# CryoVEx 2011 Alert Sea Ice Ground Team Report


**Ground Team Operating out of Alert base, April 11th-18th 2011:**
Christian Haas (PI) & Justin Beckers, University of Alberta;
Seymour Laxon, Katharine Giles & Rosemary Willatt, UCL;
Malcolm Davidson, ESA

Report compiled by Rosemary Willatt and Christian Haas

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# Introduction

## Aims and Tasks

This report describes the data collected by the ground team during the Alert sea ice component of the 2011 CryoVEx experiment, operating out of Alert base, Ellesmere Island, Canada April 11th-18th.

The aims of the experiment were to study the snow and ice characteristics of Arctic sea ice and its snow cover during winter and how they affected Ku-band radar penetration into the snow.

The tasks to be completed were as follows. Before the airborne teams overflew:

- To find three sites, two in the pack ice and one on the fast ice close to Alert, which represented as many different snow and ice types as possible.
- To deploy two corner reflectors (CRs) at each site to act as vertical height references for the airborne radar altimeter (ASIRAS) flown on the Norlandair twin otter which also operated out of Alert.
- To deploy GPS buoys beneath the CRs at the two sites in the pack ice which would transmit their locations every 15 minutes, allowing the airborne and ground teams to re-visit the ice floes for surveying at a later date.
- To place coloured tarpaulins 30 m from each CR and bin bags full of snow every 10 m from the tarpaulins as visual aids to the airborne team.

Once the CRs had been over-flown by the airborne teams, the tasks when re-visiting each site to survey were:

- To take a 20 x 20 m grid of snow depth measurements at 1 m intervals around each CR, to be used when analysing the ASIRAS data to see how far into the snow pack the radar penetrated.
- To measure snow thickness, ice thickness and ice freeboard along a transect between the two CRs.
- To use the UCL Ground Penetrating Radar (GPR) to obtain radar data including the Ku-band (at which SIRAL and ASIRAS operate, as well as the NASA radar altimeter) close to the CRs, for comparison with airborne radar altimeter data.
- To dig snow pits within the grid of snow depth measurements and record snow characteristics such as layering and grain size, density and salinity. Some of the snow pits would be where the GPR sampled for comparing the GPR return echoes to the physical snow characteristics on small scales.

## Study site locations

The team deployed six CRs, two at the 'North site' and two at the 'South site', shown on Figure 1, and two at the 'Fast site'. The North and South sites were located in the pack ice around 350 and 120 km from Alert, respectively, and accessed by Twin Otter aircraft, whilst the Fast site was located on the fast ice just a few kilometres off the coast of Alert, and accessed by skidoo.

