Locating the Hans Tausen Drill Site

By Niels Gundestrup, Kristian Keller, Thomas Knudsen and Peter Jonsson

Abstract

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The Hans Tausen drill site was requested to be on a local dome, as high as possible, with a simple flow pattern and with an undisturbed flow pattern even close to bedrock.

The first mapping of the surface elevation was performed as part of a general mapping of the elevation and gravity over Greenland. Later, NASA performed a few overflights of the ice cap. Combining the passes, it was possible to get the main features: A mountainous northern part with complicated ice flow, and two more flat southern domes. The eastern dome was higher, and thus more interesting.

In 1993, a detailed airborne measurement of the surface elevation and ice thickness was performed. Based on this, the southeastern dome was selected as the best drill site. In 1994, the position of the dome, and additional ice thickness measurements were performed from the surface. This located the exact position of the dome, and allowed staging of drilling material the same year. Finally in 1995, additional measurements of surface elevations over the northern mountains and selected parts of the southeast Dome completed the surface mapping.

The measurement showed that the bedrock was very complicated with a south-north ravine separating the two southern domes. Below the southeast dome however the bedrock was relatively flat with an ice thickness of 345 metres and bedrock changes less than 25 metres. This dome was consequently selected as the site for the drilling to bedrock in 1995.

Keywords: Glaciology; digital elevation model; ice radar.

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Introduction

Locating a suitable drill site involves a number of compromises. Ideally, the drilling should be performed on a site with minimal ice flow, now and in the past. The site should be cold, and the summer temperatures should be as low as possible because surface melting will influence the records from the ice core. Next, the bedrock should be flat in order not to disturb the ice flow close to bedrock, and thereby the oldest ice records. The accumulation should be within certain limits. If the accumulation is high, the ice core may be dated by counting annual layers, if it is low, the longest time record is obtained. In practice, not all criteria can be satisfied, and the selection involves significant compromises.

In selecting the Hans Tausen drill site, the dating problem was not considered as significant. A number of well dated volcanic layers in other Greenland cores should be recognisable in the Hans Tausen record, and this should ensure a dating in agreement with the Greenland records. Therefore a low accumulation was of higher priority.

In order to satisfy the criteria about minimal ice flow, the site should be chosen on top of a local dome, or possibly on a gently sloping ice divide. Thus the search for the drill site was concentrated on these points.

Previously, very little was known about the topography of the Hans Tausen ice cap in spite of two shallow drillings in 1975 and 1976 respectively. Both of these drilling sites were chosen based on an old U.S. Army map. Thus the position of the 1975 site is only known with significant errors (several kilometres). The 1976 site was determined by an early Transit receiver.

Recently, the National Survey and Cadastre – Denmark (KMS) has published ortho photo maps of the area. These maps have excellent accuracy and details, except on the ice due to lack of contrast. By examining these maps, it was determined that the ice margin was close to the 900 m contour. Next, three profiles from the American gravity project (Brozena 1991) provided some information. Supplemented by five NASA P3 profiles, it was possible to draw the first map of the ice cap surface topography. In 1993, intensive Twin Otter based surveys revealed surface and bedrock. In 1994, the site was selected, and materials staged on the site. Finally, during the drilling in 1995, several surface traverses supplemented the measurements of the surface topography.

In summary, the selected drill site satisfied most of the criteria: It was on a dome, the bedrock was very flat, the accumulation low and the surface ice velocites low and regular.

Knowledge prior to the 1993 survey

No regular map exists of the Hans Tausen area due to its remote location. Both the 1975 and 1976 shallow drillings used a 1957 U.S. Army map, 1:250.000, Series C501, Sheet NU 19-24,8 Edition 1-AMS. This map has errors in the order of 30 km, in addition to scaling errors. The navigation method used by the helicopters supporting the 1975 and 1976 drilling was dead reckoning, using compass and stopwatch based on a fixpoint on a glacier. This navigation showed its limits, when another outlet glacier was used as fixpoint: Then it was not possible to locate the same points on the ice cap. The 1975 site was chosen as being close to the staging point at Aftenstjernesøen, and on an ice divide as judged from visual observations from the helicopter. The actual position is only known within several kilometres.

In 1976, the same type of navigation was used. But because a prototype Transit geodetic receiver was available, the position of the drill site could be measured. Also a primitive measurement of the ice thickness along a triangular pattern on the southern part of the ice cap was made. Although the radar thickness measurement was limited due to the limited endurance of the helicopter, the sounding revealed a deep trough through the ice cap, dividing it into two separate ice fields. Based on this measurement, the 1976 drill site was chosen on the eastern part of the ice cap with ice thickness less than 300 m. The actual drill site was even further east because of navigation problems.

