NERC AIRBORNE REMOTE SENSING FACILITY PROJECT 01/18 SCIENTIFIC REPORT

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Southern Langjökull outlet glaciers: glaciological and hydrological applications of digital elevation models

Abstract
Stereo aerial photography of an Icelandic ice cap was acquired by the NERC ARSF in order to provide digital elevation data that can be used to support a range of glaciological and hydrological projects. A DEM of the Vestari-Hagafellsjökull outlet glacier has been generated from this photography, by a combination of image-matching (using Orthobase Pro) and analytical photogrammetry, with ground control points provided by GPS survey. Residual errors in the bundle adjustment of x = 1.02 m, y = 0.46 m, z = 0.38 m, are considered excellent for the photo scale and the use of ground features rather than placed targets for ground control. Some 46 km^2 of Vestari-Hagafellsjökull is covered by the DEM, with practical coverage constrained by the aircraft flying height and residual snow cover.

Background
Stereo aerial photography was requested to facilitate the photogrammetric generation of digital elevation data for the southern part of the Icelandic ice cap Langjökull (Figure 1), in support of a range of glaciological and hydrological projects, including the temporal evolution of ice-cap outlet glaciers, and the development of the seasonal snowpack. Scientifically, this work is focussed on the cryosphere (snow and ice) in the mid-North Atlantic, which is marked by the high rates of mass turnover characteristic of mild, maritime environments. Changes in the cryosphere over the coming century are likely significantly to change freshwater resources and wildlife habitats on land and offshore, with changes in the distribution and cycling of freshwater between land, atmosphere and ocean. These issues are highly relevant to NERC priorities through the importance of snow and ice accumulation and melt in the climate system of North Atlantic mid- to high-latitudes, which is strongly linked with UK climate.

Ground control
Suitable ground control did not exist in this remote area of west-central Iceland, therefore an important part of this project was the survey of new ground control points. A NERC Geophysical Equipment Pool loan of Leica GPS equipment was secured for this purpose. A base-station was established near the Icelandic Touring Club hut at Hagavatn, which was the base for the field work (Figure 1). One GPS receiver with choke-ring antenna was left at the base-station throughout the day while other points, selected for their distinctiveness on aerial photographs, were visited on foot with another, roving receiver, and their positions located in static survey mode. In practice, occupation times were limited to 30 minutes because of time constraints associated with covering long distances on foot (up to 27 km per day). At the end of each day, position data were downloaded to the supplied laptop PC for post-processing and checking, using Leica Ski-Pro software (Table 1). Between 23rd–26th July 2001, 13 control points were surveyed, to the west of Vestari-Hagafellsjökull, to the east of Eystri-Hagafellsjökull, and on the Hagafell plateau in-between these two glaciers, concentrating on areas of overlap in the ARSF aerial photographs (Table 1).

