GPR Snow Cover Survey

Data collection and post processing procedures for Nuuk Basic 2009

Table of contents

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1 Introduction

To support the studies under the Nuuk Basic monitoring program, a snow cover survey of the snow depths at three locations in Kobbefjord was carried out April 15^{th} - 16^{th} 2009.

This report describes the result of a single field campaign to Kobbefjord. Due to logistical difficulties and bad weather during the campaign, this survey has a limited extent and only gives a point measurement of snow depths and densities around each of the three Geobasic soil microclimate stations: *Soil Fen*, *Soil Empetrum* and *Soil Empetrum Salix* (Figure 2).

The procedures outlined in this document concern the field methodology, estimation of radar velocity in snow and data processing. Finally the results are summarized and commented.

The snow cover was measured with ground penetrating radar (GPR). Since snow is a relatively homogenous media and the snow/soil surface is a good reflector, GPR is very suitable for determining the snow distribution in an area, [Sand, 1998].

The post processing procedures describes how to convert the raw GPR measurements (known as *radargrams*) to snow depth information. This conversion is determined by a simple physical relation

`Snow depth = ½ TWT × velocity` **(Equation 1)**

Where `TWT` (Two-Way-Time) is the time the radar signal takes to travel from the antenna to the snow-soil interface and back to the antenna. The `velocity` is the propagation speed of the radar signal in snow.

2 Data collection

GPR measurements were carried out with an X3M radar control unit from Malå Geosceince [Ram,2002] and a 500 MHz shielded antenna. The antenna was placed on a sledge on top of 20 cm foamed polystyrene. An ordinary PC-laptop was used as a data logger. The sledge is suitable for being dragged alongside a snow scooter or pulled manually (Figure 1). This survey was carried out without the benefits of a snow scooter.

Figure 1 GPR measurement setup.

In order to achieve a precise geographical reference of the GPR measurements three courses were set out with a Leica SR530 RTK GPS which received corrections from a GPS base placed on the reference point *KOBBEFJORFIX*, which consist of a bolt anchored in rock. This yielded a horizontal precision of a few centimeters for the section nodes. Each of the three courses had four line sections as displayed in Figure 2 and the section nodes were labeled 1-5 (Figure 3). Further map details can be viewed in Appendix 1.

