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Precision Aerial Survey of Vatnajökull, Iceland by Digital Photogrammetry

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Abstract: The monitoring of Europe's largest glacier, the Vatnajökull, with satellite radar methods makes necessary to have accurate height reference data. Consequently, the National Land Survey (NLS) of Iceland in Reykjavik decided to provide a precision height base survey of a profile across the glacier.

Analysis and measurement of the imagery was performed purely digitally at Munich Bundeswehr University. The processed aerial block consists of a total of 92 images. Available was a DPW770 of LH-Systems and the block adjustment program CAP. Objectives of the task was the generation of a dense digital elevation model (DEM) of highest possible precision.

1 INTRODUCTION

The subglacial eruption (30.Sept. 1996 – 13.Oct. 1996) located in the Gjálp fissure (Fig. 1) between the volcanoes Grímsvötn and Bárðarbunga under the ice masses of Europe's largest glacier, Vatnajökull in Iceland, gave rise to a tremendous break-up of the Skeiðarárjökull tongue and subsequent catastrophic flooding (5 Nov. 1996 – 7 Nov. 1996). Within almost 2 days more than 3.4 cubic kilometers of water spread over the Skeiðarársandur to the Atlantic Ocean, devastating large parts of the sander area. Although the glaciated area had been observed by satellite imaging radar, the eruption almost came as a surprise. In order to permit more realistic forecasting of future outbreaks, Vatnajökull will be continuously monitored by satellite radar methods (MÜNZER et al., 1998, 1999).

Figure 1: Eruption site Gjálp on Oct. 12, 1996 © Oddur Sigurdsson

The most sensitive indicator for future outbreaks are elevation changes of the surface of the glacier. In order to get a set of reference height data, the National Land Survey of Iceland (Landmælingar Íslands) in Reykjavik decided to perform an image flight over the important parts of the Vatnajökull glacier (Fig. 2). The aerial photography were taken along three strips along a North-South profile of an area of about 100 by 20 km^2 from a flying height of about 8000 m.

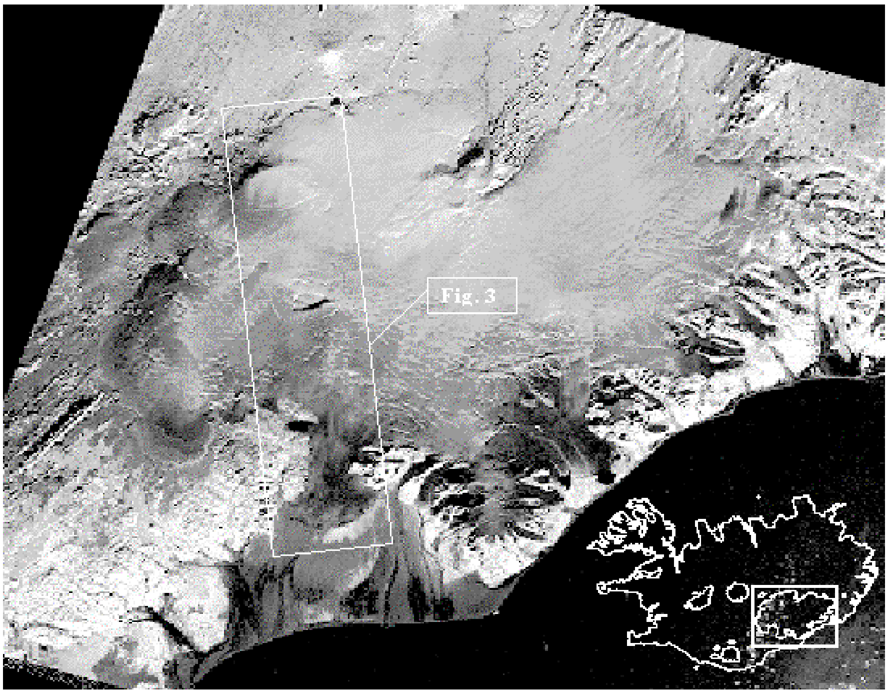

Figure 2:Vatnajökull glacier (Landsat TM, band 5, 19.10.1992) with test site of the photogrammetric DEM. © Eosat 1992

