Progress Report

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Title: Mapping the surface and surface changes of glaciers in Iceland with lidar. Progress report for 2013

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The Icelandic Meteorological Office (IMO) and the Institute of Earth Sciences (IES) of the University of Iceland have since 2008 collaborated on airborne lidar mapping of the ice surface of Icelandic glaciers and ice caps with support from the Research Fund of Iceland, (RANNIS, The Icelandic Centre for Research), the Landsvirkjun (the National Power Company of Iceland) Research Fund, the Icelandic Road Administration, the Reykjavík Energy Environmental and Energy Research Fund, the National Land Survey of Iceland and the Klima- og Luftgruppen (KoL) reseach fund of the Nordic Council of Ministers. In 2012, support was, furthermore, obtained from the Vatnajökull National Park and from the organisation Friends of Vatnajökull. Additional support for the measurements has since 2010 also been provided by the Icelandic Meteorological Office.

Figure 1 shows an overview of the glaciers and ice caps that have been surveyed in the lidar glacier mapping effort since 2008. In total, an area of approximately 14000 km^2 have been mapped, including proglacial areas and repeated mapping of some areas with rapid changes due to subglacial eruptions and emptying of subglacial water bodies. Almost all the 11000 km^2 area of glaciers in Iceland (this includes the surveying of the Scott Polar Research Institute (SPRI) of the 900 km^2 Langjökull ice cap in 2007 and 2013), leaving less than 150 km^2 of small glaciers and circue glaciers unsurveyed, mainly located in central northern Iceland.

This progress report describes the progress of the project in 2013. The surveying of 2008–2012 has been described in earlier progress reports[1] [2] [3]. The project is described in detail in a separate document that provides a general project description and a plan for the

[1] Jóhannesson, T., H. Björnsson, F. Pálsson, O. Sigurðsson and Th. Thorsteinsson (2008). Yfirborðskortlagning íslenskra jökla á heimskautaárunum 2008–2009. Áfangaskýrsla fyrir árið 2008 (Mapping the surface of glaciers in Iceland with lidar. Progress report for 2008). Icelandic Meteorological Office, memo TóJ/2008-02.

[2] Jóhannesson, T., H. Björnsson, F. Pálsson, O. Sigurðsson and Th. Thorsteinsson (2010). Yfirborðskortlagning íslenskra jökla. Áfangaskýrsla fyrir árin 2009 og 2010 (Mapping the surface of glaciers in Iceland with lidar. Progress report for 2009 and 2010). Icelandic Meteorological Office, memo TóJ/2010-05.

[3] Jóhannesson, T., H. Björnsson, F. Pálsson, O. Sigurðsson and Th. Thorsteinsson (2011 and 2012). Yfirborðskortlagning íslenskra jökla. Áfangaskýrslur fyrir árin 2011 og 2012 (Mapping the surface of glaciers in Iceland with lidar. Progress reports for 2011 and 2012). Veðurstofa Íslands, memos TóJ/2011-02, TóJ/2012-03 and TóJ/2012-06.