Both of these years no surface measurements were performed. Thus except for the Transit based fixpoint, no additional topographic information was collected. In the eighties, KMS produced ortho photo maps of the northern part of Greenland, including the Hans Tausen area. These maps are quite detailed. The accuracy is high due to numerous satellite determined fixpoints. These maps indicated that the ice margin was close to the 900 m contour line, but gave no details for the interior of the ice cap due to lack of contrast.

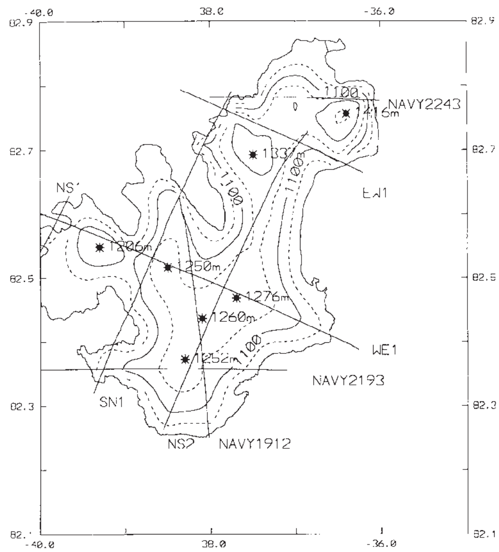


Fig. 1. The Hans Tausen ice cap topography based on 3 Navy radar altimeter crossings, and 5 NASA P3 laser altimeter crossings. The cross over between the flight lines are used to correct the elevation of the profiles, and the resulting topography is adjusted to the 900 m contour line from a ortho photo map. The icecap is highly structured with several potential drilling sites marked.

In 1992, 5 crossings were made by a NASA P3 on our request (Krabill *et al.* 1995). These crossings covered the ice cap reasonably, and were supplemented by 3 crossings by Naval Research Laboratories (NRL). The Navy aeroplane used a radar altimeter, the NASA P3 a scanning laser altimeter. Both soundings had unknown errors due to the long distance to the reference GPS receivers. Also, both of the airborne measurements were referenced to the ellipsoid, whereas the 900 m contour was referenced to sea level. A cross over analysis indicated 5 m internal errors in the NASA measurements, and 20 m for the NRL measurements. In an iterative process, a bias was added to each pass to minimize the crossing errors. Next, a common bias was added to all passes making the crossing agree at the 900 m elevation contour. In this adjustment, crossings that occurred at steep slopes were not used. Finally, the data was gridded and used to produce the topography in Fig. 1. The topography was compared with an ERS1 SAR image of the ice cap. The SAR image was enhanced to show the approximate location of the ice divide, and this agreed well with Fig. 1.

Although the data was limited, the resulting map shows a highly structured ice cap, having 4 different regimes: The Northern part seemed mountainous. The Northern part is connected with the 3 southern domes by a narrow tongue. The larger southern area had 2 clearly defined domes, of which the eastern could be separated in up to 4 individual dome structures, although the elevation difference between the individual domes was minor. All domes seemed possible drilling sites, although the point marked 1276 m seemed the most promising considering its elevation and position along the major ice divide. Although the northern part of the ice cap had higher elevations, it appeared too undulating. In order to select the best site, radar measurements of the ice thickness was needed.

1993 radar survey, description of the equipment

The radar used was the Electromagnetic Institute 1kW pulse radar, originally developed in 1968 (Lintz Christensen *et al.* 1970). The radar has a operating frequency of 60 MHz, and a pulse length from 60 ns to 1µs. Receiver bandwidth is 14MHz to 1 MHz. Originally, the radar output was stored in an analog fashion on films, requiring a later digitalisation process. Although the radar is aging, it was still considered in good working condition. The data treatment however was outdated, and a new digital system had to be developed.

The radar recording consisted of two parts: The position of the aeroplane was determined by GPS in differential mode. Although the GPS receiver (Trimble 4000) was capable of dual frequency reception, only a single frequency flight worthy antenna was available. The data was recorded each second on a laptop PC, both in the aeroplane and at the reference site at Station Nord.

Originally, the radar output was differentiated prior to recording in order to enhance the forefront of the reflections. It was decided to design a recording system that would store the unprocessed reflections. Also, a direct hardcopy readout was required to verify the radar results.

