DGPS Measurements of Glacier Surface Velocity on Storglaciären, Northern Sweden

C. Schneeberger[1], N. Short[2], B. Landl[3]

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[1]Institute for Climate Research, ETH, Zurich
[2]Canada Centre for Remote Sensing, Ottawa, Canada
[3]Institute for Meteorology and Geophysics, Univ. of Innsbruck, Austria

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Chapter 1

Introduction

Glacier velocity has traditionally been measured by placing stakes in the glacier surface, in a grid formation, and monitoring their displacement at regular intervals with field surveys. Such a grid, or stake net, has been maintained on Storglaciären in the Kebnekaise area of Northern Sweden for many years. In recent years field surveys of stakes have been made easier and more accurate by the invention of global positioning systems (GPS). This report presents results of GPS surveys of the velocity stake net of Storglaciären carried out during the summer and early fall of 2000. The measurements were performed as part of the EU Glaciology Lab5 held at Tarfala Research Station.

Chapter 2

Theory

2.1 Glacier Velocity

Glacier velocity, how fast and in which direction the ice flows, is a function of several factors. Driving stresses (controlled by ice thickness, surface slope and the influence of gravity), the viscosity of the ice (related to the ice temperature), and the nature of the bed over which it flows and the ice/bed coupling mechanisms, all interact to control the rate of ice flow. Different ice characteristics, basal sediments and bed topography will combine to produce widely varying ice speeds, from several metres a day where a lubricated base enables basal sliding, to millimetres a day where the bed is frozen and motion is restricted to internal deformation and ice creep.

Measurements of glacier velocity thus yield important information about the dynamics of an ice mass. Changes in speed may indicate changes in basal characteristics, ice temperature or thickness and are an important part of glacier monitoring. For surveys, velocity stakes are placed in the glacier surface to a depth of approx. 5 m. An additional 1 m must protrude above the surface so that the stake remains visible even after heavy snowfall. The stakes are surveyed at regular intervals and the displacement from their original positions is used to calculate the direction and magnitude of the surface ice movement.

2.2 Global Positioning Systems (GPS)

In order to accurately determine our position, we need some kind of reference point(s). At the beginning of navigation, such points were usually prominent features of the landscape: mountain tops, trees and so on. The main drawback of such points is that you have to be familiar with the area in order to locate a reference point. This problem has been avoided by celestial navigation, by using the Sun, the Moon and stars as points of reference. Since the relative position of stars and their geometrical arrangement look different from different locations, one could estimate one's position and the direction one has to take.

Since only the angle between different stars can be measured and not the distance to them, there is still a lot of triangulation geometry to be done before one can determine one's position. The more serious drawback, however, is that this approach only works if you have good visibility.

In the middle of last century people started to use radio signals to determine distances. At first, land based transmitters were used, but this did not yield sufficient coverage. Only with the use of satellite-based navigation systems, did the coverage come close to global ([1]).

The idea behind GPS is simple, the travel time of a radio signal is measured and can then be converted into physical distance using the speed of the radio signal. The speed of the radio signal is known with a relatively high accuracy. With simultaneous signals from at least 5 satellites of known locations, the accurate position of the receiver in three dimensions can be calculated.

2.3 Differential Global Positioning Systems (DGPS)

With the GPS method the position can be determined with an accuracy of several meters. This is usually accurate enough for recreational navigation, but for certain applications higher order accuracy is needed. A method to achieve this is differential mode GPS. Two receivers are needed within a reasonable distance and the position of one must be known accurately from other sources. The errors due to the satellite clock, the satellite orbit, and the ionosphere then affect both receivers the same way and with the same magnitude. If the exact position of one receiver is known, that information can be used to calculate errors in the measurements and report these to the other receiver, so that it can compensate for them ([1]). Under normal conditions, the accuracy of DGPS measurements under is in the order of millimeters.

Chapter 3

Measurements

3.1 Equipment

The measurements were performed using two Javad GPS-systems, each consisting of a receiver (Legacy) and an external antenna (Legant). The systems were powered by external batteries (12 V in both cases). One system was set up at the Enqvist-Stenen as a temporary base. After the measurements, it was tied in to the fixed base station at the Forskershuset with its known position. The other system was used as a rover on the glacier.