Analysis and photogrammetric measurement of the imagery was performed at Munich Bundeswehr University on a purely digital basis. The used hardware was a Sun Ultra 1 workstation with 256 MB RAM and 28 GB hard disk capacity. A second monitor with a polarised mask from NuVision is provided for stereo vision. In this way, a stereoscopic view is possible with passive eyeglasses. Furthermore, the workstation has handwheels, footdisk and foot switches, common to analytical devices, for stereo compilation.

The workstation runs under the operating system Solaris 2.5.1. The software package SOCET SET (softcopy exploitation tools) in the versions 3.2.1 res. 4.1.1 of HELAVA serves as photogrammetric software component. In addition, the adjustment program CAP (Combined Adjustment Program) was available at the institute.

2 DESCRIPTION OF UTILIZED DATA

2.1 Photoflight and Aerial Images

The photoflight was carried out by the National Land Survey of Iceland with a Leica RC 30 photogrammetric camera with 152 mm focal length on August 12th, 1997, i.e. almost one year after the volcanic outbreak. Vatnajökull was surveyed along a north-south profile consisting of three aerial strips covering an area of 100 by 20 km^2. Flying altitude was about 8000 m, yielding image scales in the range between 1:52 000 and 1:39 000 depending on the terrain elevations between almost sea level in the south and slightly over 2000 m on Bárðarbunga. The aerial photography was supported by kinematic GPS (Ashtech Z-XII 3). Caused possibly by strong cross winds and insufficient correction of camera swing during the photo flight along meandering strips, the images between neighboring strips exhibit a swing with respect to each other by amounts of up to 12° (Fig. 3).

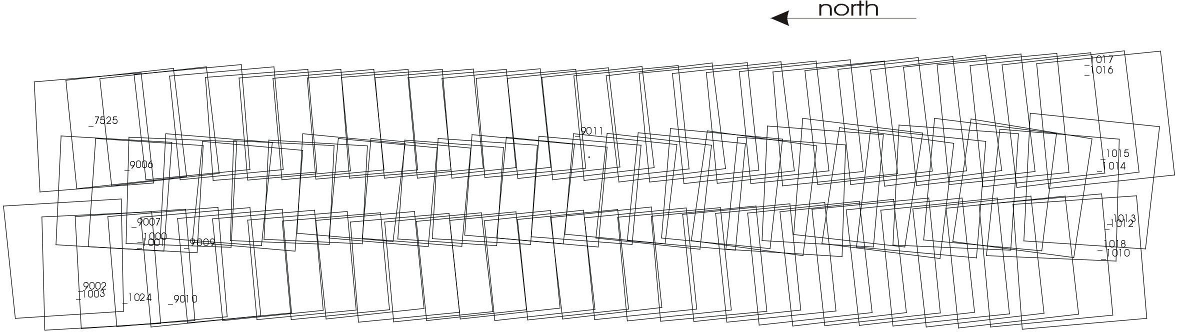

Figure 3: Aerial image block with terrestrial control

In total 92 digitized images at scanner resolution of 25 µm were made available on 14 CD-ROMs requiring a memory of 11 Gbytes. Scanning had been carried out from enhanced diapositive copies (reduction of high albedo over glacier areas) of the original negatives, and referenced to image space. This latter effect gave rise to some problems during triangulation due to the meandering strip arrangement.

2.2 Control

The coordinates of several previously marked or signalized ground points as well as some radar reflectors were made available by the Science Institute, University of Iceland. An additional set of natural control points, selected by us from the aerial imagery, was GPS surveyed by a field crew of the same institute. Unfortunately, the distribution of the 19 control points is rather inhomogeneous. One - poorly identifiable - point is situated approximately in the central part of the block on a bedrock outcrop, all the others lie on icefree ground to the north or south of the glacier area (Fig. 3). Due to the bridging distance of almost 50 km, attempts of an aerial triangulation based solely on terrestrial control consequently failed as far as the desired accuracy was concerned.