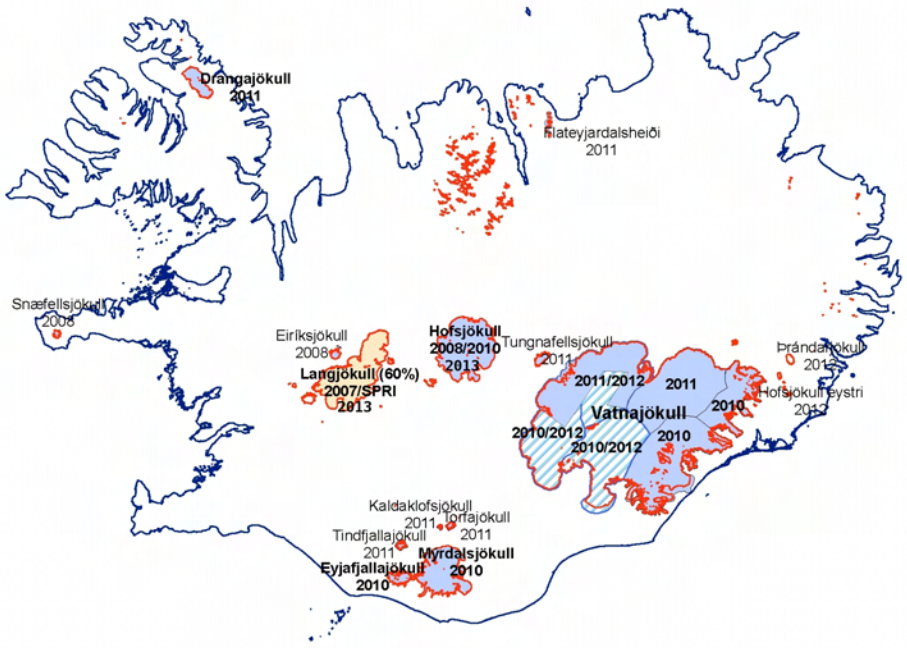

Figure 1. Status of lidar mapping of Icelandic glaciers at the end of the 2013. Hatched areas on S- and SW-Vatnajökull with an area of approximately 2200 km^2 were surveyed in 2012. The Langjökull ice cap was surveyed by SPRI in 2007 and resurveyed by SPRI in 2013. The Hofsjökull ice cap was resurveyed in 2013 in an Icelandic/Austrian collaboration.

project in 2013 that was an attachment with applications for support[4] and is also attached with this progress report.

Project status

The main project effort in 2013 was the processing of data from the lidar mapping of Vatnajökull ice cap that was surveyed in 2012. The surveying of Bárðarbunga, Grímsvötn and the Köldukvíslarjökull, Tungnaárjökull, Skaftárjökull, Síðujökull and Skeiðarárjökull outlet glaciers, which was started in 2010 and continued in 2011, was completed in 2012.

Funds from Klima og luft gruppen (KoL) of the Nordic Council of Ministers were as in 2011 and 2012 used to fund the mapping of several intermediate-sized and small ice caps

[4]Jóhannesson, T., H. Björnsson, F. Pálsson, O. Sigurðsson og Th. Thorsteinsson (2013). Mapping the surface and surface changes of Icelandic ice caps with lidar. General project description and project plan for 2013. Dated 7 January 2013.

and glaciers in Central and S-Iceland, *i.e.* Kerlingarfjöll, Snæfell, Þrándarjökull, Hofsjökull eystri and some glaciers in the southern part of Tröllaskagi. This added support, which is organised in a three-year project 2011–2013, in collaboration with the Norwegian Water Resources and Energy Administration (NVE) in Norway and the Geological Survey of Denmark and Greenland (GEUS) in Denmark, is in total 500 kDKK over the three years for surveying in Iceland.

The surveying in 2012 completed the planned measurements in the glacier mapping effort that is reported here and the year 2013 was used for data processing and reporting. Some cost for surveying carried out in 2012 was, however, not invoiced until 2013 and is therefore included in the financial reporting below.

Field support was provided by IMO in 2013 to the lidar resurveying of Langjökull by SPRI/NERC in July and of Hofsjökull by an Icelandic/Austrian collaboration in October. Results from these resurveys will be available to IMO and IES on the same terms as for data from the lidar mapping of Icelandic glaciers from 2008–2012. The cost of these survey efforts is borne by SPRI/NERC and the Austrian collaborators and is not reported here.

