is eleven times more important than the slope of the bed for determining the direction in which subglacial water flows. A recent investigation of the subglacial hydrological regime in the Institute/Möller Ice Stream region demonstrates the issues associated with the use of existing products, showing that the source of elevation (Bamber vs airborne measurements) can lead to differing predicted subglacial water flow routes. This poster proposes a synthesis surface elevation dataset that will incorporate airborne surface elevation measurements into a general Antarctic surface DEM which will be made freely available to the community and will allow significant improvements in the characterisation and prediction of subglacial hydrological routing.

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An overview of past and future surveys of Iceland conducted by the NERC ARSF

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ABSTRACT

In 2007, the UK's Natural Environment Research Council (NERC) Airborne Research and Survey Facility (ARSF) supported a range of scientific research projects in Iceland as part of the International Polar Year. Since then it has returned to Iceland on an almost yearly basis with additional scientific surveys conducted in Svalbard, Greenland and Northern Sweden, as well as Chile, Ethiopia and most of central and Southern Europe.

The facility operates a survey-modified Dornier 228 and a Leica Geosystems ALS50-II (with a full waveform digitiser). Additioionally, we can simultaniously operate imaging spectrometers (VNIR and SWIR and historically in the TIR) and collect photography via an Leica Geosystems RCD105 (but historically a Wild RC-10). Our operation is funded in support of UK science but previous EU Framework 7 schemes have also funded science from European research teams. Past surveys have benefited from execent support by Icelandic Meteorological Office for which we are very grateful. Data collected by the ARSF are available via our data archive (http://www.neodc.rl.ac.uk/).

Our previous surveys in Iceland have supported science investigating ice dynamics, calving and recession (e.g. at Breiðamerkurjökull), quantative modelling of a volcanically-influenced proglacial systems (e.g. around Kverkfjöll), the relationship between faulting and magmatism in the Krafla rift segment, the surface morphology of lava when interacting with water (Thingvallavatn), debris flows in the Westfjords Region and deformation of the surface of Eyjafjallajökull in 2010 (following the eruption).

This year (2013) we will return to Iceland in July and August to survey Langjökull, for mass balance modelling and comparisons with data collected in 2007, parts of Vatnajökull (Breiðamerkurjökull and Virkisjökull) to measure rapid ice-cap surface change and flow dynamics and once again to the Westfjords to monitor debris flows in that region. Details of the facilities past, current and future operation can be viewed at http://arsf.nerc.ac.uk/.

Validation of NASA laser altimeters at Summit, Greenland

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ABSTRACT
Operation IceBridge is a 6-year NASA mission to collect extensive high-resolution remote sensing data, including elevation, of sea ice, ice sheets and glaciers during the interim period between NASA's ICESat (Ice, Cloud, and land Elevation Satellite) and ICESat-2 missions. Field validation is essential to accurately derive elevation changes from multiple sensors and platforms. In a field validation along ICESat Track 412 near Summit, Greenland, we assess the accuracy of surface elevation products from three of NASA's laser altimeters, including the Airborne Topographic Mapper (ATM), the Land, Vegetation, and Ice Sensor (LVIS), and the Multiple Altimeter Beam Experiment Lidar (MABEL), an airborne simulator for ICESat-2. ATM and LVIS datasets were collected during IceBridge campaigns and the MABEL dataset as part of ICESat-2 mission. We compare these data with contemporaneous along- and cross-track surface-based differential global positioning system (DGPS) measurements to identify errors and in some instances correct for them. We also evaluate how DGPS and ATM products characterize surface features evident in high-resolution imagery acquired by IceBridge's Digital Mapping System (DMS).