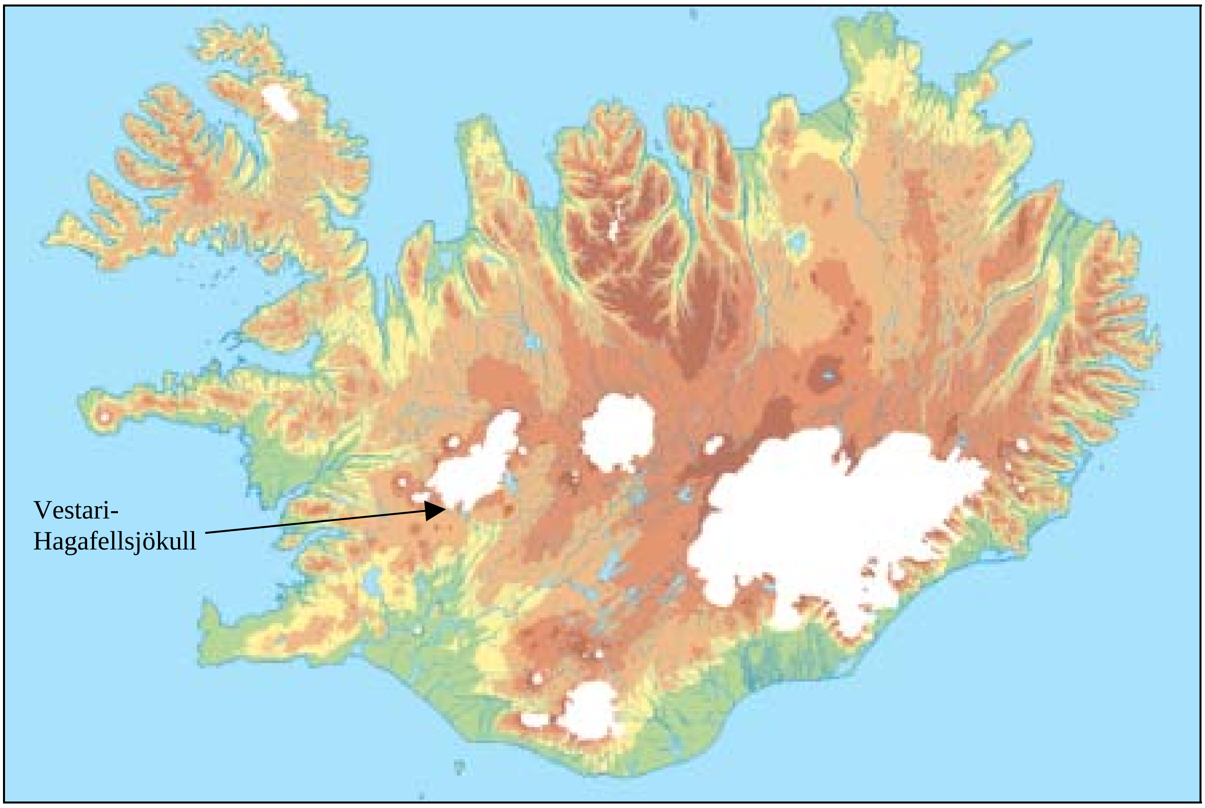

Figure 1. Map of Iceland, showing ice caps in white, and indicating the study glacier.

Processing and modelling: DEM generation

Given the aim of this project was to generate digital elevation data rather than contour maps (which would rely on terrain-following), a strategy of photogrammetrically collecting a dense array of elevation points was important, for: (1) greater effectiveness in areas of sparse detail, because all available data contribute to surface description, not just observable data at or near a contour value; (2) greater accuracy, because all elevation points are stochastically independent; and (3) more consistency than a DEM derived from standard contouring, where the surface between the contours is interpolated. Elevation point data can be collected wherever there is sufficient surface texture to allow sampling: in relatively textureless snow-covered areas this might include crevasses, supraglacial stream channels, avalanched material etc. Final grid cell size represents a compromise between data volume and accuracy, given the relatively extensive, smooth surfaces of most glaciers.

The final DEM covers the area between 7150825–7156725 m north and 523072–530847 m west in the Universal Transverse Mercator system (zone 27). This represents an area of 5.9×7.8 km, or just under 46 km^2. Elevation in this area varies between 520–840 m above the WGS84 ellipsoid. The areal coverage was dictated by the flying height of the ARSF aircraft and the residual snowcover at the time of air photo acquisition. Ideally, the photography would have been acquired later in the summer when the snow cover was further reduced, and it would have been acquired from a greater height, so that fewer photographs were involved in the photogrammetric block adjustment, reducing the possibility of error propagation. However, these constraints were clear and understood at the outset, and the project aims adjusted accordingly.

Point ID	Latitude	Longitude	Ellipsoid Ht	Coordinate Class	Coordinate Quality	StDev Latitude	StDev Longitude	StDev Ht
Base1	2586975.28	-954072.72	5732519.05	REF	0	0	0	0
Base1	2586976.37	-954072.06	5732513.62	NAV	1.1925	0.495	0.4108	1.0041
Base1	2586975.28	-954072.72	5732519.05	SPP	0.1256	0.0517	0.0415	0.1066
Rover1	2586476.81	-949758.21	5733643.76	MEAS	0.0011	0.0005	0.0004	0.0009
Rover1	2586477.57	-949756.49	5733637.38	NAV	2.9104	1.0208	1.1527	2.4698
Rover2	2584654.53	-949030.79	5734712.03	MEAS	0.001	0.0005	0.0003	0.0008
Rover2	2584655.46	-949028.23	5734703.33	NAV	2.9146	1.4539	0.9084	2.3571
Rover3	2584445.46	-946230.55	5735269.66	MEAS	0.0017	0.0005	0.0004	0.0016
Rover3	2584446.13	-946229.74	5735267.30	NAV	2.8575	0.9425	0.8793	2.5503
Rover4	2583763.68	-944764.16	5735837.72	MEAS	0.0012	0.0006	0.0004	0.001
Rover4	2583766.50	-944764.72	5735831.96	NAV	2.6419	1.137	0.9511	2.1869

Table 1. Sample (cartesian format) Ski-Pro software output for base station and control points surveyed on 23rd July 2001.