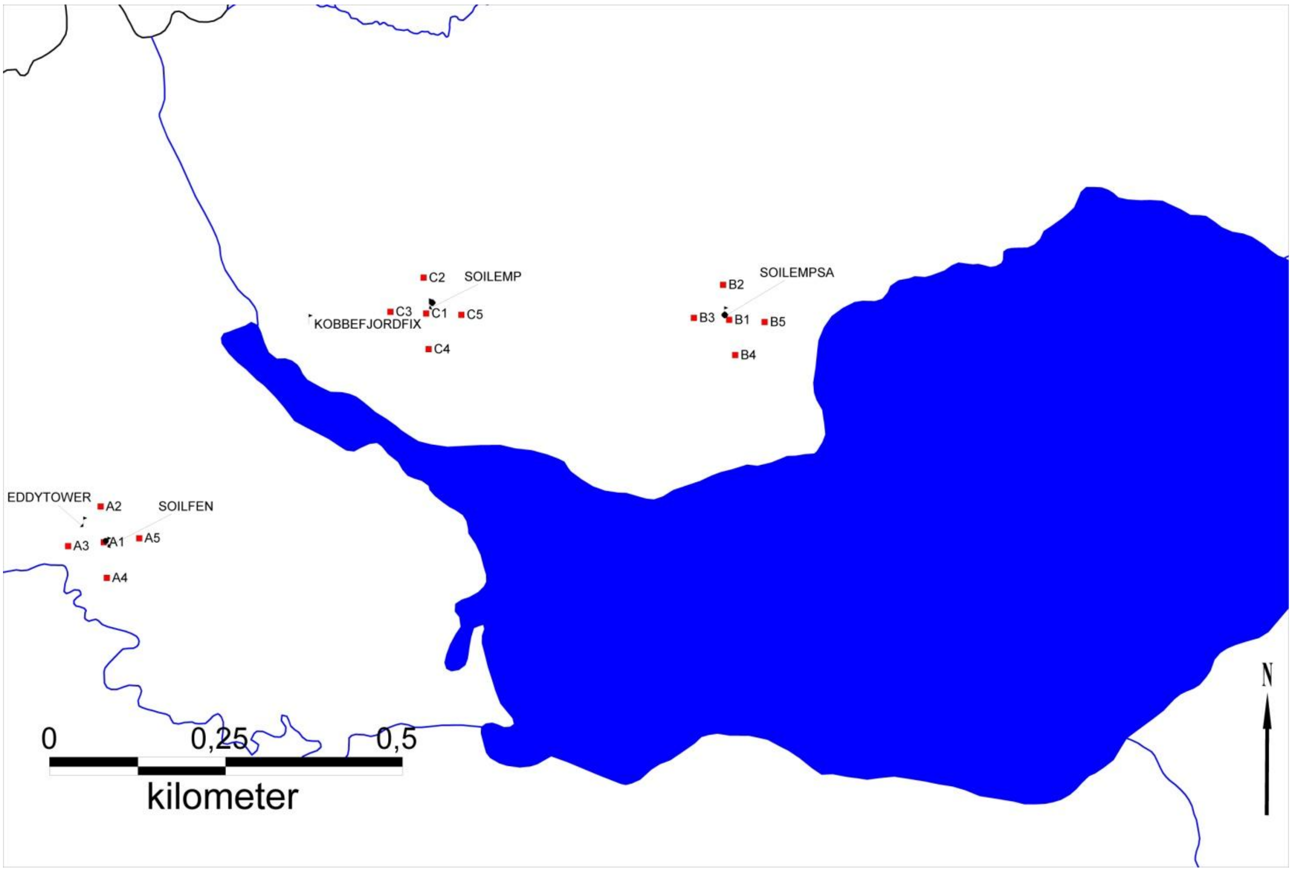

Figure 2 Map of the three investigated locations in Kobbefjord

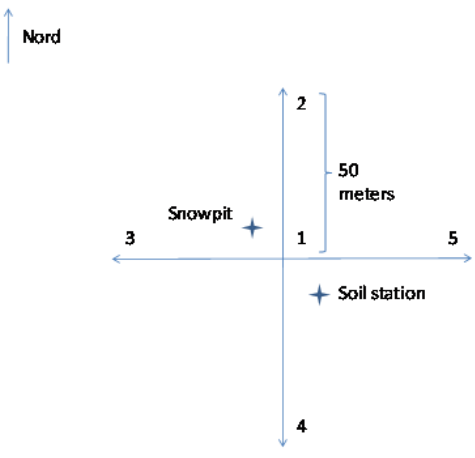

Figure 3 Outline of the measurement strategy

The four line sections (1-2, 1-3, 1-4 and 1-5) were measured both with the GPR with a horizontal resolution of 20 cm[1] and with manual stake measurements every 10 meters. Near position 1 at each of the three sites a snow pit was dug to investigate density, texture and temperature. Positions were

[1] The actual interval between GPR samples varied because snow stuck to the trigger wheel or the trigger wheel skidded along the track. See chapter 4 Post processing.

named *A* at *Soil Fen*, *B* at *Soil Empetrum Salix* and *C* at *Soil Empetrum*. Positions *B* and *C* were mapped on April 15th and *A* was mapped on April 16th.

Position	Northing	Easting	MSL Heights
A1	7 111 635.99	481 228.69	41.77
A2	7 111 686.55	481 224.31	42.93
A3	7 111 630.50	481 178.30	42.06
A4	7 111 585.42	481 233.11	41.11
A5	7 111 641.64	481 279.06	43.6
B1	7 111 951.11	482 114.75	38.94
B2	7 112 000.70	482 106.28	44.55
B3	7 111 953.89	482 064.82	46.71
B4	7 111 901.18	482 123.41	36.38
B5	7 111 947.95	482 165.13	32.96
C1	7 111 960.14	481 685.55	32.87
C2	7 112 010.88	481 681.93	31.15
C3	7 111 962.51	481 634.89	28.64
C4	7 111 909.49	481 689.06	33.86
C5	7 111 958.25	481 735.44	41.29
EDDYTOWER	7 111 657.82	481 199.77	42.23
KOBBEFJORDFIX	7 111 944.66	481 519.11	32.19
SNOWPITA1	7 111 637.76	481 231.44	41.79
SNOWPITB1	7 111 958.12	482 108.66	40.41
SNOWPITC1	7 111 975.39	481 694.15	33.59
SOILEMP	7 111 967.00	481 689.49	33.19
SOILEMPSA	7 111 955.69	482 107.88	40.76
SPOLFEN	7 111 629.21	481 233.98	42.41