3.2 Velocity Stake Surveys

The rover GPS (reciever, antenna and batteries) was carried from stake to stake. At the stakes, the antenna was placed on the top of the stake and

Figure 3.1: The antenna (*left*) and the receiver (*right*). Images are from the Topcon-homepage (`http://www.topcons.com`).

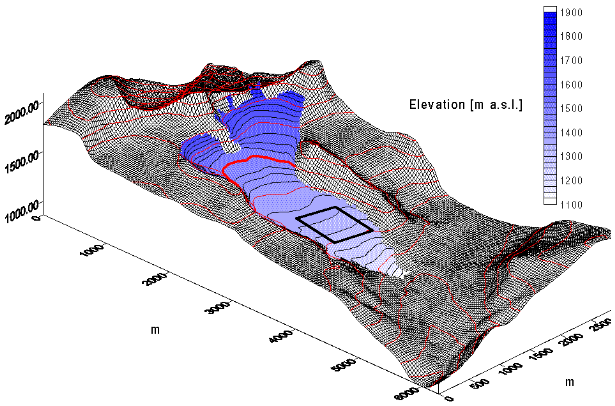

Figure 3.2: Overview of Storglaciären and the surrounding areas. The approximate location of the velocity measurements is shown by the box. Contour intervals for the glacier are 25 m (black lines) and for the surrounding area 100 m (red lines). The 1500 meter contour line is shown as thick red line on the glacier.

fixed using a screwable metal holder that fitted over the stakes. The stake position was recorded for two minutes, taking measurements every 5 seconds.

Measurements were performed on September 11, 2000. During conditions of strong winds downhill , fair weather and light snow cover. The GPS was able to get the signal from at least 5 satellites at all times, most of the time 7 or 8. This is clearly sufficient for an accurate determination of location.

These measurements were compared with data collected in an identical manner on July 17, 2000 by J. Hedfors and velocities were calculated for the intervening 56 days.

Figure 3.3: Setup of the GPS for the measurements.

Chapter 4

Data

The measurements were downloaded from the receiver to a laptop and then analyzed using special software. They were automatically tied to the fix-GPS-antenna at the Forskershuset and corrected for errors. The measurements were written to a file in the WGS84-coordinate system. Since most of the data for Storglaciären (e.g. the stake measurements from J. Hedfors) are available only in the local Swedish RT90 V 0 gon coordinate system, one of the datasets had to be converted. It was decided to convert all the data to the Swedish system, which makes plotting of the data on the existing grids much easier.

Subsequently, the analyzing of the data requires three steps

- Quality Check
- Velocity Calculations
- Data Comparison.

4.1 Quality Check

Before working with the data, it has to be ensured that the data are correct. This can be done quite easily by plotting the measured stake positions on the glacier grid and comparing them to the previously measured positions. The original velocity stake net (Fig. 4.1, as measured by J. Hedfors) consists of 42 stakes that are set up to form a grid of 6 by 7 stakes (6 stakes across glacier and 7 rows downglacier). The net is situated on the lower part of the glacier roughly between 1300 and 1400 m a.s.l. When plotting the newly measured data on the same grid, it is obvious that the locations of the stakes are almost identical, thus the measurements seem to be correct.

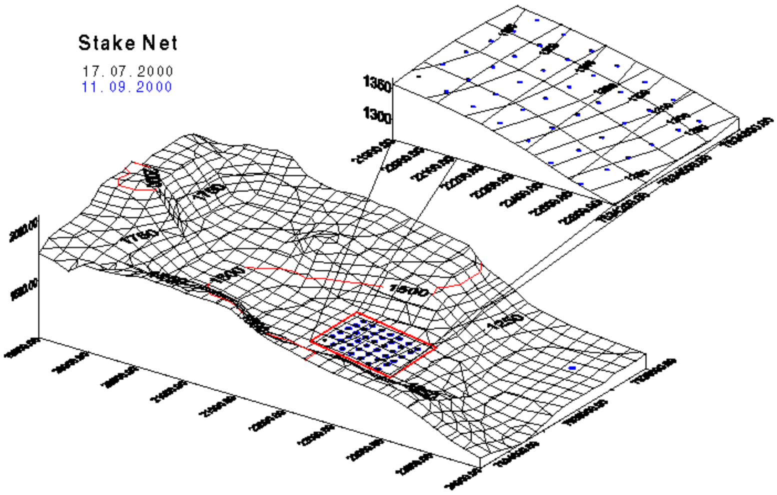

Figure 4.1: Distribution of the measured stakes used for velocity determination. Measurements from Jul. 17, 2000 (made by J.Hedfors) and Sept. 11, 2000.