Measurement technique

The airborne lidar surveying is carried out by the German mapping company TopScan GmbH ("http://www.topscan.de") using an Airvan aircraft operated by the company Norlandair in Akureyri, N-Iceland. A DHC-6 Twin Otter aircraft from Norlandair was also used for a few days of surveying in September 2012. The wavelength of the lidars operated by TopScan is 1064 nm, the height above ground in a typical lidar survey of the Icelandic ice caps is ∼2500 m and the swath width of each line is ∼1800 m. The aircraft flies at a speed close to 60 m/s or 200 km/h and the lidar instruments return ∼33 thousand points per second. The results are delivered as regular 5x5 m grids and irregularly distributed "point clouds" with the original measurements. It is technically possible to map 500–1000 km^2 in a single day with good conditions for surveying but this is seldom realised in practice. There is good experience with surface mapping of glaciers with airborne lidars both from Iceland and other countries and the technology is increasingly being used for glacier mapping in many countries. An advantage of airborne lidar is that crevassed areas and other areas on glaciers that are difficult to access on land can easily be measured. The instruments do, however, only work in cloud-free conditions and it is often necessary to start very early in the morning in order to avoid fair-weather clouds that often form above the glaciers around mid-day. Experience shows that somewhat more flying time is needed for lidar mapping in Iceland than for many other areas because of the highly variable Icelandic weather. This makes it especially important to work with a flexible survey plan with many available mapping areas to be chosen from based on the actual cloud conditions of each day.

Surveying in 2012

The surveying in 2012 was carried out in four separate efforts as described in Table 1.

Table 1. Overview of the lidar surveying in the summer of 2012.

Period	Area
10–13 July	Western Vatnajökull, Öræfajökull, gaps in the 2010 surveying of Mýrdalsjökull, Snæfell.
2–4 August	Síðujökull, Öræfajökull, Skeiðarárjökull, Kerlingarfjöll, Þrándarjökull, Hofsjökull eystri, some glaciers in southern Tröllaskagi. An area by the farm Hvoll (an area surveyed for studying problems with sedimentation in a glacier river path, separately funded).
12 August	Some glaciers in Tröllaskagi.
12 September	Gaps in Öræfajökull and Skeiðarárjökull. The Hvoll area was completed. Surveying of glaciers in Tröllaskagi was not possible because of thick new snow cover in the mountains.

A project web area at Icelandic Meteorological Office ("http://brunnur.vedur.is/pub/tj/-glaciermapping") was used for exchange of data regarding survey areas, GPS base data, logbook for the surveying of each day and various other data that made it possible for all the people working on the project to follow the day-to-day progress.

Project accounts for 2013

The income and expenses for the lidar mapping project in 2013 are given in Tables 2 and 3. The project accounts are kept in Icelandic kronas (ISK) and are given here in this currency. The current (November 2013) exchange rate of ISK against the Danish krona (DKK) and the Euro are 22 ISK for one DKK and 163 ISK for one Euro. The KoL funding used for mapping in Iceland in 2011 and 2012 was higher than one-third of the total KoL-support of that year because GEUS was unable to spend their share of the 2011-funds. GEUS therefore received two-thirds of the KoL funding in 2013. The own contribution of the project participants is based on official rates of the The Icelandic Centre for Research (RANNIS) that are used in applications to RANNIS (500 kISK monthly salary for scientists). This is considerably below the official cost of salaries at IMO and IES. If the official rates of the institutes were used, the own contribution would be higher than given in the Tables 2 and 3. The total cost of the lidar mapping in 2011–2013 according to the project plan for the entire three-year period is approximately 75 millj. ISK, including the own contribution of the project participants.

Table 2. External funding and own contributions to the lidar glacier mapping in 2013.

Funding body	**Contribution** (kISK)
Support for measurements	
Landsvirkjun	3500
Icelandic Road Administration	2000
Vatnajökull National Park	3000
Friends of Vatnajökull	3000
KoL fund of NCM	–
National Land Survey of Iceland, support for measurements	1000
Icelandic Meteorological Office, support for measurements	3400
Sub-total	15 900
Other support and own contributions	
Icelandic Meteorological Office, data pr., management	1500
Institute of Earth Sciences, Univ. of Icel., data pr., management	500
Sub-total	2000
Total	**17 900**

Continued support from some of the funding agencies in 2014 will be used to cover earlier surveying expenses of 2011 and 2012 that were beyond the project funding during those years.