Table 1 Overview of positions measured with RTK-GPS. Northing and Easting refers to UTM 22N WGS84, MSL Heights refers to geoide model gr2000g.06).

The structure of the raw data as recorded with GroundVision™ was:

datafile.rad	is an ascii header file to the recording.
datafile.rd3	is a binary data file holding the measurements
datafile.cor	Coordinate file, not used.

The .rad file that describes the GPR settings can be viewed in Appendix 3. The GPR settings were kept constant throughout the measurements. The GPS data were collected on a separate device (Leica SR530).

3 Density and velocity analysis

According to Equation 1 the velocity of the radar impulse in snow must be determined to convert the Two-Way-Times into snow depths. The velocity of the radar impulse in snow depends on the density of the snow [Sand, 1998]:

$$v = c(1+0.469\ \rho_{SNOW}/\rho_{ICE})^{(-3/2)} \quad \textbf{(Equation 2)}$$

Where

c = 2.99e8 the speed of light in vacuum.
ρICE = 917 kg/m^3 is the density of ice.
ρSNOW is the density of snow.

Snow density measurements have been carried out in snow pits along with the georadar tracks and these density measurements yielded average densities over 40 cm intervals. Surveying snow densities and texture revealed that the snow pack was inhomogeneous varying from light fresh snow to dense ice layers.

To compensate for varying densities a mean density is used to calculate the radar propagation velocity. This induces an error on the resulting snow depth that amounts to ±4% when the density varies one standard deviation from the mean density.

Snow pit	Depth interval (m)	Density (kg/m^3)	Velocity (cm/ns)
A	0-0.4	199	25.86
A	0.4-0.8	321	23.80
B	0-0.4	306	24.04
C	0-0.4	293	24.25
C	0.4-0.8	352	23.33
Mean		294	24.23
SD		58	0.96

Table 2 Summary of density measurements and resulting propagation velocities calculated from Equation 2.

All GPR measurements are processed with the assumption that the radar propagation velocity is 24.23 cm/ns as calculated from Equation 2.

4 Post processing

The snow cover survey was carried out during snowy weather and windy conditions that resulted in increasing snow depths during the survey. The fresh and less dense snow caused the georadar sledge to sink deeper into the snow. This posed a problem that was solved in the post processing of the GPR measurements by using the manual stake measurements to correct each radargram for the compression of snow under the sledge. This was done by calculating a virtual snow-air reflector, Equation 3. Equation 3 calculated where in the radargram the snow-air reflector was supposed to be (relative to the interpreted snow-soil reflector).

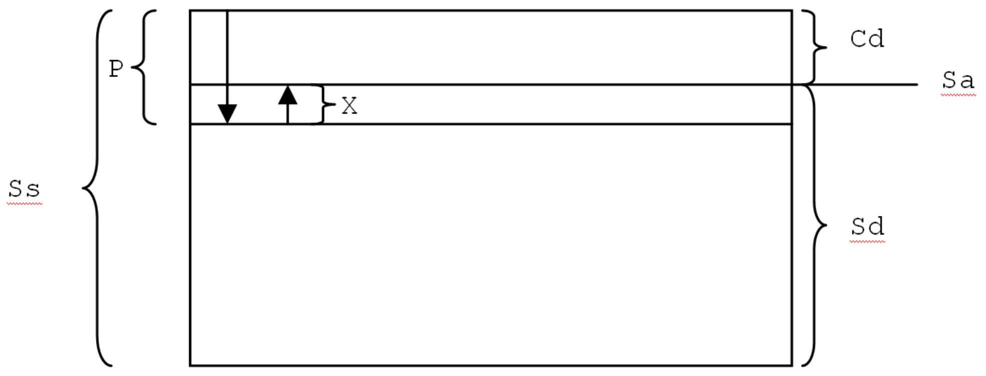

Figure 4 Schematic illustration of a raw data radargram. Depth-axis is the two way time of the radar beam.