Kinematic GPS data and camera exposure data collected during the photo flight were made available to us at a fairly late stage of the project. Together with simultaneous GPS data from the permanent station Höfn some 100 km to the east, the positions of the airborne GPS antenna could be determined for all camera exposures by differential GPS and with a spatial precision between 0.2 and 2.1m referred to WGS84. The computations were carried out with the program GeoGenius v. 1.6 from TerraSat. As shown in Chapter 3, the triangulation with GPS gave highly satisfactory results (Tab. 1).

2.3 Coordinate Systems

During processing of the image block several coordinate systems had to be employed, viz. the geodetic reference system of the Icelandic Survey (UTM), in which the control points were given, further the GPS geocentric system (WGS84) and a local topocentric system (LTC), not to forget the two photogrammetric image coordinate systems, viz. pixel-based digital mensuration system and fiducial-based image system. Within the land surveying system the three-dimensional position of a survey point is given by its UTM-coordinates on the WGS84 spheroid and by an elevation above the (local) geoid. For a limited number of control points the spheroidal elevation was given as well. This enabled the spatial referencing of all points to a common spheroid and thus to 3D space.

As all photogrammetric relations are referred to orthogonal cartesian coordinate systems, transformations from UTM to spheroidal, geocentric and topocentric (LTC) systems had to be carried out. In particular, the local topocentric coordinate system was chosen with its origin in the center of the block, z-axis vertical and x-axis directed towards. LTC coordinates were utilized throughout the entire photogrammetric process. Only for the derivation of height contours, a transformation back to UTM was necessary. The diagram in Fig. 4 schematically shows the interrelations between various coordinate systems.

