

1. Introduction

Storglaciären is a small (3.016 km²) valley glacier on the eastern flank of the Kebenekaise massif in northern Sweden. It is perhaps most known for having the World's longest continuous surface mass balance record, starting in 1946 and continuing to this day under the aegis of Stockholm University and the Tarfala Research Station (Holmlund et al., 1996; Holmlund and Jansson, 1999). Approximately every 10 years a new survey of the glacier surface elevation and its perimeter is undertaken (Stockholm University, 2015). Previous surveys were performed using aerial photographs, which presents some problems when surveying a glacier. The accumulation area of a glacier is typically covered in snow or exposed firn: snow exhibits a low contrast, near featureless surface that is very difficult to map from orthophotographs. Over fresh snow there are few if any naturally occurring markers to guide parallax measurements. Of the five historical aerial photograph datasets available over Storglaciären, only one, that from 1980, is regarded as displaying high contrast (e.g. Koblet et al., 2010). This is particularly problematic when determining elevation and introduces considerable errors (e.g. Koblet et al., 2010; Andreassen et al., 2002). The 1999 DEM over Storglaciären, the most accurate previous dataset, has positional and vertical inaccuracies on metre scales (Koblet et al., 2010). Digital stereo-photogrammetry DEMs over a Swiss glacier, constrained with 50 permanent geodetic points, were reported to have an accuracy of <0.3 m, though no accuracy assessment was demonstrated (Kropáček et al., 2014). Analyses of DEMs from aerial photographs over a Norwegian glacier reported uncertainties on the order of 2 m (Andreassen et al., 2012). Aerial photograph surveys as a basis for DEM generation are therefore known to introduce metre scale uncertainties where rigorous geodetic controls are absent. It was therefore decided that the 2010 survey would be performed "on the ground", using GNSS and Total Station surveys. A kinematic GNSS rover survey is fast, simple and effective where the glacier surface can be accessed and for other parts of the glacier the relatively new tool of reflectorless distance measuring was used. This relies on essentially the same technique as Lidar, performing repeat measurements of the same location until desired precision is achieved.

The 2010 Digital Elevation Model (DEM) is intended primarily for use in the calculation of surface mass balance within the Tarfala Research Station monitoring effort (Holmlund, 1996; Jansson and Pettersson, 2007; Stockholm University, 2015) and it is this, in combination with survey accuracy, that determines the interval between topographic surveys. In addition to this DEM a map is produced for analogue applications including planning, navigation and plotting. In most surface mass balance calculations the DEM defines the area over which point calculations are extrapolated; common extrapolation methods include elevation dependent linear functions or, as is the case for Storglaciären, ordinary kriging (Holmlund et al., 2005; Jansson and Pettersson, 2007; Kuhn et al., 2009; Huss et al., 2012). Attempts at co-kriging of surface mass balance with topography have been tried for Storglaciären but fail due to the complex distribution of

elevation, slope, curvature and aspect and their relationships with mass balance components. Mass balance may also be calculated via a volume comparison, the so called "geodetic method" (Cogley, 2009; Thibert and Vincent, 2009; Koblet et al., 2010). Alternatively mass balance may be modelled using surface topography as an input parameter
60 (Hock and Holmgren, 1996; Hock, 2003; Pellicciotti et al., 2005; Hulth et al., 2009).

There are other uses of both the DEM and the map derived from the DEM survey. Here we distinguish between the 3-dimensional (digital) DEM product and its 2-D derivative, the map. Studies of ice dynamics on Storglaciären require up to date topography in order to understand the flow patterns measured (e.g. Jansson, 1996; Pohjola, 1996).
65 Glaciohydrological studies rely on accurate topography and surface type distribution (i.e. the presence and extent of surface snow, firn and ice) (Jansson, 1996; Jansson et al., 2003; Fountain et al., 2005; Dahlke et al., 2012). Features such as glacier moulines and crevasses are also of interest for hydrological studies as well as for safety assessments but these features are transient, opening, moving and closing continuously and expressly
70 mapping such features introduces the distinct risk of dangerously misinforming both scientists and the general public and are therefore not shown in this map. More generally, the map should be an aid to visiting researchers at the Tarfala Research Station, which through the Interact project (INTERACT, 2015) number at least 10 per year.