P	Polystyrene foam
X	Compression depth
Cd	Cutting depth
Sa	Virtual snow-air reflector
Ss	Interpreted snow-soil reflector
Sd	Snow depth

Where

Sd[ns]=2(stake measurement [cm]/24,23 [cm/ns])

Cd[ns]=mean(SS-Sd) **(Equation 3)**

Now and then the stake measurements didn't correspond exactly to an obvious snow-soil reflector. This could be caused by ice at snow-soil interface or by micro topography when a stake measurement was placed slightly outside the GPR course. One of 63 stake measurements was excluded from the evaluation of the cutting depth. Otherwise a mean of all stake measurements in a line section is used to calculate the cutting depth for that line section.

The raw data as recorded with GroundVision™ is imported in to REFLEXW™, which is a software program for interpreting GPR data. As mentioned previously the actual distance between measurements may vary from the preset 20 cm. When importing the radargram the samples are spread out evenly over a distance of 50 m, as each track is exactly 50 m. The error on distance is spread out over all measurements typically about 3 cm pr. sample, se Appendix 4. Each radargram is then filtered for background noise and refined. Having identified the snow-soil reflector in the radargram, however difficult this may be, the curve is semiautomatically digitized by placing a set of uniformly spaced points located on the reflector (Figure 5 - the red line). This curve is exported for further analysis in a spread sheet.