3D velocity fields at Jacobshavn Isbrae glacier from multi-temporal terrestrial laser scanner data

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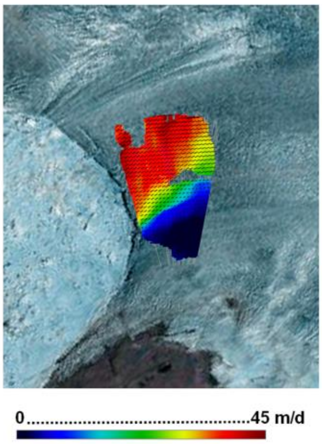
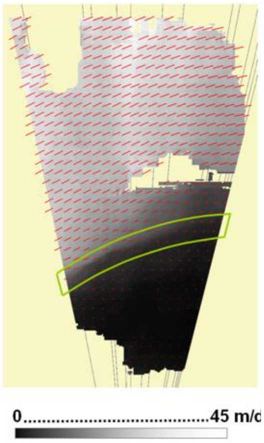
ABSTRACT
Photogrammetric techniques have been used intensively to measure flow velocities and spatio-temporal motion patterns at glaciers. Given a suitable camera station, terrestrial photogrammetric techniques offer the advantage of an almost arbitrarily high temporal resolution at very reasonable instrumental effort. The determination of 3D motion parameters, however, requires a stereo system and thus some extra effort for stereo image data acquisition and processing. Even monoscopic image sequence processing (delivering 2D velocity information) requires some extra effort (for instance a photogrammetric network) for determining a scale factor for the transformation from image into object space.
These problems can be avoided when using a terrestrial laser scanner rather than a camera. A laser scanner can be used to represent a glacier surface by a dense 3D point cloud. Provided a sufficient surface structure of a glacier (e.g. by crevasse patterns), multi-temporal 3D point clouds form a basis for the determination of 3D glacier movement velocity fields. For this purpose, point cloud matching techniques such as ICP or LSM can be applied.
We will show the results of a pilot study on using a long range terrestrial laser scanner for determining 3D velocity fields at Jacobshavn Isbrae glacier in West Greenland, discussing data acquisition modes, processing techniques and results.





Spatial variability of snow depth determined from airborne laser scanning: implication for snow course design example from Hardangervidda southern Norway

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ABSTRACT

Snow depth variability over small distances can affect the representativeness of depth samples taken at the local scale and it will therefore affect the number of measurements needed to obtain representative values. It is further difficult to obtain measurements of snow depth distribution over a large area at a resolution that approximates the scale of its "true" variability. Such measurements are needed in order to validate spatially distributed snow simulations at fine- to middle-scale or observations from satellites. Manual data collection using snow stakes or probes is labor intensive, expensive, and potentially dangerous in steep mountain environments. These issues call for new technology such as airborne laser scanning (ALS), which is a powerful tool for surveying large area within a short period. To assess snow conditions on Hardangervidda (one of Europe's largest mountain plateaus), the Norwegian Water Resources and Energy Directorate (NVE) has conducted snow measurement campaigns across Hardangervidda in 2008, 2009 by airborne laser scanning (ALS). The spatial extent of the survey area is more than 240 square kilometers. Based on the ALS snow depth data with a grid resolution of two meter were interpolated. Large variability is found for snow depth at local scale (2 m^2) and similar spatial patterns in accumulation between the two years. Based on the ALS data it possible to investigate the performance of traditional snow course survey (typically 100–2000 m long) for determining snow distribution and mean areal values compared to results obtained from a virtual snow course with ALS derived snow depth. The virtual snow courses are created by randomly selected snow data (of different length and orientation) from the ALS snow field. Results show that longer snow courses are needed in areas with large spatial variability in snow depth (typical in the western part of Hardangervidda) compared to areas with less variability.

The mass balance of Brúarjökull, outlet of N-Vatnajökull Ice cap Iceland, in the 20th and 21st century

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ABSTRACT
We describe the mass balance of Brúarjökull outlet on N-Vatnajökull, Iceland (~1600 km^2) during several time intervals of different climate conditions that span the 20th century until the present. The elevation range of Brúarjökull is 600–1750 m a.s.l. with an equilibrium line altitude (ELA) of 1200 m and (accumulation area ratio) AAR of 60%. The mass balance of Brúarjökull has been surveyed in-situ every year since 1992–1993 at ~15 carefully chosen sites. The average mass balance over different periods of the 20th and 21st centuries has been assessed from estimation of glacier volume changes by comparing series of digital surface elevation maps (DEMs) from: 1946 (revised version of published maps based on aerial photogrammetry), 1963, 1964, 1972 (from various data), 1988 (from surface profiles), 2003, 2010 (from SPOT5 satellite images and GPS surface profiles) and 2011 (airborne lidar survey). In addition, the glacier margin of the Little Ice Age maximum (LIA; ~1890) has been estimated from the location of end moraines.