Data quality and elevation accuracy of the final DEM

The final DEM was compiled by Adrian Fox (Mapping and Geographic Imaging Centre, British Antarctic Survey) from two data sources:

1. DEM automatically generated by image-matching using Orthobase Pro.
2. Data collected by analytical photogrammetry in areas where automatic DEM generation was not successful due to lack of unique surface texture.

For logistical reasons the ground survey was carried out several weeks later than the aerial photography. It is known that the surface elevation of the glacier decreases by several metres during the summer period due to ablation. Thus independent, field-surveyed check data relevant for the glacier surface at the photography date could not be collected and no statistical measure of DEM accuracy against independent data can be given. In these circumstances accuracy for the parts of the DEM generated automatically has been checked against analytical photogrammetry measurements using the same orientation parameters for the photographs. In the absence of independent check data the analytical photogrammetric measurements are held as accurate within the measurement limits of the equipment and operator. Note that in this project, where the photogrammetric data are being generalised into a DEM with a cell size of 25 m, the elevation accuracy is more important than the positional accuracy of the data.

Final DEM error is a compound of the following:

1. *Ground survey*: accuracy statistics from the post-processing of the GPS survey data indicate that the control points are accurate to better than 0.25 m. This can be regarded as a minimal contributor to the accuracy budget of the project.
2. *Residual error in the bundle adjustment*: the residual errors of x = 1.02 m, y = 0.46 m, z = 0.38 m, are considered excellent results given the photo scale and the use of ground features rather than placed targets for the control points.
3. *Orthobase DEM*: root-mean-square error for 10 randomly-chosen analytical plotter measurements against the corresponding DEM cell, for each of the three stereo-pairs from which almost all of the Orthobase DEM is derived, indicates an accuracy of:
    - 60-62 = ± 2.34 m
    - 62-63 = ± 1.70 m
    - 63-64 = ± 2.56 m

    The largest single error was 4.0 m.

Interestingly, the DEM error was observed to be negative (DEM lower than check data) for 27 of the 30 samples showing a systematic skew to the data. There are three possible contributors to this skew:

1. Systematic error in DEM computation.
2. Systematic error in measurement of analytical photogrammetry check data.
3. Effect of large DEM cell size and convex slope of glacier. Averaged elevation for the whole DEM cell tends to produce an under-estimation compared to point check data for convex slopes.

In a test of consistency of measurement by the operator, the standard deviation of 10 independent measurements of the same randomly selected point was 0.50 m, with a maximum variance from the mean of 0.80 m. Accuracy of the analytical photogrammetry data is subject to the residual error in the orientation of the photography in (2), and the possible systematic error discussed above.

Interpretation and preliminary findings

The DEM constitutes the output from this project and is a valuable product in itself in a region of rapid glacial change: copies of the data have therefore been submitted to World Data Centre C for glaciology, and to Landmaelingar Islands (the National Survey of Iceland). However, it can also be regarded as a starting point for distributed glaciological and hydrological modelling applications which require elevation data as an input. The PI has been awarded a NERC grant 'Modelling the spatial and temporal evolution of winter glacier mass balance' (NER/B/S/2001/00851) to monitor and model snowpack development at Vestari-Hagafellsjökull; winter processes are a major area of uncertainty in current glacier hydrological models. The DEM will be an important input for this project, providing topographic boundary conditions for the interpolation and distribution of both observed and modelled meteorological and snowpack data.

Conclusions and recommendations

High mass-balance gradient, flat-profiled ice caps such as Langjökull are the most responsive of ice masses in terms of climate change, but are also probably the key unconstrained class of glacier types. Too large for field survey, they are still poorly covered by satellite-based sensors. Therefore, aerial photography is a critical tool for studying these ice masses, and for acquiring the digital elevation data that modern, distributed modelling applications require. The ARSF flight was consequently highly beneficial, and any repeat would be welcomed.

The ARSF photography proved a suitable basis for photogrammetry when combined with a GPS ground control survey. Overall elevation accuracy for the final DEM is expected to be better than 3.0 m. There may be isolated larger errors in the automatically-generated parts of the DEM, but these are not large enough to show as significant spikes/pits. The largest error found against 30 check data points was 4.0 m. There appears to be a systematic under-estimation of elevation by the automatically-derived DEM compared to analytical photogrammetry data of 1.0–2.0 m.

Publications

Hodgkins, R. and Fox, A.J. 2002. Digital-elevation modelling of Vestari-Hagafellsjökull, Langjökull, Iceland. *Geografiska Annaler*, in prep.