Utilization of the results of the lidar mapping

The results of the lidar mapping have been reported at more than thirty scientific meetings and conferences (see list at the end of the report) and several reviewed papers in scientific journals and scientific reports making use of the lidar DEMs have been published (Aðalgeirsdóttir and others, 2011; Andersen and others, 2012; Jóhannesson and others, 2011, 2012; Jóhannesson, 2012; Johnson and others, 2010; Magnússon and others, 2012; Schomacker and others, 2011; Björnsson and others, 2013), or are in review (Einarsson and others, 2012; Staines and others, 2013). The digital terrain models themselves have been made available to many institutes and research groups and they are being used in several research projects, in consulting work and in several practical projects that are related to travel and rescue operations on glaciers in Iceland.

An assessment report about changes of glaciers in Iceland, Scandinavia, Svalbard and Greenland was produced within the Nordic research project SVALI (“Stability and Varia-

Table 3. Expenses of the lidar glacier mapping in 2013.

Cost item	**Cost** (Euros)	**Cost** (ISK)
TopScan expenses		
Skeiðarárjökull and S-Vatnajökull	20000	3260
W-Vatnajökull	42600	6044
Þrándarjökull og Hofsjökull eystri	9200	1500
Kerlingarfjöll	9500	1548
Snæfell	8000	1304
Glaciers on Tröllaskagi	7900	1288
Sub-total	97 200	15 844
Expenses corresponding to partner's own contribution		
Icelandic Meteorological Office, data pr., management, field work		1500
Institute of Earth Sciences, Univ. of Icel., data pr., management		500
Sub-total		2000
Total		**17 844**

tions of Arctic Land Ice", "http://www.ncoe-svali.org") in the fall of 2012 (Andersen and others, 2012). The Icelandic lidar maps were the main contribution of Iceland to this work.

The lidar map of Breiðamerkurjökull are being used in the Nordic research project SVALI ("Stability and Variations of Arctic Land Ice") for studies of glacier calving in a work package that is led by the University Centre in Svalbard (UNIS). The lidar maps of other parts of Vatnajökull and other Icelandic glaciers will be used in several other SVALI work packages in studies that take place in 2011–2015. Several research projects involving the lidar maps have been planned where older available maps will be used to analyse glacier changes over the last several decades in detail. This includes changes of Eiríks-, Dranga-, Eyjafjalla-, Torfa-, Tindfjalla- and Tungnafellsjökull among others. A paper about recent changes of Snæfellsjökull based on the lidar map of 2008 has been published in the Icelandic geosciences journal *Jökull* (Jóhannesson and others, 2011) and a paper about the Icelandic lidar mapping effort including a description of many of applications of the lidar glacier maps has been published in the journal *Annals of Glaciology* (Jóhannesson and others, 2013).

The lidar maps were used in a review of the downwasting of glaciers in Iceland during the last couple of decades (Björnsson and others, 2013) that was prepared as a part of an extensive review of the variations of glaciers and small ice caps worldwide. Preliminary results of this work were presented by Helgi Björnsson of IES at the AGU-conference in San Francisco on 5–9 December 2011 and at the IGS International Symposium on Glaciers and Ice Sheets in a Warming Climate in Fairbanks, Alaska, in June 2012.

The lidar maps are being used for mapping of crevasse areas on Icelandic glaciers in

order to improve safety of glacier travel. This effort is organised and supported by the Icelandic Association for Search and Rescue (ICE-SAR), the Iceland Glaciological Society, the Institute of Earth Sciences and several other institutes and companies. A prerelease of the lidar map of Mýrdalsjökull was used in November 2011 in a search and rescue effort on the Sólheimajökull outlet glacier where hundreds of search and rescue volunteers from ICE-SAR searched for a Swedish tourist that was lost on the glacier. The glacier lidar maps are delivered to ICE-SAR as they become available and will be incorporated into navigation equipment and used for detailed planning of search and rescue efforts on glaciers.