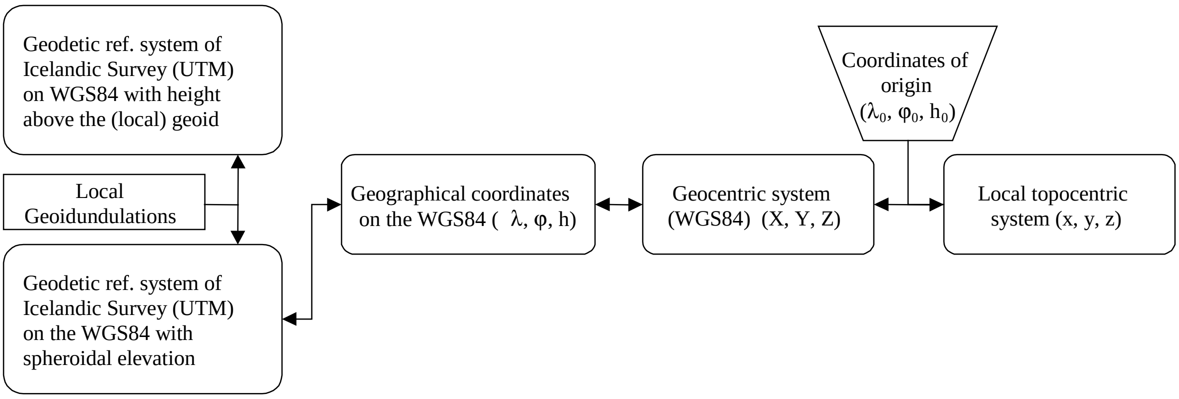

Figure 4: Transformations between coordinate systems

2.4 Geomorphology of Area

The investigated region represents a north-south profile across the western part of Vatnajökull with a width of some 20km. The terrain to the south of the glacier is characterized by fluvial and glacial deposits. Several pronounced rings of terminal moraines are followed by a vast and extremely flat sander plane with elevations ranging from slightly over 100 m down to sea level (0 m). The glacier itself rises gently to elevations around 1700 m and reaches the caldera of the subglacial volcano Grímsvötn approximately in the middle of the profile. Situated north of this caldera, right in the center of the icecap is the subsidence zone of the 1996 Gjálp eruption. Further to the north-west, and with over 2000 m the highest point, lies Bárðarbunga, an ancient central volcano completely covered by ice and snow. Still further north, Vatnajökull ends on partly steep, partly gentle slopes on a volcanic highland at 1000 m above sea level. The geomorphology of this highland is characterized by old lava flows as well as fluvial and glacial deposits.

The various glacier tongues, particularly Skeiðarárjökull are covered with a large number of dark cinder bands thus exhibiting very good contrast and texture conditions. The central region of the glacier is mostly covered by snow, the poor contrast thus representing a challenge to the photogrammetric digital matching process. The ice-free areas on both sides of the glacier consist either of steep mountains of rough bare basaltic rock formations or of smooth cinder or sandy terrain without significant vegetation.

3 RECURSIVE AERIAL TRIANGULATION ADJUSTMENT

SOCET SET's triangulation module HATS (Multi Sensor Triangulation) is the key component for digital aerial triangulation of LH-Systems' DPW770 and represents a major advantage for automated tie point measurement. HATS, however, possesses only limited adjustment capabilities with a non-transparent theoretical background. We therefore used another software package, viz. CAP (HINSKEN, 1989) for the actual rigorous block adjustment phase. The newest version of SOCET SET (4.1.1 under Windows NT), incidentally, has CAP - now denoted ORIMA - incorporated into HATS.