Applications of terrestrial lidar in sea-ice and snow research

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ABSTRACT
Repeat lidar scans have been used to advance topics of sea ice and snow research in both Arctic and alpine environments. We will present results of studies conducted from 2008–2012 in Barrow, AK, evaluating melt pond formation on sea ice and preliminary results demonstrating capability to differentiate snow grain size in alpine snow using terrestrial lidar scanners. Techniques for cold weather operation of Riegl units, and working with a moving sea ice environment will also be shared.

Elevation change, mass balance, dynamics and surging of Langjökull, Iceland, from 1997 to 2007

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ABSTRACT

Langjökull is Iceland's second largest ice cap (~925 km^2). Digital elevation models (DEMs) from 1997 (dGPS snowmobile transects interpolated by kriging), 2004 (SPOT stereo-imaging), and 2007 (airborne lidar interpolated by photoclinometry) are generated and used to investigate surface elevation changes and the geodetic mass balance across Langjökull and its major outlet glaciers. In addition, the surface mass balance of the ice cap is determined independently between 1997 and 2007 using a degree-day mass balance model, driven by daily 1 km gridded temperature and precipitation fields based on a network of weather stations across Iceland. The data are downscaled to the 30 m grid of the mass balance model using bilinear interpolation and a fixed lapse rate. The mass balance model successfully reproduces patterns of winter, summer and net mass balance measured at stakes across the ice cap over the same period. For the major outlet glaciers, and for the ice cap as a whole, the geodetic balances are compared with the modelled balances for the epochs 1997–2004 and 2004–2007. Finally, the difference between surface elevation changes and the calculated surface mass balance are used to derive patterns of the vertical component of ice velocity. Patterns are generally as expected with submergence in the accumulation area and emergence in the ablation area but there are major deviations from these patterns in the south associated with the surge-type glacier Hagafellsjökull Eystri which shows net vertical compression in the reservoir region and net vertical extension in the receiving region over the 1997–2004 epoch associated with the 1998 surge, and the reverse over the 2004–2007 epoch associated with quiescence.

An airborne laser scanner utilizing novel multiple-time-around processing for efficient wide-area and high point density mapping of mixed-terrain, ice-sheets and glaciers

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ABSTRACT
Efficiency in data acquisition is of particular importance when conducting airborne laser scanning surveys over remote terrain. In these areas, surveys are typically constrained to short time frames due to difficult weather situations or other logistics factors. Therefore, the selection of an optimal instrument is critical for successfully completing such difficult missions.
The primary specifications of interest of an airborne laser scanner are typically its pulse repetition rate and scan speed. While these parameters are helpful, they do not provide a complete picture of the instrument's capabilities. The fundamental metric for productivity is rather the total surface area which can be mapped in a finite period of time, while maintaining regular point spacing at the same time. For reference, we provide background information on state-of-the-art airborne laser scanners currently available and the effect of their specifications on achievable point density and point distribution [1].
We will present a recently introduced airborne laser scanner, the ***RIEGL*** LMS-Q780, which easily outperforms competitive instruments with respect to productivity [2]. The instrument is capable of acquiring data at high measurement rates and from high operating altitudes at the same time which is enabled by a novel technique which resolves range ambiguities appearing in such situations [3]. We demonstrate the strength of our approach on a data set acquired over difficult terrain – a scan of a mountainous region and a glacier located in the Austrian Alps, the "Dachsteinmassiv". This novel technique enables fast and efficient scanning of any terrain while maintaining high point-density and a regular point pattern over the entire swath. For the first time, a single instrument is able to map the most challenging regions with highly variable elevations in a single pass at safe flying altitudes above mountain peaks.

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CryoSat-2 Arctic sea-ice freeboard and thickness data product and its validation

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ABSTRACT

Accurate CryoSat-2 range measurements over open water and the ice surface are necessary to achieve the required accuracy of the freeboard to thickness conversion. The local sea-surface height can be determined by careful detection of leads in the ice cover by the characteristics of the radar signal. The range retrievals of ice floes are influenced by variable penetration of the Ku-Band signal into the snow cover and the surface roughness within the CryoSat-2 footprint.