The averaging and digitalisation of the received waveforms was performed by a Tektronix sampling scope. The scope was interfaced to a laptop PC using an IEEE bus, and the average of 70 waveforms was downloaded each second. The load on the PC was high. Each second, the averaged waveform should be downloaded, saved on disk, differentiated and printed. It required programming optimized for speed in order to accomplish all the tasks, but the resulting system was working very well, and the real time hardcopy profile was of great value. The radar transmitter and receiver share a single antenna. It is a quarter wavelength dipole mounted horizontally out from the aeroplane body, which thus functioned as a vertical mirror. The antenna is the same as used earlier at the Renland recognisance (Johnsen *et al.* 1992). The resulting specifications are:

1. Sample rate

The nominal speed of the ski equipped Twin Otter aeroplane is 140 kn. The take off speed is 60 kn. It is wanted to fly relatively slowly, but also to have some potential for keeping a constant height over the ice cap. Thus, the nominal speed is 100 kn, corresponding to 180 km/h or 50m/s. The total position error should not be more than 100m. Therefore the sample rate is 50m, corresponding to one sample per second.

2. Digitizing rate

The nominal pulse length of the radar is 250nsec and a 4MHz receiver bandwidth with a minimum pulse length of 80nsec and 14 MHz receiver bandwidth. To a 4MHz bandwidth corresponds a time constant of 40ns. Thus, the sampling rate should be a minimum of 40 nsec in order to preserve all information. The wave speed in ice is 170m/µs, and a sampling rate of 40 ns thus corresponds to 170/2*0,04m= 3,4 m.

3. Digitizing window length

From the 1976 survey, the maximum ice thickness expected is 800m. This corresponds to a time delay of 2*800/170 µs= 9,4 µs. The maximum expected flying height is 300 m above the snow surface, corresponding to a 2-way travel time of 2 µs. Finally, the sweep starts 2 µs prior to the transmitted pulse. Thus, the minimum window length is 9,4+2+2 µs= 13,4 µs. Thus, a window of 20 µs ensures sufficient margin. The nominal window length is 500 samples. With a length of 20 µs, the resolution will thus be the requested 40 ns. The 20 µs window allows a maximum ice thickness of 1,3 km to be recorded.

4. Storage requirements

The digitized waveform has a resolution of 12 bits, corresponding to 1:4096. For storage, this was reduced to 3 digits (0 to 999). Because the values are recorded in ASCII format with a delimiter, each sweep generates 3000 bytes. The hourly production is 3000*3600 bytes/hr= 10,8 Mbytes/hr. A 5 hours run will thus produce 54 Mbytes. This amount of data is compatible with a 128MB magneto optical drive.

5. Elevation measurements

In order to get the best possible ice thickness measurements, it is desired to fly at nearly constant elevation over the ice sheet. The elevation should be as low as possible, considering a safe flight as well as a well defined echo from the surface. The estimated minimum flight elevation is 80m. Because the aeroplane is not flying at constant elevation, it is required to know the 3 dimensional position of the aeroplane in order to calculate the surface elevation height. The performance of the GPS receivers and its associated software is thus critical.

6. Real time profile printout

In order to check the radar performance, and to give a direct printout of the profiles, the Z (differentiated) radar output is printed in real time. The differentiation is performed in software. Because the printer needs to print in real time, an inkjet printer was selected for the output. The capacity of the computer logging the radar returns was limited, and imposed severe restrictions on the processing that could be done during the flights. By using a 2*2 matrix to generate 4 levels of gray, 150 dpi resolution and flying 180 km/hr, a lengthscale of nearly 1:150.000 was achieved. The logging rate was 1 per second, corresponding to 50m. Although primitive, the real time printout worked very well, and made it possible to change flight plans depending on the survey results.

7. Aeroplane specifications

The aeroplane used was a Twin Otter based at Station Nord in Northeast Greenland. The nominal time airborne is 7.5 h using two 300 l ferry tanks, and an air speed of 140 kn or 260 km/h. The fuel consumed per mile is virtually constant down to a velocity of 90 kn, and the fuel consumption is 330 l/h at 140 kn. Additional fuel is also needed for landing on the ice cap Flade Isblink, in case landing at Station Nord is not possible. The two way distance between Station Nord and Hans Tausen ice cap is 700 km, corresponding to 2.7 hrs. This leaves fuel for 7.5 – 1.5 – 2.7 hr = 3.3 hrs over the ice cap at 140 kn, or 4.6 hr at 100 kn. The maximum survey per flight is thus 460 nm or 850 km. In practice, the achieved endurance was less, because the constant change in flight level due to the ice cap topography required much fuel.