4.2 Velocity Calculations

The glacier surface velocity can be obtained from the difference between the stake positions in the two surveys using the following equations. First, the displacement of the stakes is calculated by taking the difference between each component of the coordinate

$$\mathrm{d}x = lat_2 - lat_1 \tag{4.1}$$

and

$$\mathrm{d}y = lon_2 - lon_1, \tag{4.2}$$

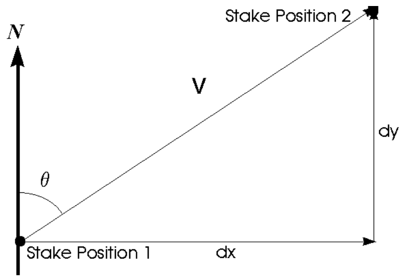

Figure 4.2: Schematic view of the velocity determination.

where the subscript $_2$ corresponds to the later of the two measurements and $_1$ is the first measurement of stake position.

From this displacement, the velocity in each direction can be calculated, if the time period between the two measurements is known, by simply dividing the displacement by the number of days

$$\mathbf{u} = \frac{\mathrm{d}x}{\mathrm{d}t} \tag{4.3}$$

and

$$\mathbf{v} = \frac{\mathrm{d}y}{\mathrm{d}t}. \tag{4.4}$$

where **u** is the speed in the x-direction (east-west, being positive if moving towards east), **v** is the speed in the y-direction (north-south, being positive if moving towards north) and $\mathrm{d}t$ is the appropriate time period.

Using simple vector geometry, the magnitude of the velocity can be calculated as

$$|\mathbf{V}| = \sqrt{\mathbf{u}^2 + \mathbf{v}^2}, \tag{4.5}$$

where **V** is the resulting velocity.

The flow direction can be calculated as

$$\theta = 90 - \tan^{-1}\left(\frac{\mathbf{v}}{\mathbf{u}}\right), \tag{4.6}$$

where θ is relative to north in degrees.

Theoretically, the velocity in all three dimensions could be obtained by measuring the displacements in these dimensions accurately enough. Due to the measurement setup, however, the vertical displacement could not be determined. The coordinates, displacements and resulting velocities are listed in Table 4.1.