To constrain these error sources of the CryoSat-2 sea-ice thickness product, we compare the satellite range retrievals with validation measurements in the Arctic.

The CryoSat Validation Experiment (CryoVEx) combines field and airborne measurements in the Arctic in order to validate CryoSat-2 data. Here we report the results from the first combined aircraft and satellite data acquisition over sea ice in the Arctic Ocean in spring 2011. During the CryoVEx 2011 campaign in the Lincoln Sea several Cryosat-2 underpasses were accomplished with two aircraft. One aircraft was equipped with ASIRAS, an airborne simulator of SIRAL, and an airborne laser scanner; the second aircraft carried an electro-magnetic induction device for direct sea-ice thickness retrieval and an airborne laser scanner as well. Both aircraft flew in close formation at the same time of a CryoSat-2 overpass.

We present our findings of the accuracy of sea-ice freeboard and thickness from CryoSat-2 data. From the combined radar and airborne laser altimetry we can estimate the nature of CryoSat-2 range retrievals over deformed sea ice and with the additional direct EM ice-thickness measurements we assess the errors of the freeboard to thickness conversion. Furthermore, we will present the corresponding error estimates of the thickness retrieval, which are essential for the estimations of trends in sea ice and the use of CryoSat-2 data, for example in sea-ice modelling studies.

Using airborne remote sensing to investigate glacier geomorphic processes

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ABSTRACT

Geomorphological mapping forms a key aspect of paleo-glaciology. Over the last 10–20 yrs, remotely sensed data in all its forms has played an increasingly prominent role in glacial geomorphology, but despite this technological advance in data acquisition, labour intensive, traditional mapping remains the most accurate method. An automated method of landform interpretation may serve to streamline the process of geomorphic mapping and subsequent reconstruction of former glacier extent and dynamics, opening up larger and less accessible areas to future research into glacial environments. Additionally, recent re-focusing on a land system approach to ice marginal and glacial bed forms would benefit from methodologies that sample across larger areas (Evans, 2005).

Given the potential of remotely sensed data and the room for methodological improvements in geomorphic mapping, this project aims to develop an automated methodology for mapping the geomorphology of Icelandic glacier forelands, using statistical information derived from lidar datasets. Such methods aim to improve consistency in geomorphological mapping using objective, consistent and accurate computer based object and pattern recognition techniques.

Preliminary results are presented from algorithm development on a lidar dataset of the pro-glacial margins of Breiðamerkurjökull, Iceland. Algorithm calibration is based on existing geomorphic mapping, amongst the most detailed and accurate available (see Evans & Twigg., 2002) with additional fieldwork planned for late June 2013.

Potentials of ALS in the analysis of geomorphodynamic processes in high alpine regions

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ABSTRACT

Airborne lidar offers a wide range of applications in mountain geomorphology. While non-recurring lidar surveys provide base information on topography and surface characteristics, repeat airborne lidar datasets allow analysing processes and quantifying respective changes. At the Institute of Geography, University of Innsbruck, Austria, unique datasets with varying repeat cycles and spatial captures are available. Due to the high spatial resolution and accuracy, these datasets facilitate not only the detection but also the quantification of geomorphic processes over large and often inaccessible mountainous regions. Hence, the focus of this study lies on the ability of airborne lidar data for the quantification of rock falls, debris flows and landslides as well as on permafrost related surface phenomena.

Annual lidar surveys of the Rofental area (Ötztal, Tyrol; 32 km^2) started in 2001, aiming at the generation of geodetic mass balances of Hintereisferner and Kesselwandferner, two of the best investigated glaciers worldwide. Due to its high vertical accuracy (0.05 m on slopes <40°), these data allow inter-annual analyses of dead ice melting and permafrost degradation as well as rock falls and fluvial processes in the non-glaciated area. Even processes with very small changing rates of less than 0.10 m per year can be quantified on the basis of these multi-temporal airborne lidar datasets.

In a larger area of the Tyrolean Central Alps (750 km^2), a bi-temporal lidar survey (2006 and 2010) allowed the detection and analysis of 189 gravitational events (rock falls, debris flows, landslides), affecting an area larger than 100 m^2. It has to be emphasized that the majority of these processes occurred in areas where permafrost conditions are likely. Regarding their permafrost content and thus their activity, the more than 400 rock glaciers in this area can be attributed with an activity index derived from this airborne lidar dataset, using both volumetric changes and surface velocities of each rock glacier.