2. Methods

75 2.1 Data Collection

Between the 24th July and 4th August of 2010 a field survey of the surface topography and extent of Storglaciären in northern Sweden was performed using two instruments from Trimble Navigation Limited (T.N.L.): an R7 GNSS and an S6 DR series Total Station. The survey consisted of kinematic GNSS surveys of the glacier surface and perimeter where
80 access was considered safe. Where safe access could not be gained, as well as in a few areas where extreme topography blocked satellite coverage, a reflectorless Total Station survey was performed from temporary benchmarks established using fast static GNSS surveys. The reflectorless survey measures the distance to target and adjusts for the height of the target using the incidence angle of the transmitted beam. This facilitates
85 remote surveys: in the case of Storglaciären reflectorless Total Station surveys were used to map surface elevations in the crevasse fields, at the margins where access was limited by avalanche hazards and along the southern boundary of the glacier, where satellite reception was too poor to achieve a fixed solution. The total extent measured this way is at most 26% by area, the interpolation between areas measured by the different methods
90 making an exact figure difficult to estimate. The GNSS data was post processed against

reference data from the Tarfala Research Station's own base station (also a Trimble R7). This base station had previously been fixed into the SWEREF99 reference system with the aid of the SWEPOS post processing service ([Lantmäteriet, 2015](#)).

The kinematic GNSS survey has a nominal accuracy for height measurements of 15 mm + 1 ppm, which would give a maximum error of 20 mm at the antenna for those points farthest from the base station (see [Trimble Navigation Limited, 2013a](#)). To this must be added the imprecision introduced by the positioning of the antenna over the surface or detail being measured. The antenna was mounted on a pole attached to a backpack and the height above the ice surface measured at regular intervals throughout each day. The survey controller was set to record a data point every 5 seconds and as such no guarantee could be made that the surveyor's stance at the time of data collection gave the same signal height as that measured when standing still. This error is estimated to 5 mm through the combination of ice surface roughness and the influence of the gait of the surveyor. Data acquisition in this manner naturally creates anisotropic data distribution; there are many points, densely spaced, along the survey lines but between survey lines there is no data. Lines were surveyed following topographic features rather than at evenly spaced grid locations but with a maximum distance of 75m between lines maintained where possible. This method was chosen firstly because of difficulties accessing all parts of the glacier but also because the data was to be processed to a Triangulated Irregular Network (TIN).

Temporary benchmarks were set as required using tripod and tribrach. Surveyed with the R7 GNSS, the accuracy of the coordinates at the tribrach was 2 mm + 0.5 ppm (see [Trimble Navigation Limited, 2013a](#)). From this the S6 Total Station could measure distance with an accuracy of 2 mm + 2 ppm and angles to 0.15 mgon (see [Trimble Navigation Limited, 2013b](#)). This would give a maximum measurement error in height of 1.5 mm at a distance of 600 m from the instrument. These instrument errors may sum to no more than perhaps 50 mm in height and if we assume that each station remains stable for the duration of its use then the instrument itself introduces no further errors of any significance. A far greater error source is targeting, given that the Total Station was used mostly to survey inaccessible areas of the glacier. Targets were located from some distance and, in some cases, at quite oblique angles. The errors introduced here are essentially impossible to quantify and vary from data point to data point. Experience of surveying and of glaciers suggests that these errors should, in the majority of cases, be no greater than 100 mm. Much larger errors, of several metres, are relatively easy to identify and discard but errors on scales of around 1 m are difficult to detect in isolation. These can be more easily found when compared to neighbouring points and observations in the field. As each survey was processed the same day such errors were relatively easy to identify and rectify.