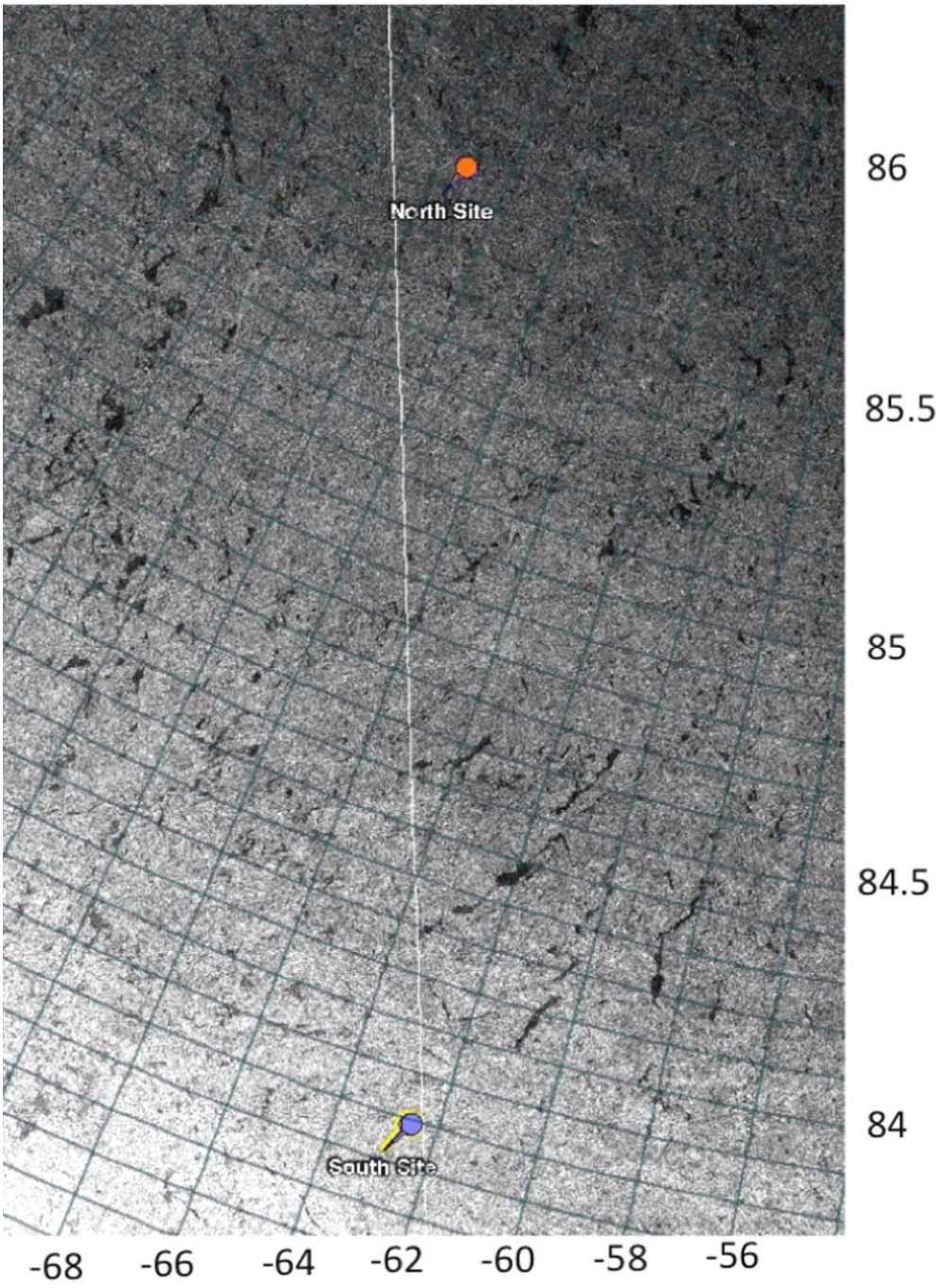



**Figure 1: ASAR Imagery from April 15th with CryoSat-2 track superimposed in white showing North and South sites. ASAR: 201104152147.**

## Data Description

This document contains the data collected when the CRs were deployed, such as GPS positions and CR elevation above the surface, and when they were surveyed, including extensive snow depth surveys, snow pits and locations of GPR sampling. A separate report will be prepared containing more detailed descriptions of the GPR data and its analysis.

The nomenclature used in the report is as follows: The corner reflectors are labelled by the site name and colour of the tarpaulin placed behind them, orange (O) or blue (B) and the relative location for each pair – West, East, etc., so that SB (West) was the CR at the South site with the blue tarpaulin, and was West of other CR at the South site. Snow pits where radar data were obtained were labelled 1, 2, 3 and so on. Snow pits unrelated to radar shots are labelled #n, where n is the snow pit number, or CHn and the site label.

A GPS buoy was placed directly beneath corner reflector apex, and these transmitted their locations (latitude, longitude) at 15 minute time intervals. Hand-held GPS positions were also obtained.

**Figure 2: Corner reflector on wooden stand with GPS buoy beneath it.**

One key piece of information for analysing ASIRAS data is the distance from the CR apex to the snow surface. This is recorded in the deployment sections for each site with the snow depth at the CRs.

An overview of the data is given in Table 1. The names of the CRs are shown, and the snow pits and the number of GPR shots near each CR. For each GPR shot, nine snow depth measurements were taken over the radar footprint (around 1 m) and (if time permitted) a snow pit was made and the snow characteristics were recorded. In addition snow pits were made at other points near the CR.

**Figure 3: The UCL GPR**

On each validation site (North Site, South Site, Fast Ice), profiles of ice thickness, snow thickness, and freeboard were obtained between the two corner reflectors

and snow grids. Ice thickness was measured with an EM31 induction sounder, snow thickness with a ruler stick, and freeboard by means of laser levelling using a rotating construction laser (except at the North Site where there was not enough time for laser levelling due to the weather-related, delayed arrival at the site). In addition, ice thickness, snow thickness, and freeboard were measured at a few drill-holes for calibration.

**Figure 4: (Left) EM31 SH mounted on a sled (photo by Don from MSC); Drilling a hole for a thickness measurements (photo K. Giles).**

All measurements were georeferenced by means of a handheld GPS integrated into the EM data logger, which continuously stored position and EM measurements at a sampling rate of 1 Hz. Snow thickness and surface elevation were measured next to the EM instrument with point spacings of approximately 10 steps, and the distances between measurements were calculated afterwards by means of the GPS information. The graphs in the sections for each site below (Figures 22&23, 44&46, and 69&70) show the three ice thickness profiles thus obtained, with coincident ice thickness, snow thickness, and freeboard information. The EM thickness (i.e. snow plus ice thickness) is displayed negatively, while freeboard and surface elevation are displayed positively (or snow thickness as in the case of the North Site). Freeboard was calculated by subtracting snow thickness from the measured surface elevation.

**Figure 5: Range pole with laser detector (photo R. Willatt); Tripod with rotating construction laser (photo S. Laxon)**

In addition to the combined ice and snow thickness and freeboard measurements along the main center line between snow grids, further ice thickness measurements were performed by dragging the EM31 parallel to the main profile. This resulted in statistically more reliable estimates of the thickness characteristics of each site, and provides insight into the across-track thickness variability which may be important for the interpretation of ASIRAS and other airborne measurements. Data were resampled to a constant point spacing of 5 m to remove biases due to variable walking speed or longer stops, during which data were continuously recorded as well. Results are included in Table 2 at the end of this report and are shown by various graphs for each site.