# [−]	Lat [m]	Lon [m]	Lat [m]	Lon [m]	dx [m]	dy [m]	Δ [m]	**u** [cm/day]	**v** [cm/day]	|**V**| [cm/day]	θ [°]
1	21935.766	7534278.000	21933.57227	7534277.500	2.19232011	0.31000000	2.214128971	3.914857149	0.553571403	3.953798771	81.95
2	21948.014	7534374.000	21945.37500	7534373.500	2.63720012	0.80449998	2.636854887	4.709285736	1.436607122	4.708669186	73.04
3	21960.078	7534473.000	21957.33789	7534473.000	2.74085712	0.20533334	2.740857124	4.894387722	0.366666675	4.894387722	85.72
4	21971.881	7534574.500	21969.20898	7534573.500	2.67018747	0.80903125	2.669786215	4.768191814	1.444698691	4.767475605	73.14
5	21985.043	7534666.500	21982.52344	7534666.000	2.51822066	0.64075732	2.518220186	4.496822357	1.144209504	4.496821404	75.72
6	21988.799	7534772.000	21986.88477	7534771.500	1.91332030	0.27808595	1.913320303	3.416643381	0.496582031	3.416643381	81.73
7	22037.369	7534266.000	22035.09180	7534265.000	2.27769566	0.98991305	2.107753754	4.067313671	1.767701864	3.763846159	66.51
8	22047.006	7534358.000	22044.42578	7534357.500	2.57999992	0.35440001	2.579999924	4.607142925	0.632857144	4.607142925	82.18
9	22058.639	7534460.000	22055.97070	7534459.500	2.66799998	0.90785003	2.656620502	4.764285564	1.621160746	4.743965149	71.21
10	22066.912	7534552.000	22064.22852	7534552.000	2.68255997	0.28160000	2.682559967	4.790285587	0.502857149	4.790285587	84.01
11	22078.850	7534656.000	22076.19922	7534655.500	2.64886951	0.40369564	2.648869514	4.730123997	0.720885098	4.730123997	81.33
12	22088.797	7534758.500	22086.67969	7534757.500	2.11636353	0.61340910	2.116363525	3.779220819	1.095373392	3.779220581	73.84
13	22135.523	7534255.000	22133.32422	7534254.500	2.19854999	0.32245001	2.198549986	3.925982237	0.575803578	3.925982237	81.66
14	22147.721	7534347.000	22145.08789	7534346.500	2.63262510	0.29758331	2.632625103	4.701116085	0.531398773	4.701116085	83.55
15	22158.160	7534447.500	22155.59570	7534447.000	2.56488895	0.23233333	2.564888954	4.580158710	0.414880931	4.580158710	84.82
16	22167.561	7534548.000	22164.82422	7534547.500	2.73587990	0.24056000	2.735879898	4.885499954	0.429571420	4.885499954	84.98
17	22179.609	7534647.500	22176.95898	7534647.500	2.64967990	0.30555999	2.649679899	4.731571198	0.545642853	4.731571198	83.42
18	22192.807	7534744.000	22190.54102	7534743.500	2.26638103	0.39314285	2.266381025	4.047108650	0.702040792	4.047108650	80.16
19	22234.727	7534243.000	22232.69727	7534242.000	2.02845454	0.80836362	2.027938843	3.622240305	1.443506479	3.621319294	68.27
20	22244.232	7534340.000	22241.55469	7534340.000	2.67851257	0.11135294	2.678512573	4.783058167	0.198844537	4.783058167	87.62
21	22253.744	7534436.500	22250.87305	7534436.000	2.87080503	0.39362711	2.870805025	5.126437664	0.702905536	5.126437664	82.19
22	22264.691	7534533.500	22261.82617	7534533.500	2.86414289	0.07095237	2.864142895	5.114540577	0.126700655	5.114541054	88.58
23	22276.729	7534634.000	22274.00586	7534633.500	2.72395229	0.66857141	2.723950863	4.864200592	1.193877578	4.864197731	76.21
24	22287.738	7534733.000	22285.49414	7534732.500	2.24542856	0.35238096	2.245428562	4.009694099	0.629251719	4.009694099	81.08
25	22333.551	7534238.000	22331.67773	7534237.500	1.87399995	0.53352380	1.873999953	3.346428633	0.952721059	3.346428633	74.11
26	22346.490	7534336.000	22343.62305	7534336.000	2.86836362	0.14659090	2.868363619	5.122077942	0.261769474	5.122077942	87.07
27	22359.531	7534440.500	22356.51758	7534440.500	3.01250005	0.10641667	3.012500048	5.379464149	0.190029770	5.379464149	87.98
28	22364.352	7534532.500	22361.46484	7534533.000	2.88700008	0.18500000	2.887000084	5.155357361	0.330357134	5.155357361	86.33
29	22375.322	7534626.500	22372.55859	7534626.000	2.76433325	0.30024999	2.764333248	4.936309338	0.536160707	4.936309338	83.80
30	22384.631	7534727.000	22382.54883	7534726.500	2.08254170	0.40812501	2.082541704	3.718824387	0.728794634	3.718824387	78.91
31	22426.523	7534215.000	22425.07227	7534214.000	1.44990480	0.68619049	1.449898481	2.589115620	1.225340128	2.589104414	64.67
32	22446.602	7534320.500	22444.19141	7534320.000	2.41074991	0.41350001	2.410749912	4.304910660	0.738392830	4.304910660	80.27
33	22457.789	7534417.000	22454.93555	7534417.000	2.85438085	0.05314286	2.854380846	5.097108841	0.094897963	5.097108841	88.93
34	22463.748	7534515.500	22460.97852	7534515.500	2.76922727	0.04981818	2.769227266	4.945048809	0.088961035	4.945048809	88.97
35	22476.156	7534618.500	22473.49023	7534618.000	2.66604352	0.68630433	2.666040182	4.760791779	1.225543499	4.760786057	75.56
36	22488.049	7534716.500	22486.13086	7534716.500	1.91627276	0.19786362	1.916272759	3.421915531	0.353327900	3.421915531	84.10
37	22531.859	7534207.500	22530.80664	7534206.500	1.05400002	0.63475001	1.053999066	1.882142901	1.133482099	1.882141232	58.94
38	22545.426	7534315.500	22543.31641	7534315.500	2.10833335	0.07683333	2.108333349	3.764880896	0.137202382	3.764880896	87.91
39	22556.281	7534403.000	22553.76953	7534403.000	2.51245451	0.01809091	2.512454510	4.486526012	0.032305196	4.486526012	89.59
40	22566.338	7534500.500	22563.66602	7534500.000	2.67152166	0.34426087	2.671521664	4.770574570	0.614751577	4.770574570	82.66
41	22575.420	7534617.000	22572.97461	7534616.500	2.44390488	0.64042854	2.443904161	4.364115715	1.143622398	4.364114761	75.32
42	22583.471	7534704.500	22581.71680	7534704.500	1.75245690	0.12450000	1.752456903	3.129387379	0.222321436	3.129387379	85.94