A comprehensive overview on the ability of repeat airborne lidar surveys in high mountain terrain is given, showing the capacities of airborne lidar data for both the (volumetric) process quantification and the process analysis. Against the background of climate change impacts, such investigations are highly relevant as shown by the introduction of a rock glacier activity index or the analysis of gravitational processes.

Experimental results from photon-counting laser altimetry system MABEL

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ABSTRACT
NASA's upcoming second-generation ICESat-2 (Ice, Cloud, and Land Elevation Satellite) will employ a photon-counting laser altimetry system with low pulse energy laser and single-photon-sensitive detectors. To verify this novel system, to simulate ICESat-2 data over cryospheric targets, and to generate data for algorithm development, NASA developed the airborne system MABEL (Multiple Altimeter Beam Experimental Lidar) in 2009, with the first flights available in late 2010. To mimic the ICESat-2 satellite observations as closely as possible, MABEL is mounted on NASA's aircraft ER-2 and operates at 20 km altitude. At the heart of the system is the transmitter fiber select box with 107 fibers for the 2 wavelengths of 532 nm and 1064 nm, respectively. At any given time, 16 of the 532 nm and 8 of the 1064 nm fibers can be coupled to the transmitter fibers, thus defining the flexible viewing geometry. The transmitter telescope with a diameter of 12.7 cm has a 100 µrad field of view with a laser footprint of 2 m at 20 km altitude. The maximum view angle is about ±1.05 km cross track. The receiver fiber array in the receiver telescope is aligned to the transmitter array. The sixteen 532 nm receiver fibers are routed to a 16-channel photomultiplier tube detector and the eight 1064 nm receiver fibers are routed to eight individual single-photon-counting detectors.
In this paper, we report about the first results of MABEL over cryospheric targets, including the detection of ice surfaces with various degrees of roughness and the detection of surface elevation changes from repeat flights. Finally, we compare the results with other laser altimetry systems, such as NASA's ATM (Airborne Topographic Mapper) and LVIS.

Airborne lidar measurements to support CryoSat-2 validation

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ABSTRACT

After the successful launch of CryoSat-2 in April 2010, the first direct validation campaign of the satellite was carried out in the spring 2011 and partly repeated in 2012. DTU Space has been involved in ESA's CryoSat Validation Experiment (CryoVEx) with airborne activities since 2003. To validate the performance of the CryoSat-2 radar altimeter (SIRAL), the aircraft is equipped with an airborne version of the SIRAL altimeter (ASIRAS) together with a high resolution laser scanner (lidar). Of particular interest is to study the penetration depth of SIRAL into both land- and sea ice. This can be done by comparing the radar and laser measurements, as the laser reflects on the air-snow surface, and thus can be used as a reference surface for the radar signal. Additionally, the lidar is used to identify detailed ice structures and different ice classifications.

The two campaigns focused on five main validation sites: Devon ice cap (Canada), Austfonna ice cap (Svalbard), the EGIG line crossing the Greenland Ice Sheet, as well as the sea ice north of Alert and sea ice around Svalbard in the Fram Strait. At each validation site, scientists took in situ measurements, to link satellite and airborne data with ground data. Selected tracks were planned to match CryoSat-2 passes and sea ice flights out of Alert were coordinated with the Alfred Wegener Institute (AWI) Polar-5 carrying an EM-bird and NASA's Operation IceBridge carrying a variety of instruments for sea ice and snow retrievals. The paper presents an overview and first results of the 2011–2012 airborne campaigns with special focus on the lidar measurements to demonstrate their use for CryoSat-2 validation.

"–20% in 10 years" – Ten years of experience with laser scan applications on Austrian glaciers

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ABSTRACT

Glaciological research on Hintereisferner, one of the largest valley glaciers in the Ötztal Alps (Austria), has a long tradition going back to first investigations in the late 19th century. Since the glaciological year 1952/53, annual mass balance measurements have be carried out. In addition to this 60 years long mass balance dataset, on basis of the direct glaciological method, in 2001, within the EU research project OMEGA, the first airborne laser scanning (ALS) data were acquired. Until 2012, 22 ALS campaigns have been conducted in this area, thus providing a world-wide unique multi-temporal ALS dataset for a glaciated alpine catchment.