The lidar maps of Hofsjökull and Sólheimajökull have already been used in reviewed scientific papers about the geomorphology of the proglacial areas adjacent to the ice margins (Johnson and others, 2010; Schomacker and others, 2011). The maps are also used in several other geomorphological research projects by the same researchers where further publications are planned. Several other research groups at the University of Iceland, the University of Innsbruck and Cambridge University have also requested lidar maps for use in geomorphological research projects.

The lidar glacier maps are already widely used in various consulting and research projects as is described in the following list.

- The river paths of Markarfljót and Svaðbælisá, as well as the lower, ice-free hillsides of the Eyjafjallajökull volcano were surveyed with lidar as a part of the monitoring of the eruption of Eyjafjallajökull in 2010 (separately funded). The 2010 lidar map of Eyjafjallajökull shows the eruption sites within the top crater of the volcano, the path of lava flow towards north down the Gígjökull outlet glacier, the path of a swift jökulhlaup down the southern side of the volcano and fracture lines and widespread flow marks due to lahar floods on the southern slopes. These results have been used in collaborative projects related to the Eyjafjallajökull 2010 eruption and they have been presented at several national and international meetings and conferences.

- The outlet glacier Skaftárjökull in W-Vatnajökull and the proglacial area adjacent to the glacier margin were surveyed by lidar in 2010 in order to study accumulation of glacier sediments that cause problems when they are transported by the Skaftá river and accumulate farther downstream. The Skaftá cauldrons in W-Vatnajökull were also surveyed in the same survey effort providing useful information about the subglacial water bodies below the cauldrons that are the source of jökulhlaups (glacier outburst floods) in Skaftá that may also cause problems for the rural settlements along the lower part of river. (Separately funded).

- Lidar surveying, carried out in relation to the glacier surveying, has been very useful for measuring snow depth in snow avalanche starting areas above several villages and towns in W-, N- and E-Iceland that are threatened by avalanches. (Separately funded).

- The lidar maps of Breiðamerkurjökull, Öræfajökull and other outlet glaciers in SE-Vatnajökull are being used by Snævarr Guðmundsson and Hrafnhildur Hannesdóttur

in their analysis of the variations outlet glaciers of S- and SE-Vatnajökull, which is part of their MSc and PhD studies.

- The lidar map of Mýrdalsjökull has been used by Finnur Pálsson and Sverrir Guðmundsson at IES in consulting work for the consulting company Vatnaskil regarding glacier mass balance and runoff from the watershed of the Hólmsá river east of the ice cap. Vatnaskil is working on the development of a runoff model for Hólmsá for the power companies Landsvirkjun and Orkusalan.

- The lidar map of Eyjabakkajökull and part of Brúarjökull were useful in the updating of an elevation model of the ice surface that was produced for the consulting company Vatnaskil for a hydrological model of inflow to the Hálslón hydropower reservoir operated by Landsvirkjun.

- The lidar map of Hofsjökull was used by the consulting company Vatnaskil for setting up and calibration of hydrological models of glacier rivers in Central Iceland that are used by Landsvirkjun for revising design and operation plans of hydropower plants.

- The lidar map of Öræfajökull in S-Vatnajökull will be used for hazard assessment related to jökulhlaups (glacier outburst floods) caused by an eruption in the subglacial volcano. This hazard assessment is one of first assessments in a general assessment of volcanological hazards in Iceland that was started in 2011.

- The Icelandic Road Administration has used the lidar maps of Markarfljót and eastern Mýrdalsjökull in connection with the design of roads and bridges and protection dams for roads.