Table 4.1: Measurements of stake coordinates and resulting displacements and velocities

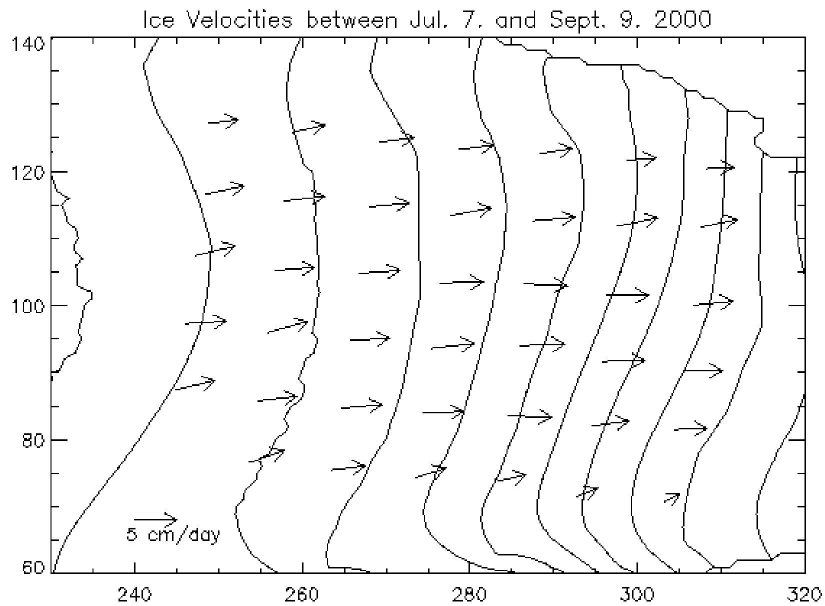

Figure 4.3: The surface flow field as determined by Differential GPS measurements.

The resulting velocities are also plotted in Fig. 4.3. They show a distinct pattern. Velocities are aligned along the line of strongest surface gradient and they appear to be smaller near the glacier margin and largest near the centerline (as one would expect from the theory, see for example [4]).

Velocities near the southern margin (especially towards the east) seemed to be unusually small and strongly deflected towards the centerline of the glacier. Thus, there seems to be a strong lateral compression and the ice in that area must be almost stagnant. This is also confirmed by a visual inspection of the area.

4.3 Comparison of Data with Previous Measurements

Velocities of Storglaciären have been measured regularly since the 1970s. Seasonal trends in magnitude have been clearly identified with maximum speeds obtained during the summer and early fall ([2]). Studies by [3] show the area overlapping with our stakes to have velocities of 4.2 - 4.4 cm/day in July, 5.5 -6.5 cm/day in August and 3.6 -3.7 cm/day in September. Their simultaneous weather and borehole measurements enable the authors to conclude