The total number of data points collected was 12,548 or approximately one point in every 240 m², which if evenly spaced, would be one point every 16 m. The distribu-

tion of this data is not even but rather strongly biased towards the lines covered by the survey team. Furthermore, the ablation area is covered by a higher spatial density of survey points than the accumulation area, due to the varying coverage of the two survey methods. The heterogeneity of the data distribution leads to inappropriate interpolation results; TINs acquire multiple, elongated triangles along survey lines, blocking triangulation between survey lines whilst statistical methods such as Inverse Distance Weighting (IDW) are biased towards the along line distribution of values. Therefore the data was thinned down to 2956 points, extracted along survey lines using a maximum Euclidian distance of 20 m. The TIN calculated from this data was gridded to a pixel spacing of 5 m for use with mass balance calculations; however, the nominal resolution for most of the glacier is 20 m.

2.2 When to map a glacier

The surface of a glacier is dynamic, the ice itself moves, if only slowly, on the time scale of a GNSS survey; more importantly, the snow and ice surfaces are ablating during the summer and are therefore lowering. In the ablation area this lowering is partly countered by the dynamic response of the glacier but by no means entirely so. Average ablation area surface lowering was approximately 0.15 m/day for the ablation area and < 0.15 m/day for the accumulation area during the time of survey. Emergence velocities (resulting in uplift caused by ice flow regimes) in the ablation area are >1 m/yr for most of the ablation area, reaching an estimated 2.6 m/yr near the glacier front (Pettersson et al., 2007). Whilst it is not unreasonable to question the timing of the survey, especially as it required several days to perform, the ablation occurring during the survey is expected to be considerably less than the errors associated with photogrammetric aerial photograph surveys.

An ideal time for the survey, when considering the exposure of the summer surface and its stability would, in the case of Storglaciären, be sometime in mid September. A minor consideration for this study was the availability of staff and resources at this time; at the end of the melt season but before first snow fall, the Tarfala Research Station staff would be performing mass balance surveys on several glaciers and thus not readily available for other mapping work. More importantly, the 2010 data was intended to be comparable with previous data from 1959, 1969, 1980, 1990 and 1999 (Koblet et al., 2010). These data were collected from aerial photographs which entails specific requirements such as relatively cloud free conditions and, as far as is possible, a snow free surface. The risk of snow fall in late August and early September is quite large and only a thin layer of snow is required to severely impair the possibility of using aerial photographs to map surface elevation. For these reasons the previous surveys have been performed

in late July and early August and therefore the 2010 survey, whilst not dependent on the same conditions, was also performed during this period.

2.3 Identifying the perimeter

170 The definition of an object boundary requires clear protocols to explain subject decisions
and promote reproducibility. For glaciers, decisions must be made such as when to in-
clude ice-cored moraines, ice-marginal snow bodies and other features. In the north-
ern cirque of Storglaciären there are several perennial snow and ice fields above the
bergschrund; at the front of the glacier snow cover often forms an apron. In Raup
175 and Khalsa (2007) users are instructed to include ice above the bergschrund as ava-
lanching from this region often contributes to glacier mass balance. The mass balance
programme run by Tarfala Research Station includes this mass in its field survey of the
glacier proper, indeed all avalanche mass, regardless of origin, is included if it has fallen
onto the glacier. Extrapolating mass estimates from the avalanche covered areas back to
180 their sources would introduce a large overestimation of accumulated mass. As the mass
balance programme is one of the main end users of the DEM it was deemed inappro-
priate to include these perennial fields into the main body of the glacier. Their extent is
indicated by a red, dashed line on the map.

Whilst there was no apparent dead ice on Storglaciären there has for some time been
185 an area of snow on the northern flank, near the front, that has had little interaction
with the rest of the glacier. This snow patch is down slope of an abrupt end to the
northern margin of the glacier and at first glance may appear to be the continuation
of this flank. It is tempting to interpret the interruption as rock fall or other debris
covering the glacier surface but this is not the case, instead this is a ridge of bedrock
190 called a riegel. The riegel runs north-south, across the flow line of the glacier, strongly
influencing glacier dynamics and in turn, topography. Below the riegel the lee effect
allows for deep snow cover to build up in winter. This field has long been considered
an active part of the glacier, at least in terms of mass balance. During 2010 this field
seemed intact and stable, if somewhat down wasted, but by 2013 it was evident that it
195 was no longer connected to the glacier in any meaningful way. The map is intended as
a representation of the glacier in 2010 and this region is therefore kept in the map. This
treatment of dead ice and marginal snow fields has been implicit in previous models of
the glacier surface and will continue in future surveys, rationalising protocols to be in
line with praxis.