- Consultants working on aircraft approach planning for the airport at Höfn in Hornafjörður, south of Vatnajökull, have used the lidar maps of SE-Vatnajökull in their work.

- Many uses of the lidar maps are possible in illustrative materials for tourists and at various sight seeing places and museums where information about glaciers is presented to the public. Information about the lidar mapping has been sent to the Vatnajökull National Park, to the Glacier Museum at Höfn in Hornafjörður and to several other parties that might find the lidar maps useful in their work with tourists and the public. An MSc student at the University of Iceland has been hired to use the lidar maps of SE-Vatnajökull for the production of this type of tourist information.

Papers and reports using results from the lidar mapping published in scientific journals

Aðalgeirsdóttir, G., S. Guðmundsson, H. Björnsson, F. Pálsson, T. Jóhannesson, H. Hannesdóttir, S. Þ. Sigurðsson and E. Berthier (2011). Modelling the 20th and 21st century

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Einarsson, B., T. Jóhannesson, Th. Thorsteinsson and E. Gaidos (2012). Flood discharge and subglacial water storage during a rapidly-rising jökulhlaup from the western Skaftá cauldron, Vatnajökull, Iceland. *J. Glaciol.*, in revision 2013.

Johnson, M. D., A. Schomacker, Í. Ö. Benediktsson, A. J. Geiger, A. Ferguson og Ó. Ingólfsson (2010) Active drumlin field revealed at the margin of Múlajökull, Iceland: A surge-type glacier. *Geology*, **38**, 943–946, doi: 10.1130/G31371.1.

Magnússon, E., F. Pálsson, H. Björnsson and S. Guðmundsson (2012). Removing the ice cap of Öræfajökull central volcano, SE-Iceland: Mapping and interpretation of bedrock topography, ice volumes, subglacial troughs and implications for hazards assessments. *Jökull*, **62**, 131–150.

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Presentations/posters/abstracts related to the lidar mapping

Belart, J. M. C., E. Magnússon and F. Pálsson (2013). Mass balance analysis of Drangajökull ice cap from historical photogrammetry and lidar. In: Jóhannesson, T., and E. Magnússon, eds., *Lidar measurements of the cryosphere, Reykholt, Iceland, 20–21 June 2013*. (Poster)

Belart, J. M. C., E. Magnússon and F. Pálsson (2013). Digital elevation models and orthophotographs of Drangajökull ice cap deduced from historical aerial photographs and lidar. In: Järvinen, O., ed., *Nordic Branch meeting of the International Glaciological Society, Lammi, 31 October – 2 November, 2013*. (Poster)

Björnsson, H., S. Gudmundsson, F. Pálsson, E. Magnússon, O. Sigurðsson, T. Jóhannesson, Th. Thorsteinsson and E. Berthier (2011). Contribution of Icelandic ice caps to sea level change. *AGU Fall Meeting 2011, 5–9 December, San Francisco, CA, USA*.

Björnsson, H., S. Guðmundsson, F. Pálsson, E. Magnússon, T. Jóhannesson, O. Sigurðsson, Th. Thorsteinsson and E. Berthier (2012). Glaciers in Iceland and climate change since the end of the 19th Century. Presentation 63A435 at the *IGS International Symposium on Glaciers and Ice Sheets in a Warming Climate, University of Alaska Fairbanks, Alaska, USA, June 2012*.

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Guðmundsson, S., E. Magnússon, H. Björnsson, F. Pálsson, T. Jóhannesson, E. Berthier (2012). Mass balance and volume changes of Eyjafjallajökull ice cap, from 1984 to 2010, deduced by multi-temporal elevation maps. *Spring Meeting of the Geoscience Society of Iceland, Reykjavík, May 2012*. (Poster)

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Hillshades of the surveying of the summer of 2012

The following figures show several glaciers, ice caps and glacier-covered areas that were surveyed with lidar in July to September 2012 in order to give an indication of the size of the surveyed areas and the quality of the results. The figures all show hillshades illuminated from the NW of digital elevation models derived from the lidar measurements. More figures of the surveyed areas are given in the general project description that is an attachment with this progress report.