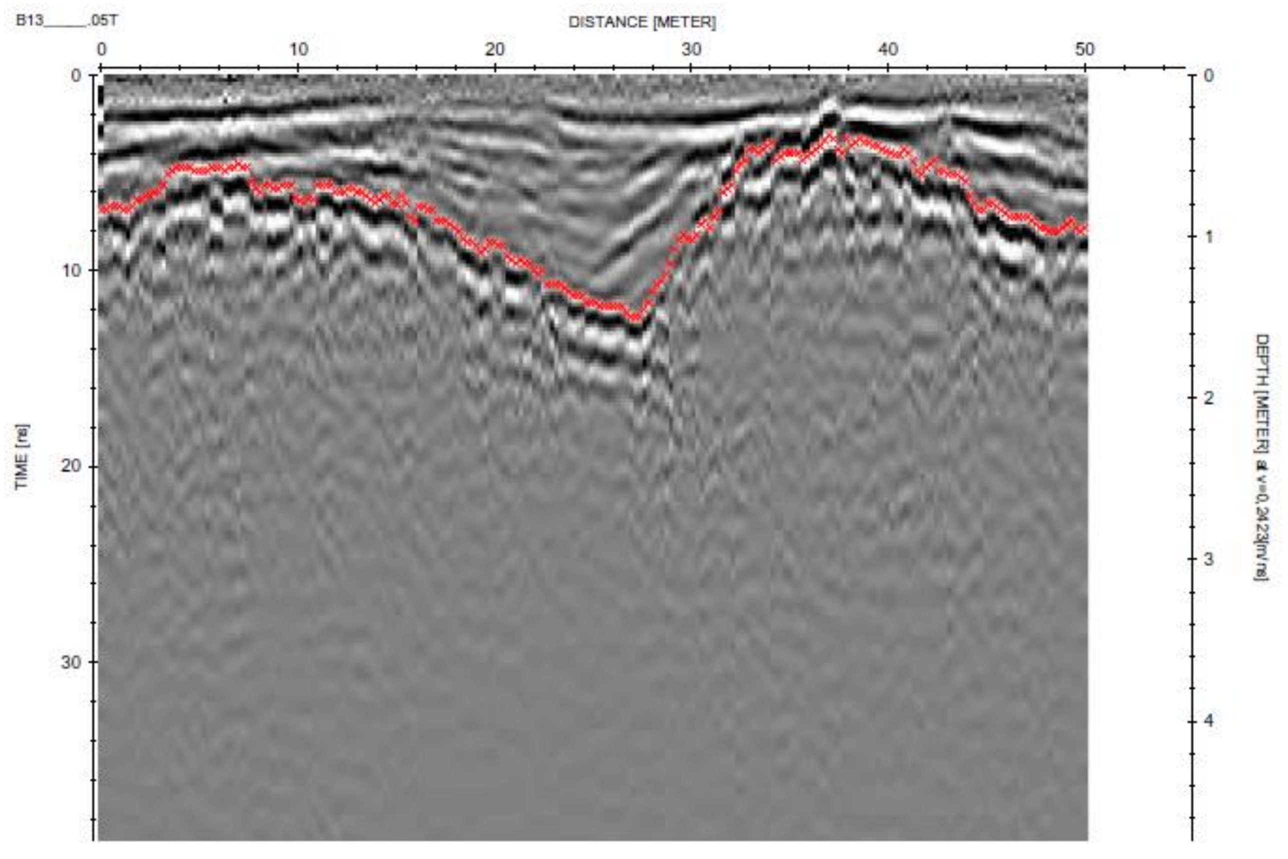

Figure 5 An interpreted radargram. The red line is the interpreted snow-soil reflector.

5 Results

The snow depth data shown in Appendix 2 and in the data file Appendix 4 has an empirical distribution as shown in Figure 6 and Figure 7, and it is characterized by the statistics in Table 3.