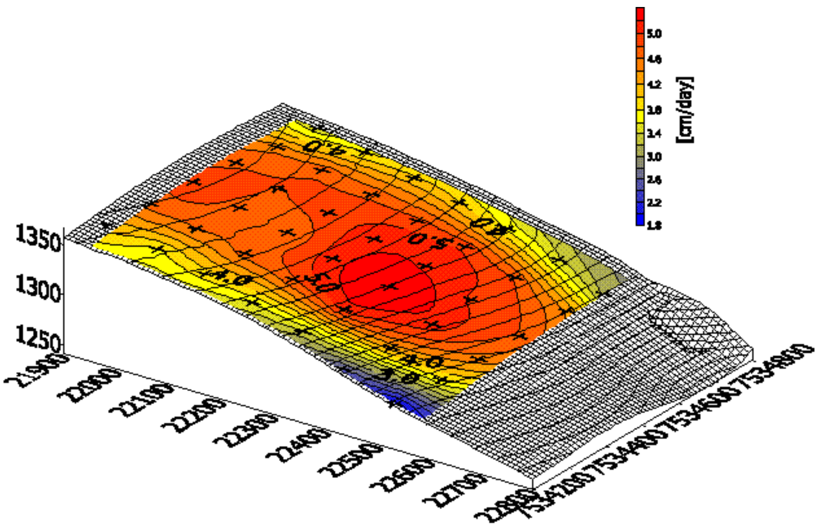

Figure 4.4: Surface velocities as determined by Differential GPS measurements.

that the velocity patterns are linked to high meltwater inputs and high basal water pressures, hence increased rates of basal sliding.

Our measurements represent July-August-September averages and centerline velocities of between 4.5 and 5.5 cm/day agree well with these other studies and indicate that the glacier behaved normally during the summer 2000.

The trend of maximum horizontal velocity along the centerline in the ablation area, decreasing outward toward the margins, reported by [3], is clearly demonstrated in the arcs of the velocity profiles in Figure 5.2.

Other studies have reported rotation of flow to be more parallel to the centerline during seasonal increases in velocity [5] and velocity peaks related to heavy rainfall and high temperatures ([3]). Unfortunately our study is not comprehensive enough to comment on these trends.

Chapter 5

Discussion

When analyzing the velocity measurements, the local bed topography is important. Fig. 5.1 shows the location of the velocity stakes relative to the ice thickness. Storglaciären has four distinct overdeepenings with three ridges running across the glacier bed.

The stake net is located in the area of the lowermost subglacial ridge. The glacier surface in some parts of that area is heavily crevassed, which indicates important changes in the local flow field.

By plotting the velocity distribution along the rows of stakes, a characteristic feature can be seen. Due to large lateral shearing near the glacier margin (glacier-rock interface), the horizontal velocity almost disappears near the edge. Near the centerline of the glacier, it is usually largest.

But velocities also vary from row to row. Velocities in the most upstream row are the smallest. It is in the area of least surface gradient. It is also the area of largest ice thickness, due to a trough in the bed topography. The rows downstream of this have larger velocities, both due to steeper slope and a ridge in the bed topography. Below the ridge, velocities slow down again towards the next trough. This trough is less pronounced than the previous one, and thus the velocity decrease is less.

The influence of the bed topography on the flow field is apparent when plotting the flow field over the bed topography as done in Figure 5.3. It is striking that the highest velocities are slightly downhill of the pronounced ridge in the bed topography. The lowest speeds are generally measured near the margin but are especially low over the margins of the deep bedrock depression. Comparing figure 5.3 with Figure 4.4 also shows that this is the area where the flow direction deviates most from a straight west-east movement.