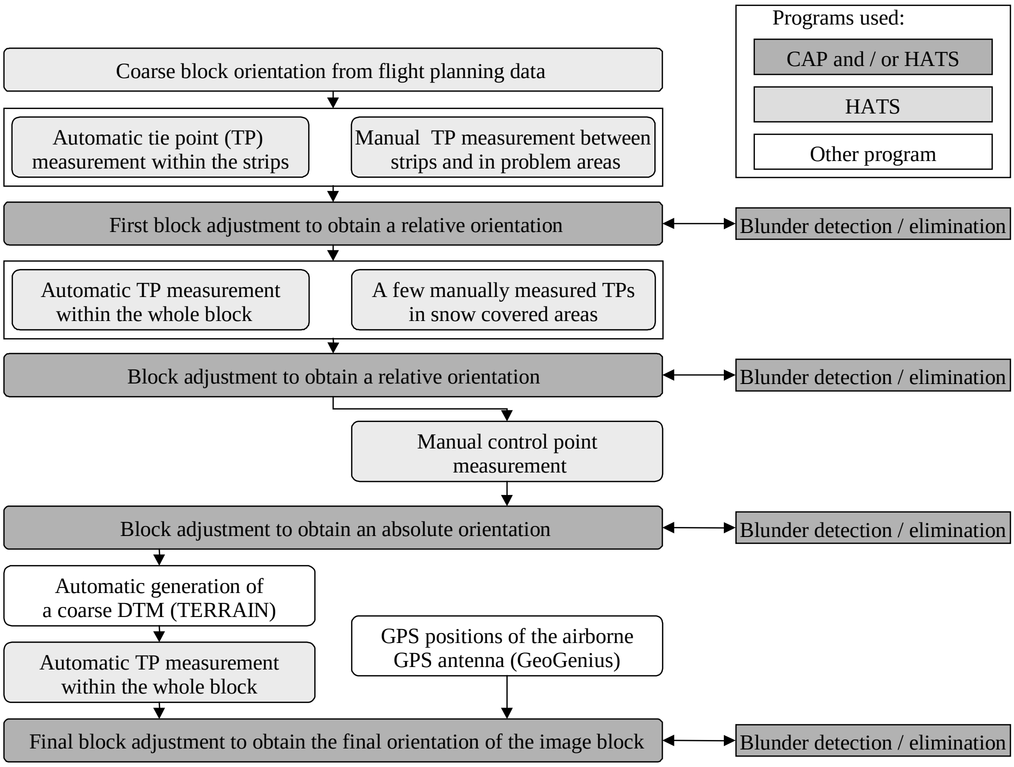

Figure 5: Block diagram of recursive image triangulation

One of the most important lessons we have learned is that tie point measurement on the one side, and block adjustment on the other side, must not be considered as completely separate processes. Both performance and final accuracy of the block are highly dependent on the way how measurement phase and adjustment phase are interconnected within each step of the recursive process (Fig. 5).

3.1 *Image tie point measurement with HATS*

In order to obtain best possible geometric ties between the images, our strategy was, to measure - possibly automatically - as many tie points as can be managed by HATS, the maximum number of tie points between two images being 98 in SOCET SET v. 3.2.1. and arbitrarily many in Version 4.1.1. Automatic measurement by digital image correlation consists of parallax determination for corresponding points in two images. A serious limiting factor is the necessity of providing rather good approximate initial values for the orientation of the images. Kinematic GPS-data were not available in an early stage of the project, we, therefore, had to restrain to flight planning data. Since the relatively large swing angles between neighboring flight strips could not be considered within the flight planning data, automatic tie point measurement turned out to be reasonably satisfactory only within individual strips. Problems occurred with snow covered parts of the glacier where big failure rates had to be taken into account. With first approximate orientation parameters provided thus by HATS, in a second step additional tie points were measured in manual mode both within and between the strips until enough tie information was obtained for successful triangulation of the block. Blunders in the observations detected by block adjustment were then deleted and the process was repeated. With these approximations tie points in the entire block could then be measured automatically. Although neither their number nor distribution were optimal at this stage, they turned out to be sufficient for further improvement of the block-relative orientation (BLUDOVSKY, 1999).

In the subsequent step all available control points were measured in the images and introduced into block adjustment. Both accuracy and reliability of the resulting absolute orientation of the block allowed for the automatic computation of a first coarse digital elevation model (DEM). SOCET SET Version 4.1 even offers the possibility of incorporating the DEM into automatic tie point measurement. A final automatic tie point measurement carried out in this way brought satisfactory results, both with respect to the number of successfully measured points and concerning the distribution of the points.

3.2 *Bundle Block Adjustment with CAP*

The Institute of Photogrammetry and Cartography has direct access to two software packages for aerial triangulation, viz. HATS integrated into SOCET SET and CAP (Combined Adjustment Program) originally developed for close range photogrammetry. The advantage of HATS lies in its full integration into SOCET SET. No additional software interfaces are required, and a project can be processed under the same computer surface (Motif) from beginning to end. Bad performance and hardly any flexibility regarding additional observations, however, represent serious disadvantages.

CAP is an external program package running under MS-Windows. Since SOCET SET does not offer suitable interfaces to CAP we had to create our own interface routines. Prior to block adjustment, all image coordinates measured in the images, object coordinates of control points and approximate object coordinates of all tie points, have to be transferred from SOCET SET into CAP compatible format. After block adjustment the orientation parameters determined by CAP have to be exported back into SOCET SET compatible format. CAP is extremely flexible regarding incorporation of additional observations or unknowns. CAP also permits statistical tests for the results and can thus recognize blunders in the data. Due to CAP's high performance, different adjustment versions can be quickly computed and analyzed.

As an example, within HATs one computation for the orientation in the final configuration took several hours whereas CAP required only 2 minutes. This shows in an impressive way the high performance of CAP.

The block was finally adjusted together with the computed object coordinates of the airborne GPS antenna (see 2.2) transformed from WGS84 to LTC. At this stage the calibrated focal length was allowed to vary slightly (result after adjustment: -0.0049 mm), and the eccentricity between GPS antenna and camera perspective center was introduced by a reasonable constant amount.