200 In order to maintain consistency with other survey methods the delineation of the bound-
ary in the field attempted to consider how a remote sensing analyst might interpret the
surface and topographical clues. Despite this there is an inconsistency between the 1999

aerial photograph based survey and the 2010 ground based survey on the southern flank of the glacier. Here there is an area of lateral moraine that has been ice cored and is often snow covered or at least contains snow patches. In 2010 this area was judged to not be a part of the glacier and seemed to be easily distinguishable as inactive moraine, its flat form suggesting an absence of ice core. The absence of a core of ice in the moraine is the deciding factor in this case. These marginal features illustrate the dynamic nature of glaciers and the need to continuously update DEMs for mass balance calculations.

2.4 Data processing

The survey data, after processing to SWEREF99 TM for the (x,y) components and RH2000 for elevation (z), was interpolated to a surface by creating a Triangulated Irregular Network (TIN). The TIN was then sampled to a raster grid and masked to the measured perimeter of the glacier. This raster grid is the DEM for Storglaciären in 2010 as illustrated in the map associated with this article.

2.5 Other considerations

The background of the map, those areas outside Storglaciären, consists of contours derived from the [Koblet et al. \(2010\)](#) reanalysis of aerial photographs from 1999. The DEM produced by that work contains some linear artefacts, some of which are highlighted in figure 1. These features seem to result from tiling at some stage of the model creation rather than representing the edges of the photographs themselves.

In the new, 2010 DEM other linear features may be found, but these only become evident when creating derived products such as slope. In figure 2, a map of surface slope reveals triangular facets resulting from the TIN, which served as the base from which the final raster grid was created. These can clearly be seen in the accumulation area of the glacier and are illustrated more closely in figure 3. The facets exist elsewhere but are more evident in those areas where field data is sparser. The TIN itself is constrained by the original survey lines and these are surveyed along perceived break lines in topography and then supplemented where possible. Therefore these facets may be considered as a simplification of the topography rather than an error, though it is an important consideration should the underlying DEM be used for modelling glacier mass balance as slope and aspect are common parameters for energy balance type models ([Hock, 2005](#); [Hock and Holmgren, 2005](#)). Nevertheless, much of the glacier surface is relatively smooth with a mean slope of 10° (with a minimum slope of 0.5° and a maximum of 75°). The 1999 DEM was produced from 1:30000 scale photographs with a grid