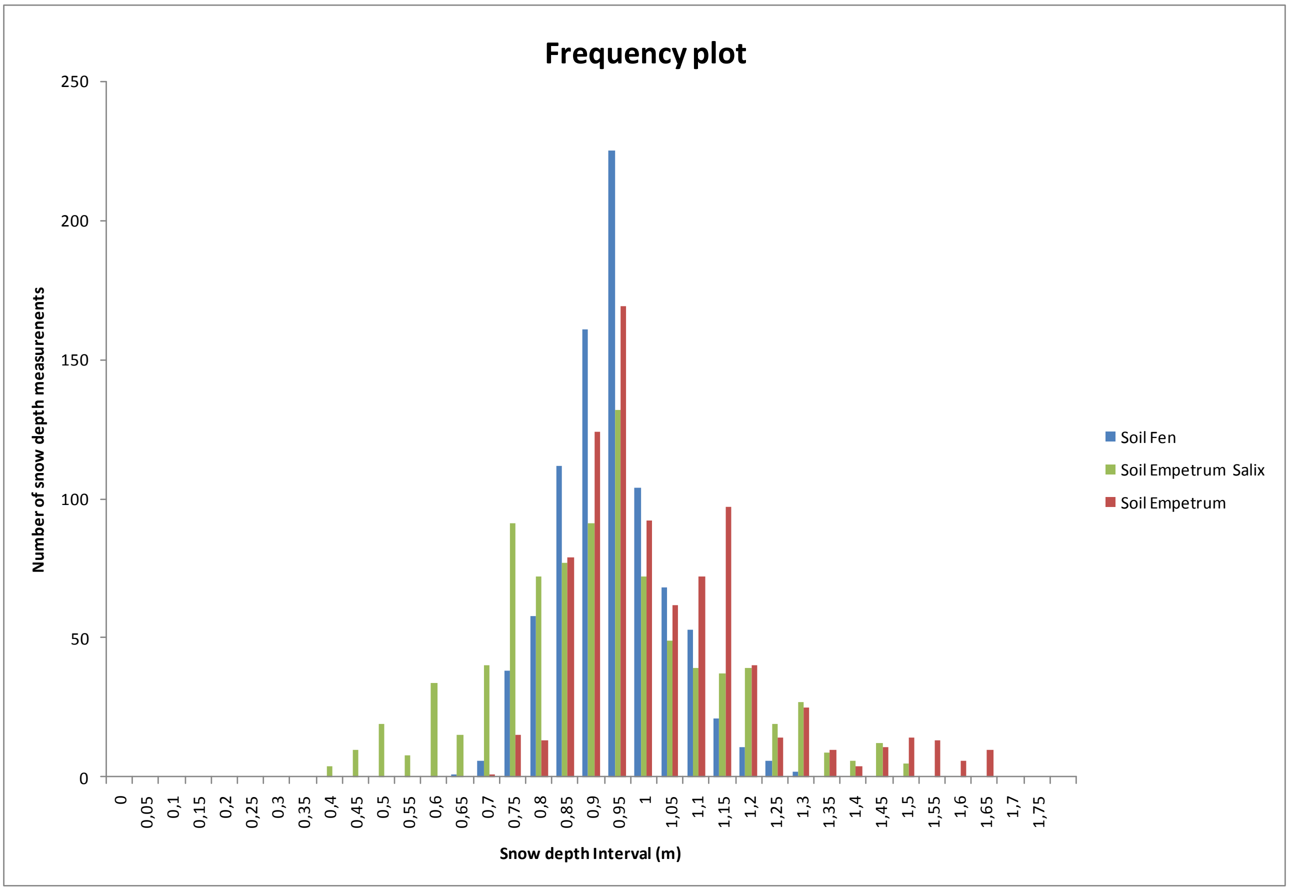

Figure 6 Frequency plot of the recorded snow depths for the three sites.