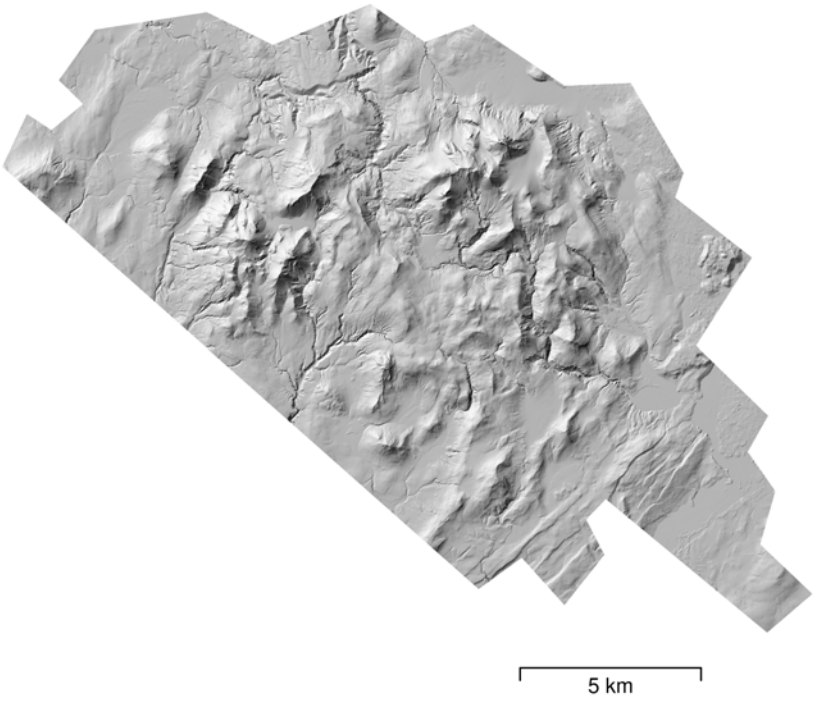

Figure 2. A hillshade of the lidar DEM of glaciers in Kerlingarfjöll, Central Iceland, from August 2012.

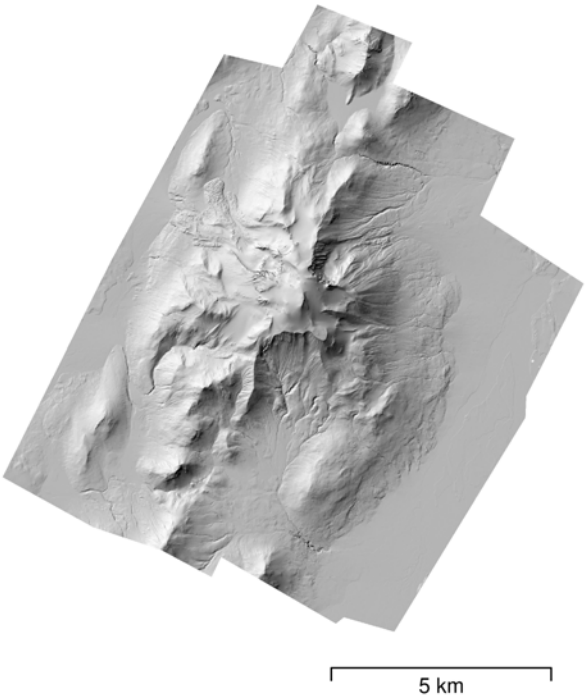

Figure 3. A hillshade of the lidar DEM of glaciers on Snæfell volcano, Eastern Iceland, from July 2012.