Normally GPS satellites with an elevation angle of less than 10^0 are not used in the processing. Thus, the maximum tilting of the aeroplane should be less than 10° in order to keep tracking all satellites while the aeroplane turns. With a speed of 100 kn, this corresponds to a turning diameter of 2.6 km. Thus, the nominal turning diameter was 3 km corresponding to a curve length of 4.7 km and a time of 1,6 min.

1993 airborne survey

The survey had two purposes: to make a general mapping of the ice cap, and a more detailed mapping of the most promising area. Due to the constraints of the turning radius, the main lines were 1,8 km apart, with 900 m line spacing in the key area. The GPS reference was at Station Nord, tied to the local geodetic marker. Prior to the flight, all way points were programmed in the GPS, so in theory the pilots should just follow a straight line, make a curve with 1 nm radius and continue on the next while keeping a nearly constant flight elevation over the ice cap with a minimum elevation of 250 feet. In practice, this was not possible. First, the distances between the way points were so small, that unless the aeroplane was exactly on track and with the correct heading, the GPS navigator would assume that a nearby way point was passed, and switch the route ignoring the intervening tracks! Next, the surface was changing so rapidly that it was not possible to keep a constant distance to the ice cap surface. As a result, the aeroplane had to follow a more gently varying flight level.

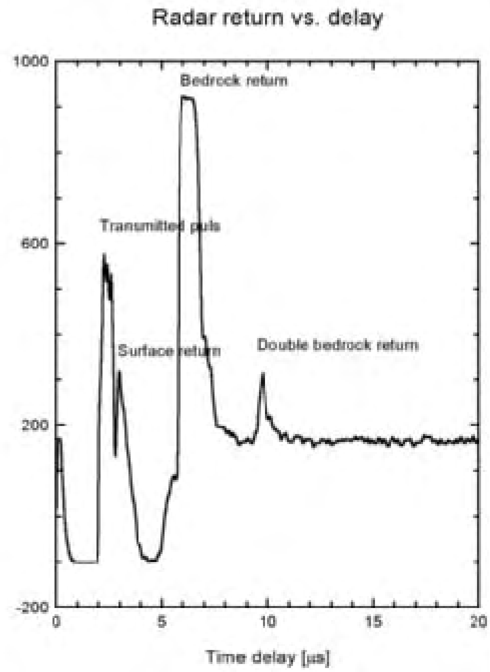


Fig. 2. Radar waveform as recorded during the measurements. The recording starts 2 µs before the pulse is transmitted. The surface return is 0,82µs after the transmission corresponding to a flying height of 123 m. The bedrock return saturates the receiver, and a double bedrock return is also recorded.

It was originally planned to use also a GPS reference at the ice cap. This was only used one day, because first the aeroplane could not land on the ice cap directly from Station Nord due to landing weight restrictions, and secondly the surface was quite warm, demanding much fuel to take off. As a result, all airborne measurements are referenced to the GPS station in Station Nord.

A typical radar return is shown in Fig. 2. The recording is started 2µs before the 250µs pulse is transmitted. On the recording, the transmitted pulse appears jagged. This is caused by attenuation by the transmit/receive switch, and the receiver suppression. The surface echo is recorded 0,82µs later corresponding to a flying height of 123 m. The bedrock echo is very strong, saturating the receiver. It has a two way travel time of 2,93µs. The measured ice thickness is thus 248 m using a wave speed of 169 m/µs in the ice. Finally, a double echo is recorded. This echo is the bedrock reflection as reflected by the aeroplane, and later by the bedrock. No internal layers in the ice cap is recorded. This is partly due to the reduced receiver sensitivity in the first microseconds after the pulse is transmitted. Later, it was learned that the ice cap had little ice accumulation and high summer temperatures. Due to this, the internal layering is difficult to detect with the present radar.