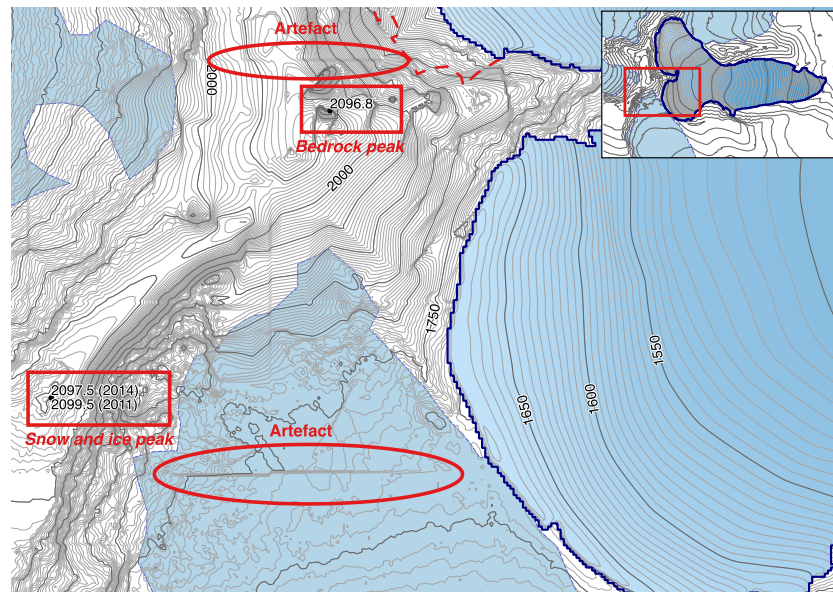


Figure 1. Artefacts in the orthophotograph derived DEM of 1999 (see Koblet et al., 2010). Also indicated is the elevation change in Kebnekaise's Sydtoppen

spacing of 5 m (e.g. Koblet et al., 2010). When produced his DEM was the most accurate representation of the surface of the glacier. The mean horizontal error relative to differential GNSS surveyed points was 2.74 m; vertical accuracy was assessed as "too low by a few metres" (e.g. Koblet et al., 2010).

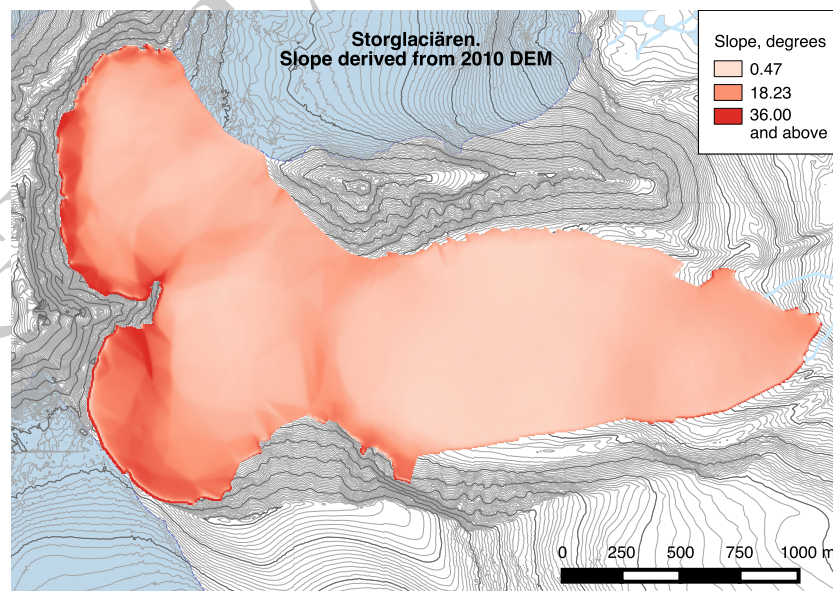


Figure 2. The surface slope of the glacier derived from the DEM. Triangular facets are found at the western margin of the glacier as a result of interpolation using a T.I.N.