This is a short paper which aims to focus on issues in the photogrammetric mapping of glaciers and digital elevation data acquisition, with a short GIS-based study of change in the geometry of Vestari-Hagafellsjökull since compilation of the Icelandic Survey 1:50,000 map (which is based on aerial photographs acquired between 1989–1991).

Further publications will arise from NERC grant NER/B/S/2001/00851, but these are unlikely to be submitted before 2004.

Results and accuracy statement for DEM generated for Vestari-Hagafellsjökull, Langjökull, Iceland (supplied by Adrian Fox, BAS).

Overall results of bundle adjustment:

X(westing) = 1.02 m   y(northing) = 0.46 m   z(altitude) = 0.38 m

Residuals at the control points (metres):

Point ID	rX	rY	rZ
1	2.5651	0.0818	-0.3286
2	0.0838	-0.1932	0.0630
3	-0.5408	0.1099	0.5844
4	-0.1867	0.6518	-0.2794
5	-0.5804	1.0102	0.2540
6	0.4196	0.1273	-0.0292
7	0.0091	-0.2247	-0.0092
8	-0.9413	-0.1087	0.5559
9	1.6257	-0.6604	-0.8783
10	0.0774	0.2655	-0.1917
11	-0.4038	0.0577	0.3359
12	-0.8146	-0.3756	0.0398
13	-1.3131	-0.7417	-0.1164

The exterior orientation parameters
(UTM coordinates, WGS84 z datum; not sea-level)

photo	ID	Xs	Ys	Zs	OMEGA	PHI	KAPPA
58	1	523158.4179	7153406.5030	3688.9851	3.5062	7.0029	-176.2180
60	2	525364.8461	7153324.6725	3684.6074	-3.1593	5.1000	178.4488
62	3	527607.8315	7153230.6693	3682.5865	-0.9019	5.3153	176.3006
63	4	528729.9488	7153143.5738	3679.6823	-3.2329	4.2015	180.6811
64	5	529826.7527	7153121.7143	3680.8796	2.6210	3.5904	182.7097
65	6	530945.9698	7153091.8402	3680.4414	-1.4378	2.5678	-178.5933
66	7	532061.5197	7153087.3703	3680.5843	-0.3265	2.4430	-178.0628
67	8	533224.1364	7153073.7934	3679.6197	-0.9531	3.1299	180.5648
68	9	534323.0391	7153098.5993	3679.1500	-2.1737	3.5413	-175.3924
70	10	536546.9345	7153173.9238	3684.8501	-3.4087	3.7802	-179.7163
72	11	538790.2394	7153188.3456	3691.1403	-2.1788	5.5609	-180.8669
74	12	540994.2015	7153114.1105	3684.9464	-7.3149	5.3201	181.5967
75	13	542108.7313	7153134.8358	3690.3335	-4.0803	5.2124	-176.1390
79	14	544579.2608	7156599.3282	3676.2261	-1.7975	2.4948	-2.7407
80	15	543469.3394	7156613.3799	3669.6188	-3.3919	3.9273	-1.2033
81	16	542323.2183	7156633.1074	3665.2498	-2.3292	4.6496	0.3098
82	17	541201.3246	7156620.2940	3664.6638	-0.6453	4.8747	-1.8007
83	18	540082.4547	7156615.6504	3663.3493	-0.5510	5.3720	-1.6238
84	19	538964.2483	7156590.0836	3657.3022	-0.0920	3.1220	-1.1237
85	20	537843.1368	7156578.7323	3651.6595	-0.2636	0.4997	-5.2878
87	22	535630.3387	7156609.9409	3665.0825	-1.4358	-0.3159	-1.4623
88	23	534508.4464	7156594.7900	3666.8538	-0.9988	-0.6488	-1.4840
89	24	533388.2372	7156590.6340	3668.5178	-0.2743	-1.1274	-3.0194
90	25	532281.1673	7156595.7418	3670.5104	-0.2256	-1.5561	-2.9315
91	26	531179.2579	7156597.5853	3672.4805	-0.2313	-1.6583	-1.9653
92	27	530070.1590	7156591.8140	3671.9292	-1.1429	-1.1033	-2.0753
93	28	528950.8335	7156603.5122	3671.1780	-0.9688	-0.5304	-3.4834
94	29	527835.9971	7156611.4289	3672.8798	-1.1411	0.0767	-1.1969
95	30	526715.7690	7156609.8467	3673.8087	-1.7731	0.4983	-1.3009
96	31	525584.4818	7156626.6870	3672.7361	-1.4049	1.0651	-1.8210
97	32	524478.9091	7156640.2446	3674.6027	-0.7684	1.4162	-0.9651
98	33	523356.9574	7156631.8222	3675.9374	-0.6853	1.5681	-0.5242