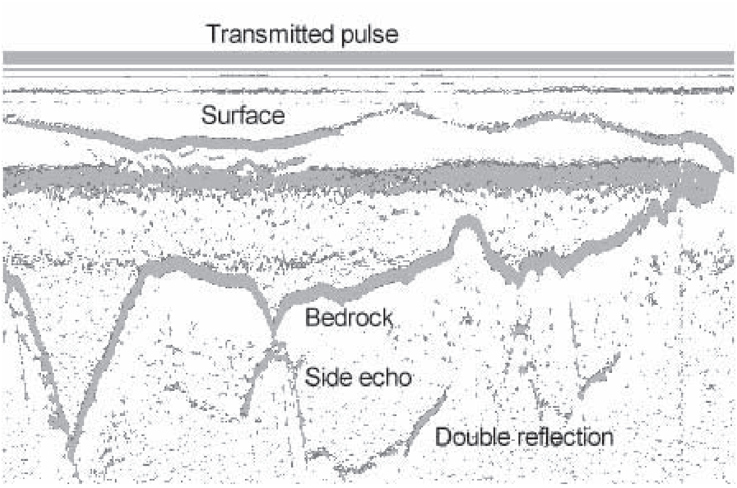


Fig. 3. Profile from a crossing over the drill site. The top line is the transmitted pulse. The surface return shows a changing flight elevation. The dark line is an artifact. West the deep trough is recorded, followed by a profile with almost constant ice thickness. At east, the ice thickness is recorded to the margin of the ice cap.

Fig. 3. shows a recorded west-east profile passing near the drill site. The upper line is the transmitted pulse. It is divided into several lines due to the differentiation of the signal. The surface echo is clear, although weak when the aeroplane passes the crest of the ice cap, and the distance between the aeroplane and surface is minimum. The broad dark line below the surface is an artifact caused by the regulation of the transceiver gain. The deep trough is clearly measured, although the horizontal resolution is limited because the radar always picks up the nearest point. In an area with fast changing bedrock topography, the radar will not be able to resolve the bedrock. It can also be seen, that the trough may in fact be deeper than indicated. Several double reflections are measured, as well as a nearby mountain. The ice thickness is measured to the edge of the ice cap. No internal layering is detected. Although the profile shows several artifacts, both surface and bedrock is easily identified.

The digitized profiled is shown as Fig.

4. At left (west) the trough is shown to be deeper than 600m. It is also clear, that the V-shape may be caused by lack of resolution. The position of the drill site is indicated. It is placed near the center of an almost flat horizontal part of the bedrock. This should assure that the flow of the glacier ice is not disturbed by bedrock undulations.

A corresponding ice thickness profile for the northern part of the ice cap is shown in Fig. 5. The horizontal scale is approximately the same as for Fig. 4, and the track of the profile is indicated in the insert. Compared to Fig. 4, the area is highly mountainous, and the ice flow will be disturbed by the rapidly varying ice thickness. Clearly this area is not optimal for an ice core intended to cover many years of undisturbed ice flow.

Fig. 6. shows the resulting surface topography with all measured points indicated. Most lines are from the airborne sounding, easily recognised by the gentle curvature between the lines. The airborne measurements are supplemented by an intensive grid around the drill site, and some longer surface tracks. One such track goes from the drill site to the northern ice cap. It passes over 4 domes. The northernmost dome was the staging point for the "Hare Glacier" study, and the tracks made by this study indicate the glacial outlet.

The processing of the map was not easy. The 3-dimensional position of the aeroplane was computed by differential GPS with respect to the GPS receiver at Station Nord, and the distance from the aeroplane was obtained from the surface return of the ice radar. In general, the elevation thus measured is accurate to 10m or better, but at times the translocation program (Trimble Post-nav II) had a tendency to be unstable. This resulted in significant elevation errors. In order to assure a high precision of the data, the results from the Trimble program was passed through a filtering program. This program identified all less accurate positions using several methods, including the estimated error from the program, and the vertical velocity of the aeroplane. All doubtful points were removed from the database, and are not indicated here. The parameters in this selection process demanded some trial and error, but as indicated by the shape of the map, it was highly successful. The instability is very likely caused by the use of only a single frequency antenna combined with the relatively long distance to the reference at Station Nord and poor vertical geometry of the GPS constellations.