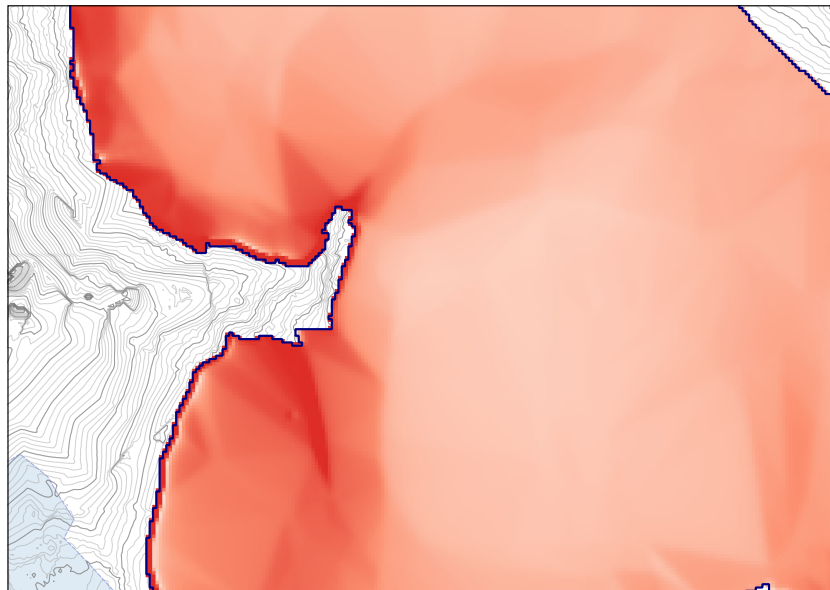


Figure 3. A close-up of the western margin of the glacier illustrating triangular facets resulting from interpolation using a T.I.N.

240 A further feature highlighted in figure 1 and shown in the main map is the change in elevation of Kebnekaise's Sydtoppen. This peak is officially Sweden's highest mountain top but its upper reaches consist of a snow and ice pack some 30 m thick. Both Sydtoppen and Nordtoppen, which is entirely bedrock, were surveyed using the Trimble R7 rover and base station in 2011 and a Trimble Geo7X rover in 2014. Nordtoppen remains
245 at 2096.8 m a.s.l. whilst Sydtoppen has lowered to 2097.5 m a.s.l. by 2014, just 0.7 m higher. This trend is likely to continue and is of some interest for glaciologists, tourists and mountain safety experts alike.

3. Conclusions

A new DEM and map of Storglaciären was produced exploiting the precision available
250 from modern in situ survey methods. Data density in the accumulation zone is much lower than for the ablation zone for both methods but for different reasons; however, as each data point in the new model is a more accurate representation of the surface it represents, the model as a whole is improved. The smoothness of the elevation data is not maintained in products derived from it. Derivatives, such as slope and curvature
255 as well as aspect, exhibit faceting created by the initial TIN, which itself is strongly influenced by the original survey lines.

When compared with the previous DEM, derived from aerial photographs, these artefacts seem less problematic as there is considerably less noise in the data and the TIN leaves only artefacts which can be directly attributed to features of the topography. The previous data does have some advantages over the 2010 data as it covers a much larger area and does so almost instantaneously. These advantages are not insignificant, especially in glacier surveys, where the survey object experiences almost constant change. However, the majority of the errors in the older dataset, particularly over steep and low contrast regions, are not repeated in the method applied to the 2010 dataset and hence the 3-D accuracy of the latter product is superior.

The area calculated for Storglaciären from the 1999 DEM is 3.189 km² and the area in 2010 is 3.016 km²; however 0.110 km² of this is the moraine area on the southern side judged to no longer be part of the glacier. This leaves 0.064 km² of change, most of which stems from small differences in how high elevation, steeply sloping, snow filled gullies were interpreted.

The differences in elevation between 1999 and 2010 datasets is clearly visible in the displacement of contour lines at locations along the glacier perimeter. These are partly due to the interim 11 years during which continued down wasting of the glacier resulted in a shift of some contour lines up glacier, i.e. westward. Other differences should be interpreted as either parallax errors due to a lack of reference points or are due to orthorectification errors introduced partly by the steep terrain but also again by the paucity of available control points. The results of the mapping, in the form of a digital elevation model and 2-D map, will be available to interested researchers via the Bolin Centre for Climate Research, Stockholm University (www.Bolin.su.se).

4. Software

"Trimble Business Center" [Trimble Navigation Limited \(2015\)](#) was used for the post processing of GNSS data from the R7 rover unit against the base station R7 unit. This software handles Trimble's proprietary T01 and T02 data formats, allowing object coding to be maintained. It also allows data export in a variety of data formats and coordinate systems, thus all data was exported in SWEREF99 TM.

From temporary benchmarks, surveyed using GNSS, Total Station data was gathered. This data was processed to SWEREF99 TM coordinates and combined with the GNSS data using "SBG Geo" ([SBG, 2015](#)).

For the creation of the Triangulated Irregular Network, GDAL was used via the Quantum GIS (QGIS) interface ([QGIS Development Team, 2014](#)). GDAL via QGIS was also used

for interpolating the TIN to a raster grid and for creating the contours and slope data. QGIS was also used for preparation of the final map.