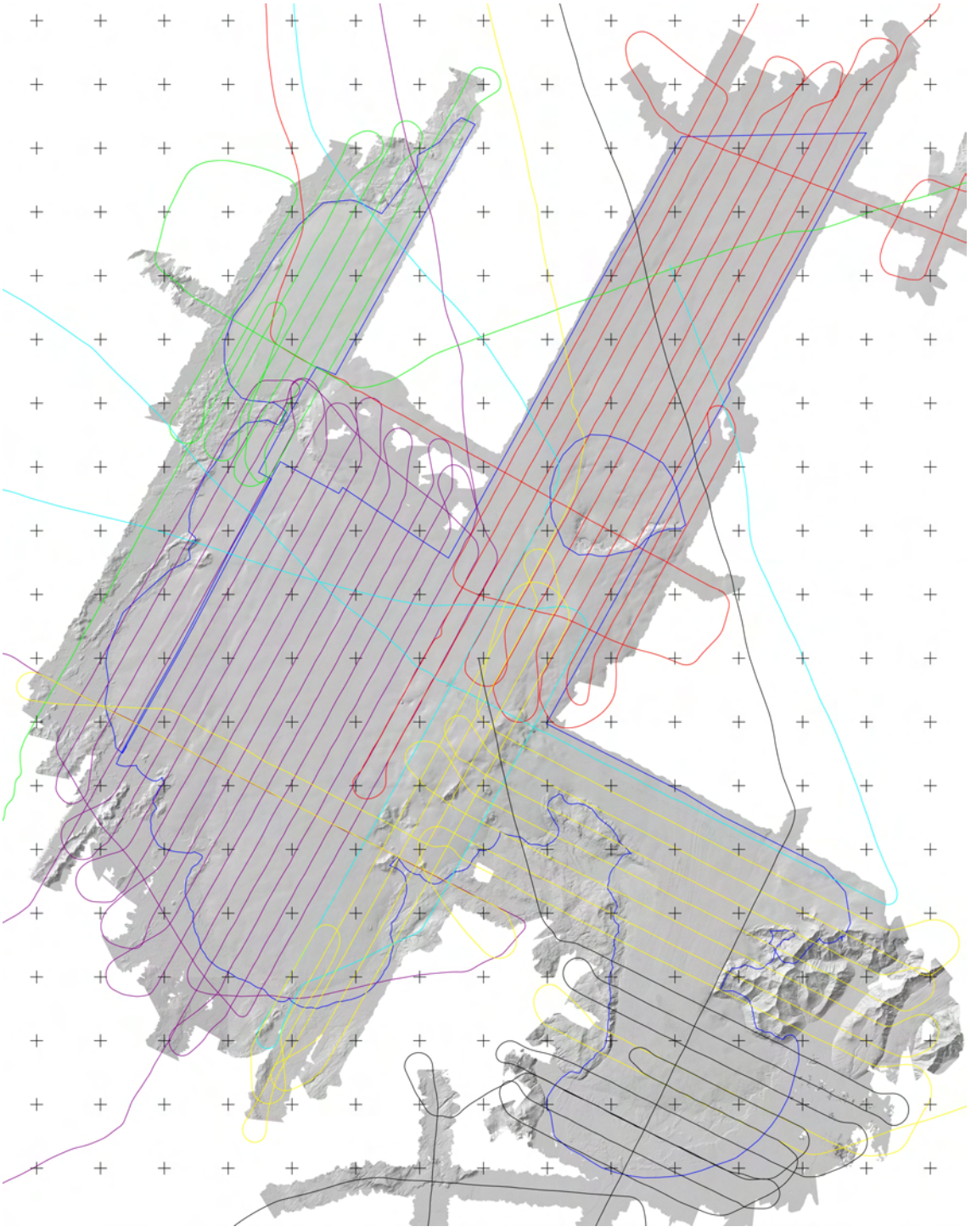

Figure 4. A hillshade of the lidar DEM of Western Vatnajökull, from July and August 2012.