3.3 Results

The final results - particularly the achieved accuracy - of the adjusted block are shown in Tab. 1. They show the medium standard deviations of the orientation parameters for the image block.

Table 1: Resulting block adjustment accuracy

σ_x [m]	σ_y [m]	σ_z [m]	σ_ω ["]	σ_φ ["]	σ_κ ["]
0.229	0.225	0.170	6".90	5".90	3".52

4 DEM GENERATION WITH SOCET SET

Most parts of the investigated area are ideally suitable for automatic DEM generation by means of digital photogrammetry. The main advantage is, that there is no disturbing vegetation or urban building within the project area. This means that the surface visible on the images is exactly identical to the surface of the DEM to be generated. Another advantage for the automatic DEM generation is given by the high texture in about 80 % of the image data used. On the other hand, automatic DEM generation for the snow covered areas in the central part of the block is rather difficult and needed the assistance of a human operator.

4.1 Automatic DEM Generation

The automatic generation of digital elevation models is made possible by SOCET SET's module TERRAIN. TERRAIN not only allows DEM generation for single stereo models but also for arbitrary large blocks in one step. A special adaptive algorithm finds an optimal combination of images for the parallax measurement (ZHANG, 1997; BACHER, 1998). Essential advantage of such an approach is that partial DEM's need not be merged later, thus providing a homogeneous DEM data set. This entails reduced additional editing work by the human operator and, thus, yields substantial time savings. For automatic derivation of a DEM with SOCET SET, solely the involved imagery, desired DEM raster width, and the computational mode (either GRID or TIN) are required. The border of the total area is determined fully automatically.

Total computation time required for the 100 x 20 km^2 DEM area at 25 m raster amounted to less than two days on a Sun Ultra 1. In fact, the DEM could be processed over a weekend.

4.2 Interactive Editing of DEM

A first visual quality control may be carried out with the help of a terrain shaded relief (TSR). In this way, topographic discontinuities can easily be recognized from densely textured gray value changes, while areas with homogeneous slopes exhibit more uniform grey values (Fig. 6). Regions with only a few successfully measured points develop artifacts, i.e. artificial triangular or radial structures (Fig. 7). A further possibility of visual control is given by overlaying the stereo models with contour lines derived from the DEM. Stereoscopic inspection immediately reveals incompatibilities between stereomodel and contour lines.

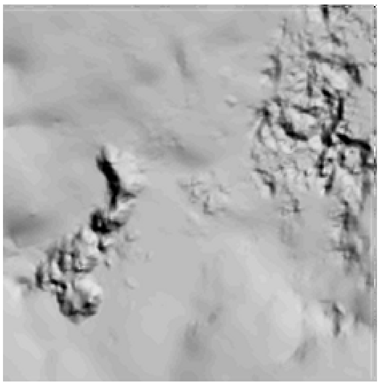

Figure 6: TSR with errors caused by clouds

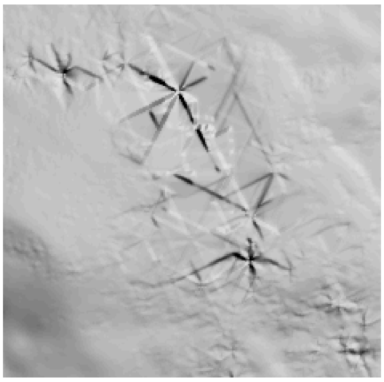

Figure 7: TSR with artificial triangular in regions with only few successfully measured points

By this way, roughly 10% of the total DEM area was found to be contaminated by errors. Regions obviously prone to errors may be caused by weak surface texture, partial coverage by clouds or fog, very steep slopes with dark shadows. Surprisingly large errors were found along a relatively broad (~500 m) band along the entire margin of the DEM. We suspect this inexplicable phenomenon to be caused by software errors in conjunction with automatic border determination.