5. Data

The GNSS receiver was set to record a point every five seconds as the surveyor walked across the glacier surface following a pseudo-regular grid and lines that would best describe the topography when interpolated to a TIN. This judgement was based on the surveyor's previous experience of terrain modelling using these techniques. Similarly, the points measured by Total Station were chosen to produce the best representation of the actual surface after triangulation. Some gaps in the data have been left deliberately to allow interpolation over crevassed surfaces where acquiring representative data would not be feasible, both because of access and because of the variation in the surface. The total number of data points collected was 12,548 and was thinned to 2956 using a distance based algorithm running. This was done on a csv file of the processed data using the following "awk" code:

```
" awk -v OFS="," -F"," 'NR == 1{xo = $3; yo = $2; zo = $4; print xo,yo,zo; next}
{x = $3; y = $2; z = $4; xd = xo - x; yd = yo - y; xyzd = sqrt((xd2 + yd2 + zd2));
if (xyzd < 20) next; else print x,y,z; xo = x; yo = y; zo = z}' Points.csv > Points_thinned.csv "
```

This is not very intelligent code as it does not check all distance matches but it suffices here. The data are shown in figure 4.

6. Map Design

The map is intended to be as simple as possible, displaying the elevation data primarily. This data comes from two sources and two years. The topography of all terrain outside Storglaciären is derived from Koblet et al. (2010) and the 1999 aerial photographs of the region. This data is included to put the glacier into a topographical context but also to illustrate differences in both method and the actual elevation of the glacier surface 11 years later in 2010. The 2010 data is very much smoother than the other data due, in part, to better precision, which leads to few artificial breakpoints in the glacier surface. This smoothness means that the colour gradient shows no distinct features other than a general trend. The contours overlaying this colour gradient highlight more the large scale features of the glacier surface.

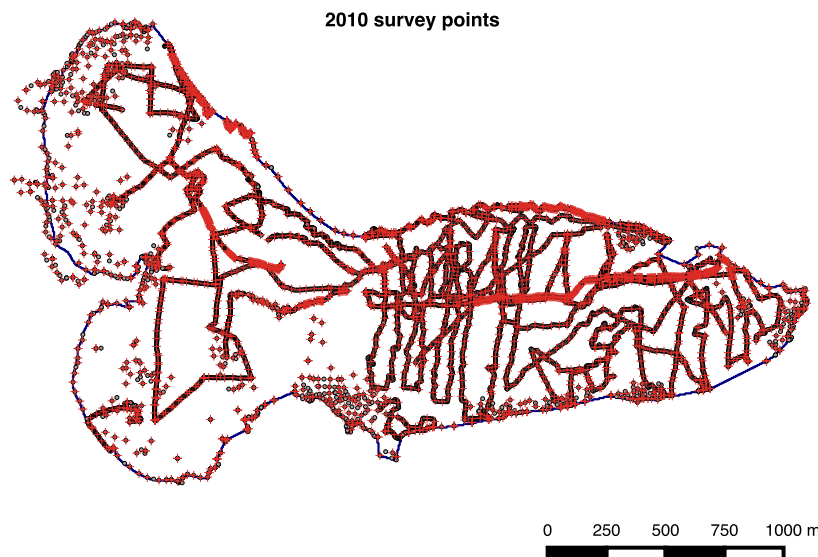


Figure 4. The locations of all data points used in the creation of the 2010 DEM. Individual points not connected to a survey line (shown in black), including those on the western boundary of the glacier, were measured using a reflectorless Total Station.

Red has been used to highlight points that may be of interest to any discussion of what is and is not a glacier, which is part of a wider discussion within the remote sensing of glaciers. Other glaciers and water bodies are coloured thematically in order to avoid confusing the reader but this may come at a the cost of blurring the distinction between Storglaciären and the rest of the map. For this reason the glacier's perimeter has been picked out in a dark blue line so that Storglaciären stands out.

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