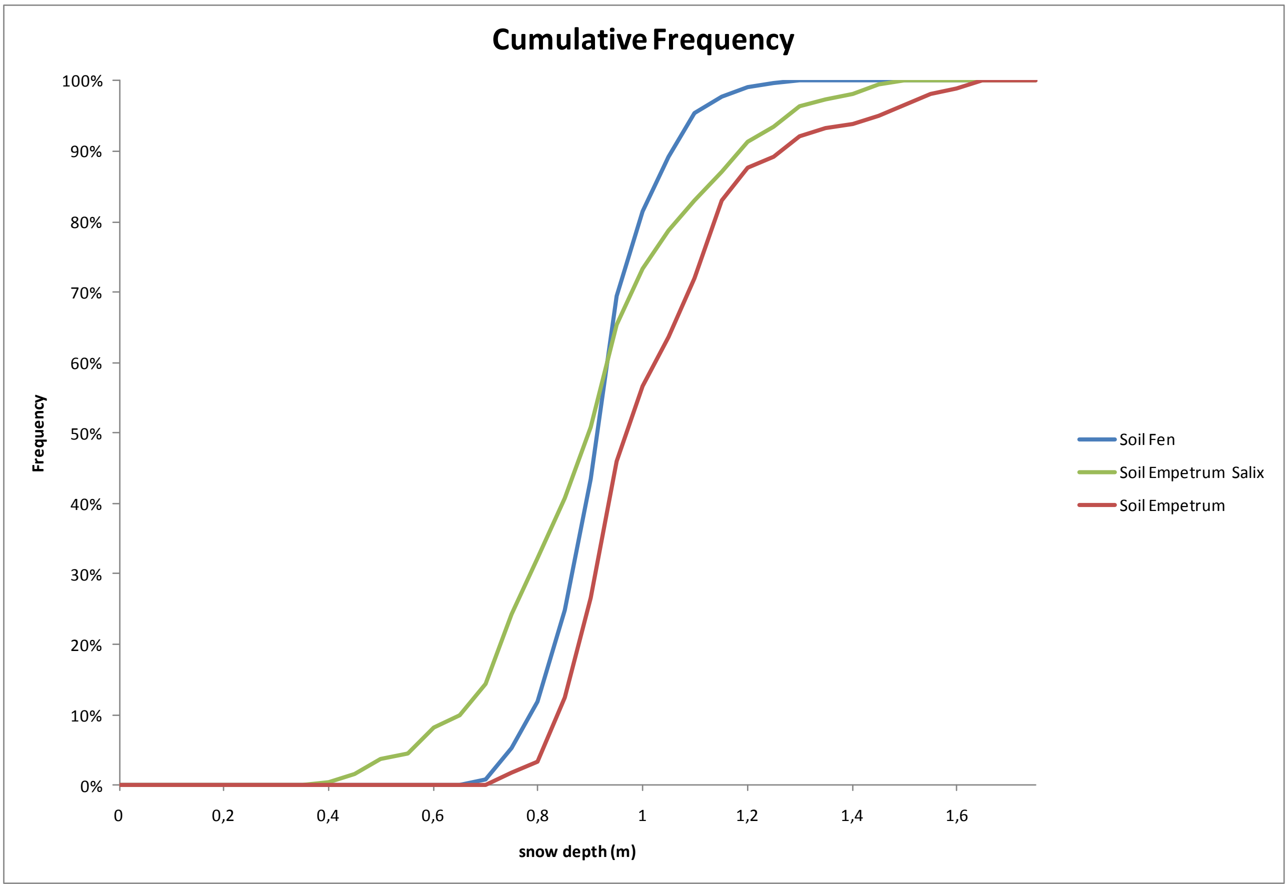

Figure 7 The cumulative frequency as a function of depth for the three sites

	Soil Fen (A)	Soil Empetrum Salix (B)	Soil Empetrum (C)
Mean snow depth (m)	0.914	0.898	1.018
Median (m)	0.903	0.881	0.969
Standard deviation	0.101	0.209	0.182
Variance	0.010	0.044	0.033
Skewness	0.441	0.221	1.236
Minimum	0.638	0.374	0.682
Maximum	1.277	1.497	1.629
Number of observations	866	907	872

Table 3 Summary statistics for the GPR snow depth measurements.

The error on the snow depths can be evaluated by comparing the absolute differences between the stake measurements and the corresponding snow depth. The snow depths derived from the radar measurements have an average precision of about 7 cm at *Soil Empetrum Salix* and *Soil Empetrum*. The precision is higher at *Soil Fen* (5 cm).

	Soil Fen (A)	Soil Empetrum Salix (B)	Soil Empetrum (C)
Mean absolute difference (m)	0.053	0.072	0.071
Number of observations	21	21	21

Table 4 Empirical evaluation of the mean error.

Results from the snow profiles are summarized in Table 5. Since the radar beam velocity is calculated on basis of an overall mean snow density, the layer of fresh snow that accumulated during the survey is not differentiated in the density measurements (even though this layer obviously has a lower density than the average of older snow.)

Depth interval (cm)	**Temperature (°C)**	**Density (kg/m^3)**	**Comments**
Snow pit A at *Soil Fen*. Total depth 98 cm			
[0-20[	n.a.	199	22 cm fresh snow over night
[20-40[	n.a.		Ice layered
[40-60[	n.a.	321	Recrystallized
[60-80[	n.a.		
[80-100[			
Snow pit B at *Soil Empetrum Salix*. Total depth 65 cm			
[0-20[	-1.1	306	5 cm fresh snow
[20-40[	-0.8		
[40-60[	-0.7		
[60-80[			
[80-100[			
Snow pit C at *Soil Soil Empetrum*. Total depth 85 cm			
[0-20[	-1.9	293	5 cm fresh snow
[20-40[	-1.7		Ice layered
[40-60[	-1.6	352	Recrystallized
[60-80[	-1.5		Ice layered
[80-100[			

Table 5 Results from snow pit excavation. Temperatures were recorded at the top of each depth interval.

6 Comments

In this survey snow depths and densities were measured at three sites over a two day period. During the time between measuring snow depths at *Soil Empetrum*, *Soil Empertum Salix* and *Soil Fen* the snow depths increased by approximately 17 cm. When comparing the mean depths, 17 cm should be subtracted from the measurements at *Soil Fen*.

An ANOVA test was carried out on the three data sets (with 17 cm being substracted from snow depths at *Soil Fen*), see Appendix 4. This test show that the three snow depth means are significantly different (α=0.01) and that the sampling method has gathered enough data to show that it is very unlikely (P=3 10^{-204}) that the difference observed is due to a coincidence of random sampling.

When comparing the snow depths (Figure 8) we can tell that there is a significant but not very large difference in means. We can interpret that the snow depth distribution at the Fen site is unlike the two other distributions. The lesser snow depth variance at the Fen site is likely to origin from the flat topography. The two other sites are situated at locations with varied terrain resulting in varying snow depth.

Repeated surveys will show whether the observed differences in snow depths are site dependent or the result of this year’s weather history. (If it turns out that the snow depths are site dependent, then it is reasonable to spread out the snow depth distribution to similar landscape/vegetation classes.)