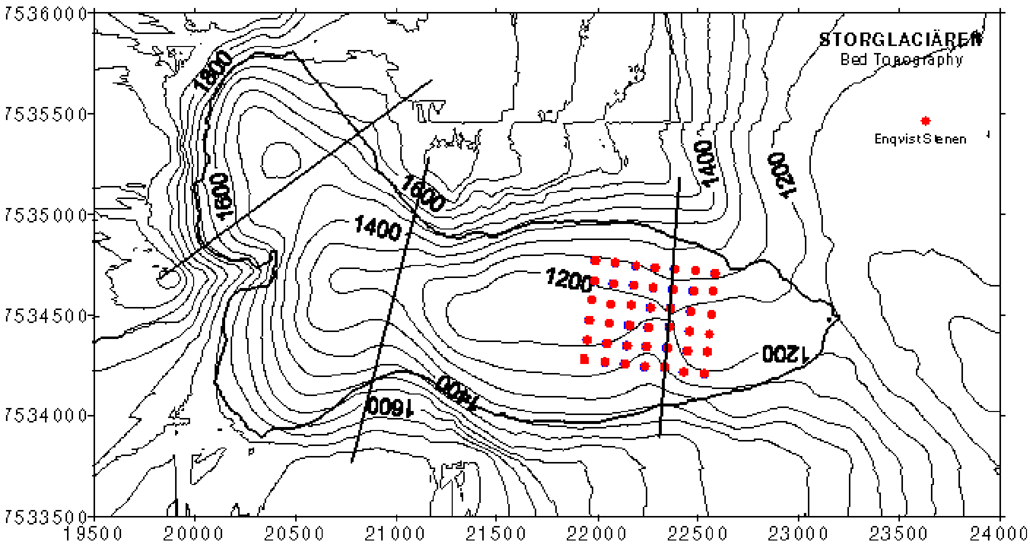

Figure 5.1: Location of the velocity stake net relative to the ice thickness. Storglaciären has four distinct overdeepenings with three ridges running across the glacier bed.

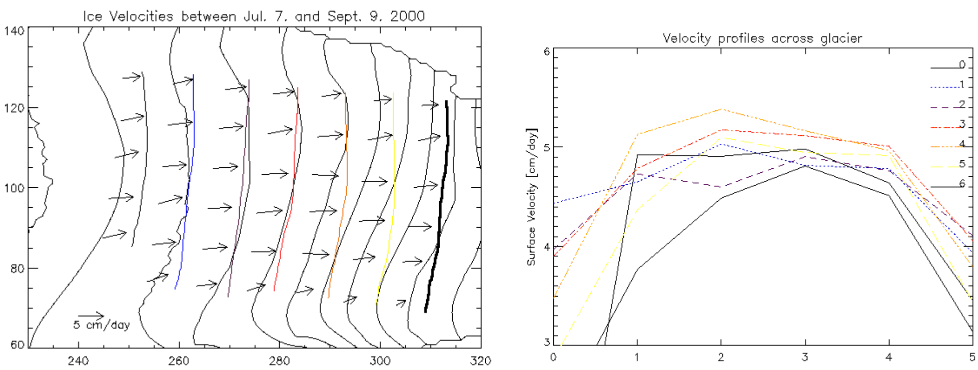

Figure 5.2: Across glacier surface velocity profiles and their setting on the glacier.

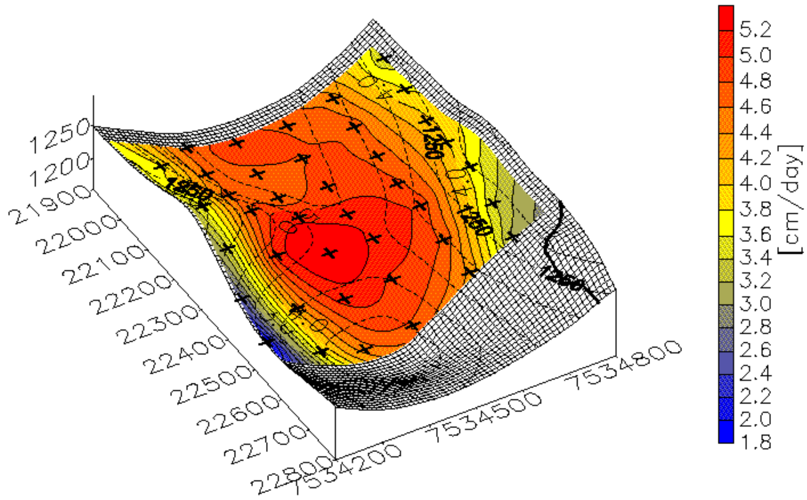

Figure 5.3: Measured surface flow field plotted over the glacier bed topography.

Chapter 6

Conclusions

The study demonstrates the practical simplicity and effectiveness of using DGPS for glacier velocity surveys. The results for Storglaciären show speeds of between 4.5 and 5.5 cm/day for the glacier centerline during the peak flow months of July, August and September. These agree well with other observations. Comparisons of the surface velocities and the bedrock topography show slowest speeds over the deepest bedrock trough, highest velocities over the bedrock ridge, and slightly reduced speeds below the ridge, flowing into the next, slightly smaller bedrock depression.

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