The annual data of the end of the glaciological year provide high quality topographic information which allows for calculating the glacier mass balance by applying a geodetic approach. In a first approximation, the net mass balance is determined by converting the thickness change of the glacier to mass change assuming ice melting on the entire glacier and thus applying ice density of 0.9 g/cm^3. Under global warming conditions resulting in general trend of negative annual mass balances from year to year, and when considering a cumulative longer period of five or more years, this simple method may need only very small correction as most of the volume loss can be addressed to ice melt. Nevertheless, on an annual basis some correction have to made when comparing the ALS based results to those from the direct glaciological method. The factor describing the deviations between the two methods ranges from 1.60 (2004/05) to 0.55 (2002/03). These two years represent the least and most negative extremes within the monitored decade.

ALS data can provide further valuable information to improve these annual mass balance results, e.g. by deriving information on the quality of surface material from the intensity information of the received laser pulse. This application allows distinguishing between ice, firn and snow. Furthermore, feature tracking in multi-temporal data can be used to calculate surface velocities over the entire glacier area.

NASA's Operation IceBridge: using instrumented aircraft to bridge the observational gap between ICESat and ICESat-2 laser altimeter measurements

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ABSTRACT

NASA's Operation IceBridge images Earth's polar ice in unprecedented detail to better understand processes that connect the polar regions with the global climate system. Operation IceBridge utilizes a highly specialized fleet of research aircraft and the most sophisticated suite of innovative science instruments ever assembled to characterize annual changes in thickness of sea ice, glaciers, and ice sheets. In addition, Operation IceBridge collects critical data used to predict the response of Earth's polar ice to climate change and resulting sea-level rise. IceBridge also helps bridge the gap in polar observations between NASA's ICESat satellite missions.

Combined with previous aircraft observations, as well as ICESat, CryoSat-2 and the forthcoming ICESat-2 observations, Operation IceBridge will produce a cross-calibrated 17-year time series of ice sheet and sea-ice elevation data over Antarctica, as well as a 27-year time series over Greenland. These time series will be a critical resource for predictive models of sea ice and ice sheet behavior. In addition to laser altimetry, Operation IceBridge is using a comprehensive suite of instruments to produce a three-dimensional view of the Arctic and Antarctic ice sheets, ice shelves and the sea ice. The suite includes two NASA laser altimeters, the Airborne Topographic Mapper (ATM) and the Land, Vegetation and Ice Sensor (LVIS); four radar systems from the University of Kansas' Center for Remote Sensing of Ice Sheets (CReSIS), a Ku-band radar altimeter, accumulation radar, snow radar and the Multichannel Coherent Radar Depth Sounder (MCoRDS); a Sander Geophysics airborne gravimeter (AIRGrav), a magnetometer and a high-resolution stereographic camera (DMS). Since its start in 2009, Operation IceBridge has deployed 7 geophysical survey aircraft, 18 science instruments. All IceBridge data is freely available from NSIDC (http://nsidc.org/data/-icebridge) 6 months after completion of a campaign.

Airborne laser scanning in Iceland

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ABSTRACT

Since 2008, TopScan has been annually in Iceland for airborne laser scanner measurements, and has since then captured about 12.000 km². The captured areas include among others the Vatnajökull as one of the biggest glaciers in Europe and the Eyjafjallajökull after its eruption in 2010.

The paper reports on the experiences from these survey flights, in particular the questions: Complicates the situation between the Arctic Circle and the Gulf Stream and the related climate conditions the data acquisition? Are airborne laser scanner measurements in Iceland different from measurements in other areas?

Introductorily, the measurement principle and the state of the technics of ALS will be shortly explained and some of the various applications will be presented.

Finally, an outlook on the ongoing developments will be discussed. Promising developments such as bathymetric systems, being able to recognize the topography under water or a combination of ALS with hyperspectral sensors. Research and commercial applications can expect improved classification results, for example in hydrograpghical projects for a more efficient detection of the water-land-boundary.