It is important to notice the large variation in snow depths, especially when having to reproduce the survey for between year comparisons but also when setting up a measurement strategy with a hydrological focus. This survey has described the snow depths at three relatively small areal units and found that even a small areal unit has a distinct snow depth distribution. When describing snow depths at the scale of most terrain models (relevant to hydrological modeling), this observation argues that snow depth data is best described as a statistical distribution rather than point measurements.

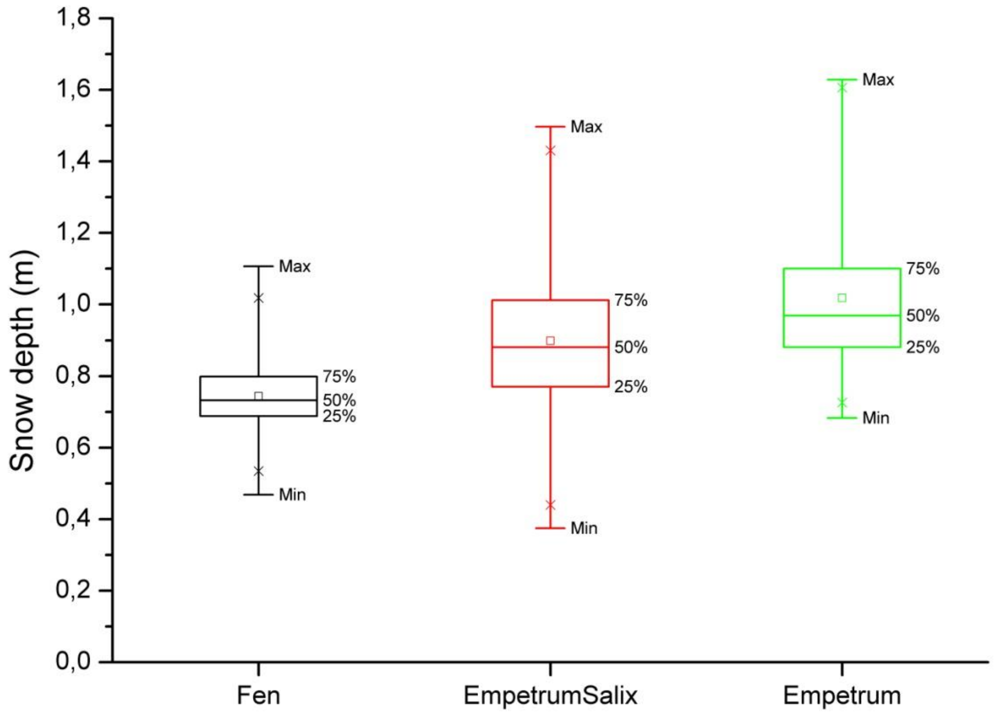

Figure 8 Box Chart when 17 cm is subtracted from the measurements at Soil Fen. The chart displays minimum, maximum and mean snow depths together with 1, 25, 50, 75, and 99% percentiles.

7 Conclusion

In this report a procedure for collecting and processing GPR data for evaluating snow depths for the Nuuk Basic monitoring program is outlined. Conversion of the Two-Way-Times into snow depths was done with respect to analysis of snow density and velocity of radar impulses in snow. The surveying method has yielded snow depths with satisfying precision and has formed a statistical basis for comparing snow depths in different landscape/vegetation classes.

Other conclusions which are important to future surveys:

- It is important to have a uniform grid of stake measurements for each radargram.

- Reliable density measurements are important to get a theoretical estimate of the velocity of the radar impulses in the snow.
- REFLEXW is very suitable software for processing radargrams.
- Controlling the radar unit with GroundVision™ version 145 and a Windows based laptop did cause frequent unexpected breakdowns during the field survey.
- Snow scooter transportation is a requirement when working in Kobbefjord at winter time due to the weight of the equipment in combination with low accessibility.

9 References

[Gro,2002] GroundVision™. See www.malags.com

[Ram,2002] MALÅ GeoScience, RAMAC X3M, Hardware Manual
RAMAC GroundVision Version 1.3 Software Manual
http://www.malags.se/Solutions/Products/X3M-Series/X3M-Integrated-Radar-Control-Unit.aspx

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