Summary Table of Error Budget		
Project stage	***Error x and y (m)***	***Error z (m)***
Control points	< 0.25	< 0.25
Bundle adjustment	X = 1.02, y = 0.46	0.38
Orthobase DEM (against analytical check data)		± 2.50 RMSE
Analytical photogrammetry (operator consistency)		< 1.0

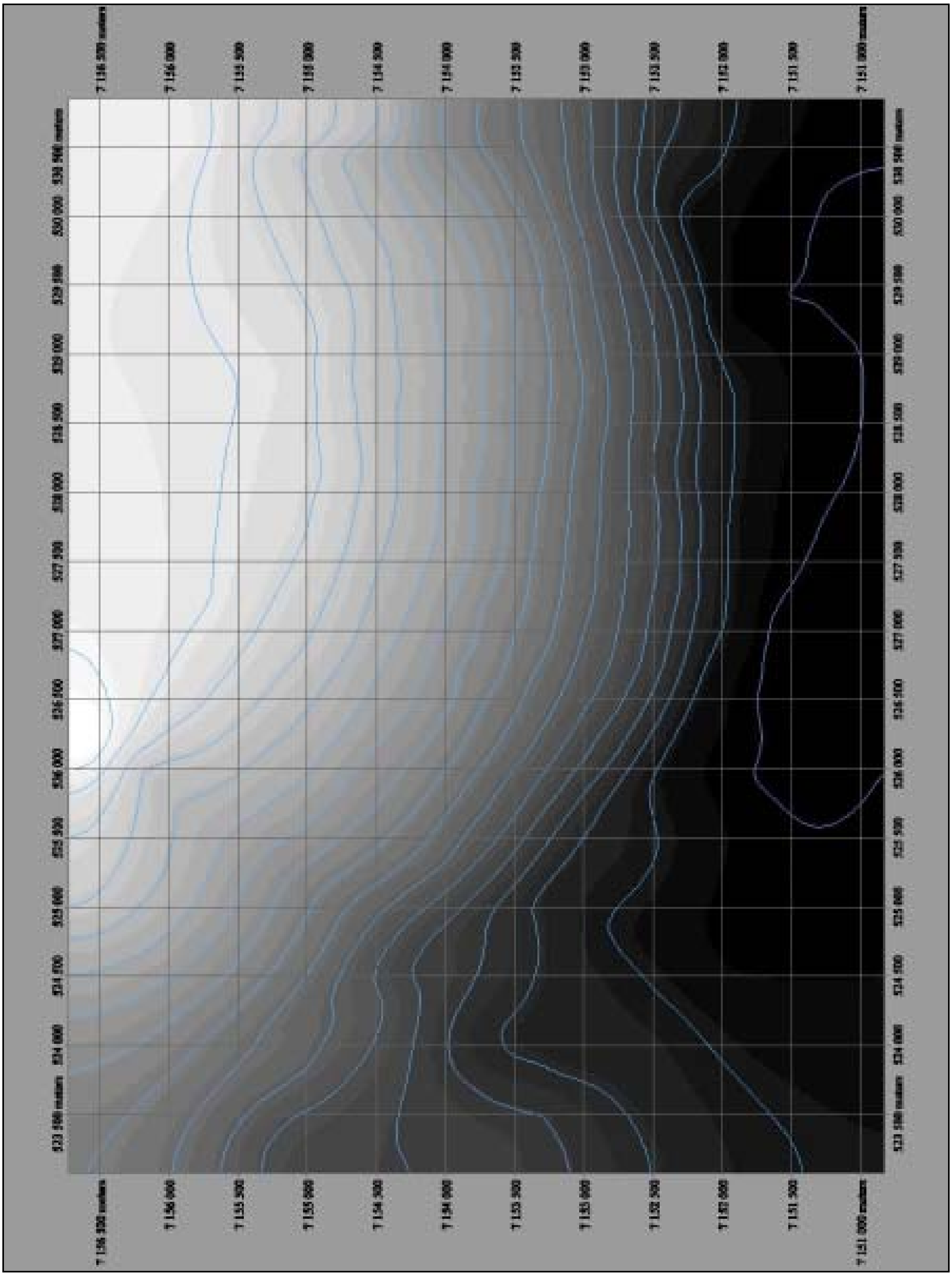

Figure 2. The Vestari-Hagafellsjökull DEM. The greyscale intensity, dark to light, represents elevation. North is towards the left of the page. Contours have been added to give an impression of the shape of the glacier terminus, but the DEM is primarily for use as model input, rather than for topographic mapping per se.