TERRAIN provides three DEM editing possibilities, denoted Post-Editor, Area-Editor and Geomorphic-Editor, all of which were used.

The Post-Editor was mainly employed in regions of rough terrain where a large number of densely packed points had to be corrected. Editing is performed such that after having automatically moved to a raster point, only the new - presumably correct - elevation must be measured stereoscopically by setting the measuring mark onto the stereo model surface. Proceeding to another point initiates replacement of the old elevation by the new value. This type of editing provides high accuracy but at the expense of considerable time consumption.

With the Area-Editor corrections to the DEM may be brought forward within previously specified areas marked by polygons. The original data are smoothed or interpolated anew. As the data are not remeasured but only manipulated computationally, the method should be used with some care.

The Geomorphic-Editor allows for stereoscopic visualization and - within specified areas - remeasuring of profiles or contour lines. The method is particularly suited for editing larger regions with prevailing uniform topography, requiring, however, an experienced stereo operator.

4.3 Discussion of Results

The entire DEM was computed within a 25 m raster and required more than 19 MB of floating point memory.
The visual control of the TSR and the derived contour lines overlaid over the stereomodels showed blunders only in the central parts of the image block where the glacier is covered with snow. In the erroneous parts it was necessary to edit the DEM interactive. This part of the evaluation took about two weeks and could be done only by an experienced stereo operator.

The finally edited DEM in Fig. 8 is shown in terms of LTC-coordinates, i.e. as undeformed surface in 3D-space. In fact, any kind of geometrical comparison of the glacier surface with future results should be performed within a cartesian coordinate system. This requires rigorous transformations to and from spheroidal and UTM-based coordinates (see 2.2). Elevation contour lines, however, are only meaningful if the elevations are referred to a reference spheroid or - better - a geoid.

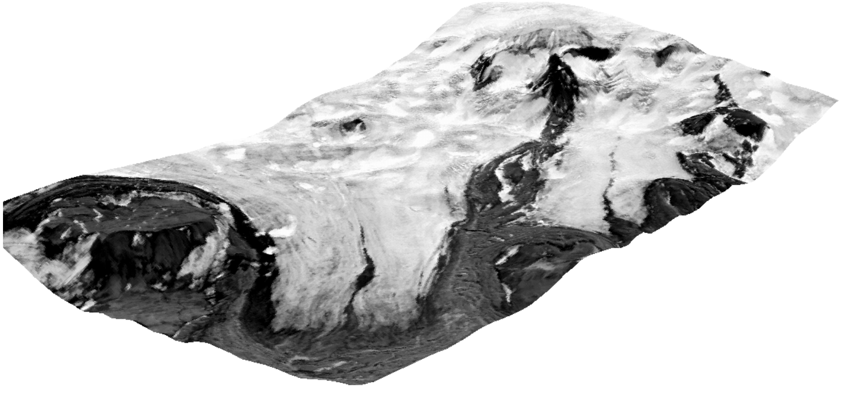

Figure 8: Perspective 3D representation of part of Vatnajökull

In order to transform the DEM from LTC back to a useful coordinate projection, the DEM was exported from the DPW770 as an ASCII DEM, i.e. a list of x, y, z coordinate triples. As shown in Fig. 4, each point of this list was then transformed to UTM-based coordinates with the heights above the reference spheroid or the geoid, depending on the requirements of the DEM user. The result again is a list of UTM-based coordinates that can be imported as a new project back to SOCET SET. SOCET SET again enables interpolation of a regular grid from the mass of TIN points. The final DEM can then be exported to most of the popular DEM formats.

5 CONCLUSIONS

A precise DEM of a part of the Vatnajökull glacier, Iceland, was produced in a purely digital way. Several areas - in total 10% of the block - with little or vanishing contrast had to be interactively edited.
The elevation accuracy of the final DEM is estimated between 1 and 2m. Final statements about accuracy can be made after a reference GPS measurement of some profiles in summer 1999.

Acknowledgements

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