The surface measurements are referenced to a GPS receiver near the drill site. They are processed kinematically, and have a relative accuracy of 10cm. The 900 m contour line from the ortho photo map is used as border line. Compared with Fig. 1, the map is significantly more detailed, although it is sur-

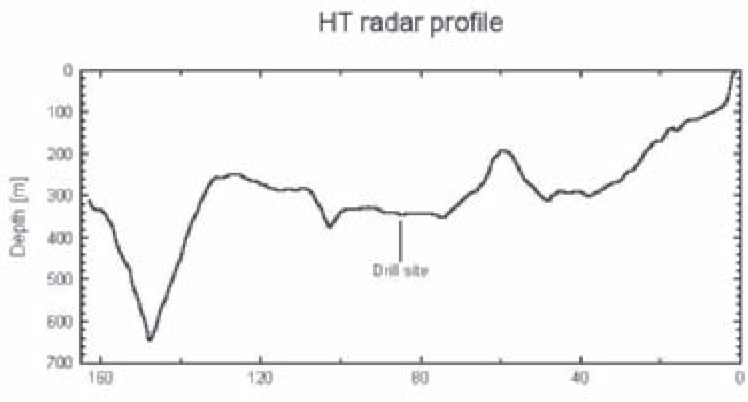
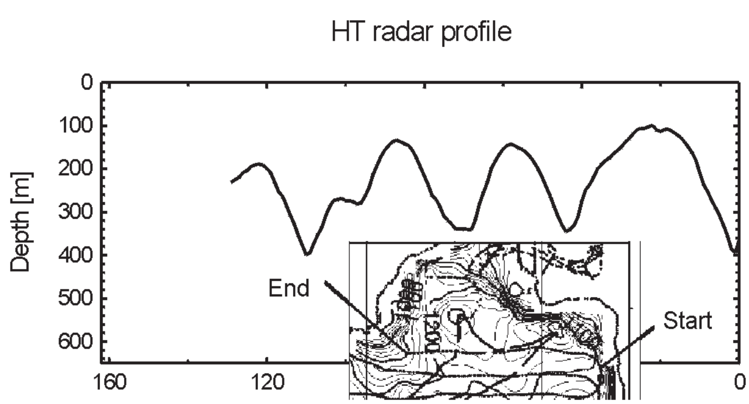


Fig. 4. The same profile digitized. The drill site is marked. Because the radar records the first return, the shape of the trough can not be resolved. It is seen, that the drill site is in area with very smooth bedrock. The profile spans 22 km.

Fig. 5. Profile from the north part of the ice cap. The ground track is indicated in the insert. The area is quite mountainous, with ice thickness rapidly varying between 100 and 400 m.This topography makes the area unsuitable for a drilling to bedrock.



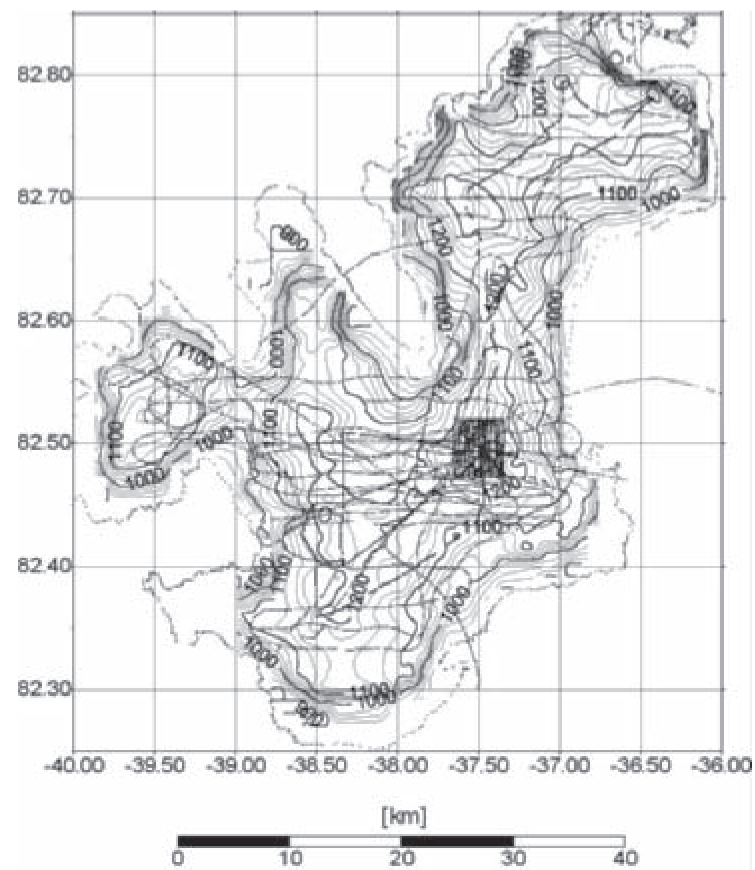


Fig. 6. Surface topography with all measurement lines marked. The densely hatched area is near the drill site. The flight lines have been chosen to give a good representation of the topography of the ice cap, with additional flight lines at the most promising places.

prisingly to see how well Fig. 1 compares with the final map.

The bedrock topography as measured by the airborne soundings is shown in Fig. 7. Only the two southern parts of the ice cap as separated by the deep trough draining the area, has areas which are flat, and thereby useful for the drilling. Based on the surface elevations, the area around 82.5N 37.5W was selected as the position for the drill site.

Based on the 1993 airborne measurements, the general location was thus determined. In 1994, it was the purpose to identify the exact location of the top of the dome, and later to stage material there for the 1995 drilling. Also, the detailed topography of both bedrock and surface should be measured close to the drilling site. The first aeroplane landing at Hans Tausen brought surveying equipment to locate the exact top of the dome. This was easily done because the aeroplane landed very close to the site. The camp was erected, and after a few days, the surface program started. The intention was to measure the topography, and at the same time install poles for a strain net around the drill site.

The resultant surface topography is on Fig. 8. Also, all measurement points are marked. The dome is very regular, indicating a regular ice flow. The surface

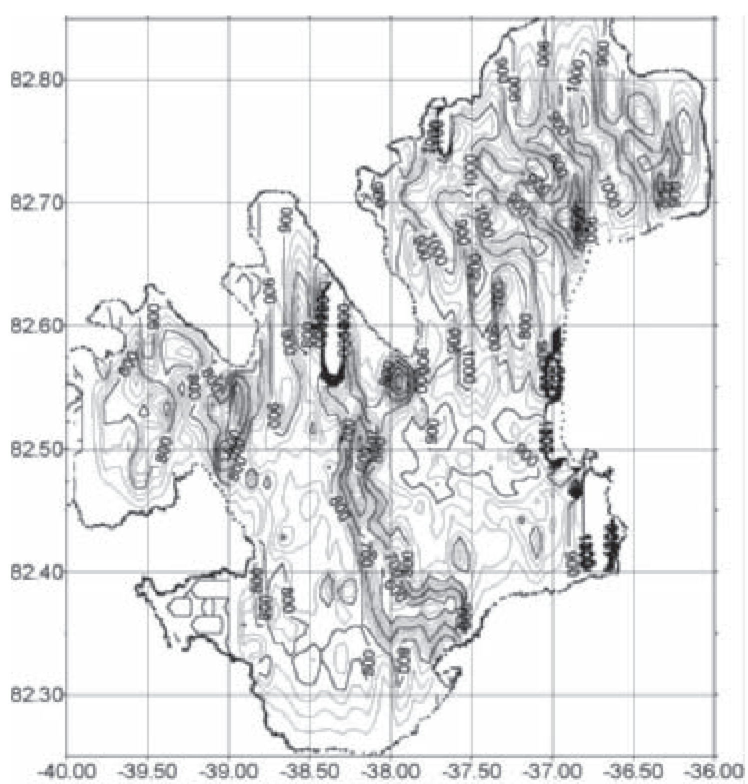


Fig. 7. Bedrock of the ice cap. The mountainous northern part and the deep trough separating the two southern domes are recorded. In general, the bedrock topography is quite irregular, and only around 82.5N 37.5W is there an area with less undulations.

measurement lines were intended to be 300 m apart. However part of the measurements had to be made in low visibility conditions with visibility down to 40 m. Although the navigation was based on GPS receivers, it was very difficult to follow a straight line in white out conditions as seen on the figure.

The bedrock topography is shown in Fig. 9. Although the figure is only based on the airborne measurements, it clearly indicates, that the bottom is flat, with changes not exceeding 20 m (6 percent of the ice thickness) near the drill site.

Summary

Both surface and bedrock of the Hans Tausen ice cap has been measured. In addition to providing a general mapping of the ice cap, a position optimized for the drilling has been found. The selected drill site has a combination of low accumulation, flat bedrock, and local well defined dome, making it close to an optimal drilling site with only few trade offs. The site selection was performed through several steps, taking 3 years. First a preliminary map was constructed from aeroplanes passing the area in connection with other projects. Based on this map, a general airborne survey was executed, later followed by surface measurements for both the exact position of the drill site, and for mapping special features. In summary, all the objective of the site selection process was fulfilled.

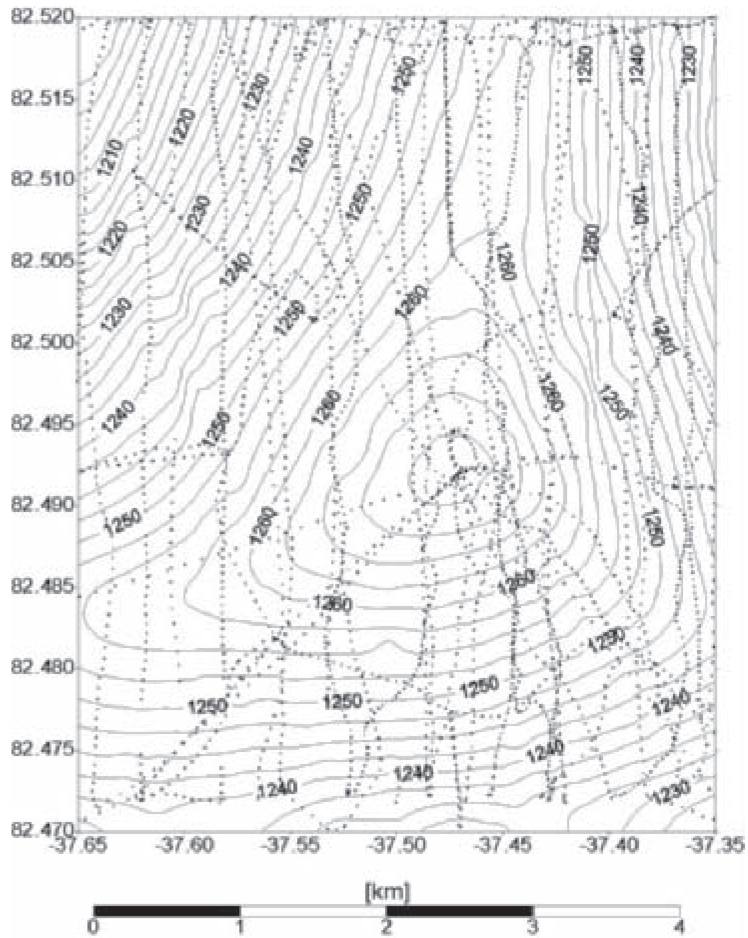


Fig. 8. Surface topography around the drill site based on surface kinematic measurements. All measurement point are marked. The dome is quite regular with a size of around 1 km, or 3 times the ice thickness.

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The airborne survey had not been possible without the skill and dedication of the Flugfelag Nordurland's crew headed by Captain Ragnar Magnusson. The survey required the Twin Otter aeroplane to follow the designated tracks very closely. At the same time, the flight level was changed constantly. Because the aeroplane has no autopilot, this demanded constant attention by the crew.

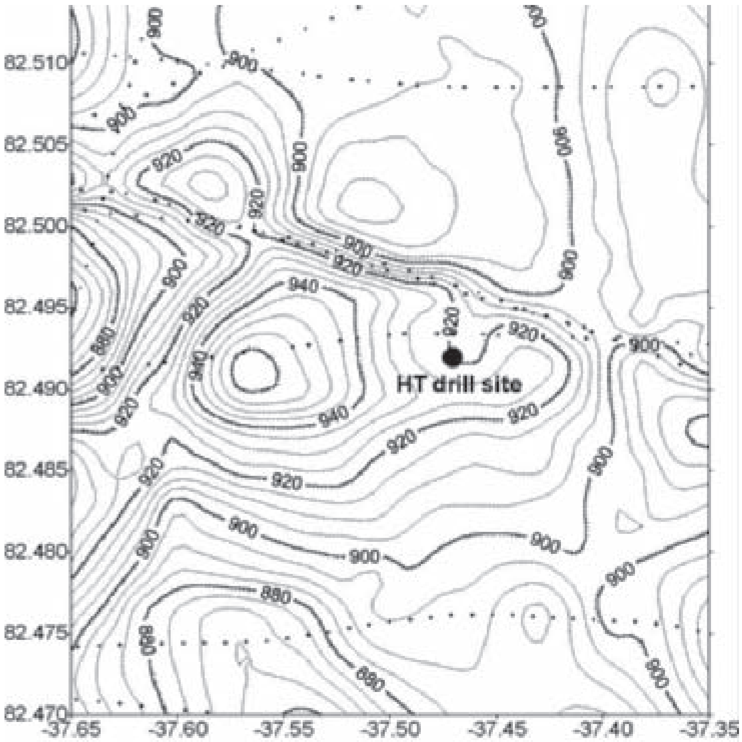

Fig. 9. Bedrock topography around the drill site based on the airborne measurements. All measurements pointes are marked. The contour lines are hatched downstream. The bedrock is relatively flat, with changes of about 20m.

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