**Table 1: Overview of ground data obtained**

| Site | Deploy Date | Survey Date | Transect/Profile Data | | | | CRs | Snow pits | GPR shots |
|---|---|---|---|---|---|---|---|---|---|
| | | | EM | Snow | Ice | Freeboard | | | |
| North | Apr 14 | Apr 15 | Y | Y | Y | Y | NO (East) | 0 | 0 |
| | | | | | | | NB (West) | 5 | 3 |
| South | Apr 14 | Apr 16 | Y | Y | Y | Y | SO (West) | 1 | 2 |
| | | | | | | | SB (East) | 4 | 3 |
| Fast | Apr 11 | Apr 17-18 | Y | Y | Y | Y | FO (South) | 6* | 6 |
| | | | | | | | FB (North) | 0 | 0 |

*Only four of these six snow pits were within the 20 x 20 m grid around FO, two lay around 50 m outside it.

In addition to the data shown in Table 1, a grid of snow depth measurements at 1 m spacing was done on a 20 m x 20 m grid around each CR.

## North site

The North site CRs were deployed on April 14th. The site was over-flown by ASIRAS on April 14th and surveyed by the ground team on April 15th. Coordinates when the CRs were deployed were:

CR1 (Orange/East) on N site: 85° 34.932 ',-69° 34.560 ' (85.582, -69.576)
CR2 (Blue/West) on N site: 85° 34.992 ',-69° 37.896 ' (85.583, -69.631)

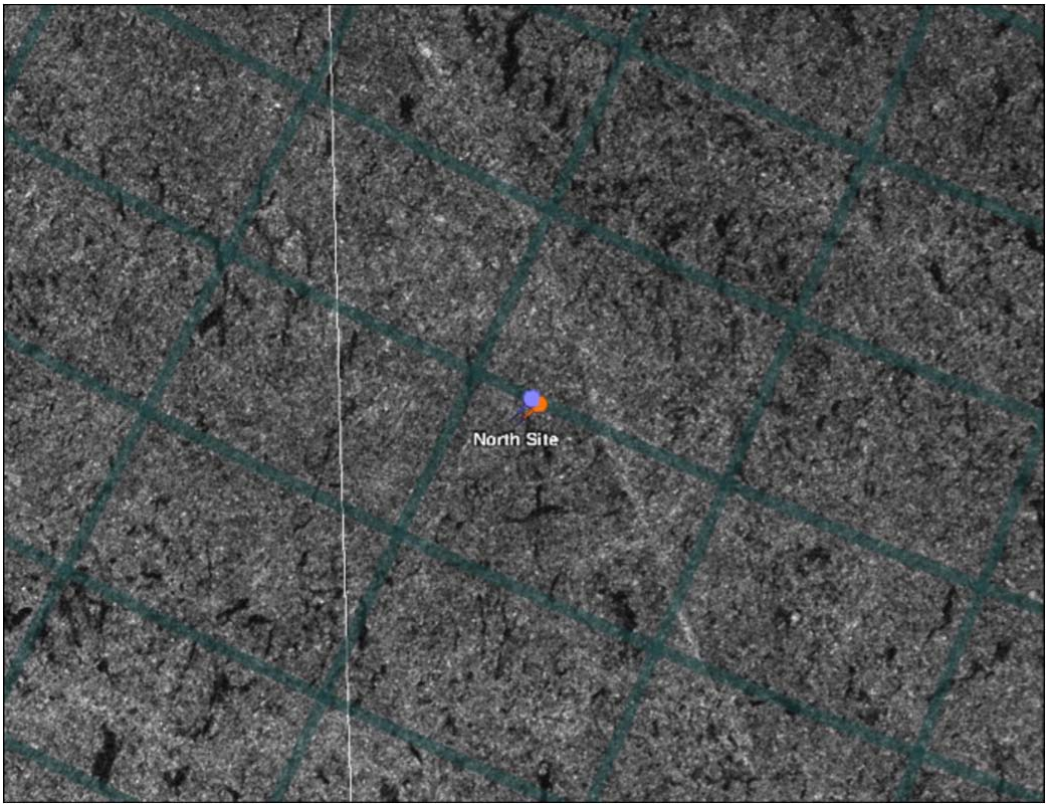



**Figure 6: ASAR Imagery from April 15th with CryoSat-2 track superimposed in white. The grid spacing is 0.1° latitude, 2° longitude.**

### General Notes on the North site

The ice was very level, very hard when drilled, and when the snow was removed the ice surface was dark and solid indicating melt ponds on surface. There was a ridge (around halfway) between the CRs – this should be visible with the laser and ASIRAS, and instruments on other aircraft. There was a mixture of soft snow and hard, crusty snow. CH drilled the ice near the plane (near NB), the ice thickness was 180 cm with soft snow on top. Figure 9 shows the layout of the North site CRs.

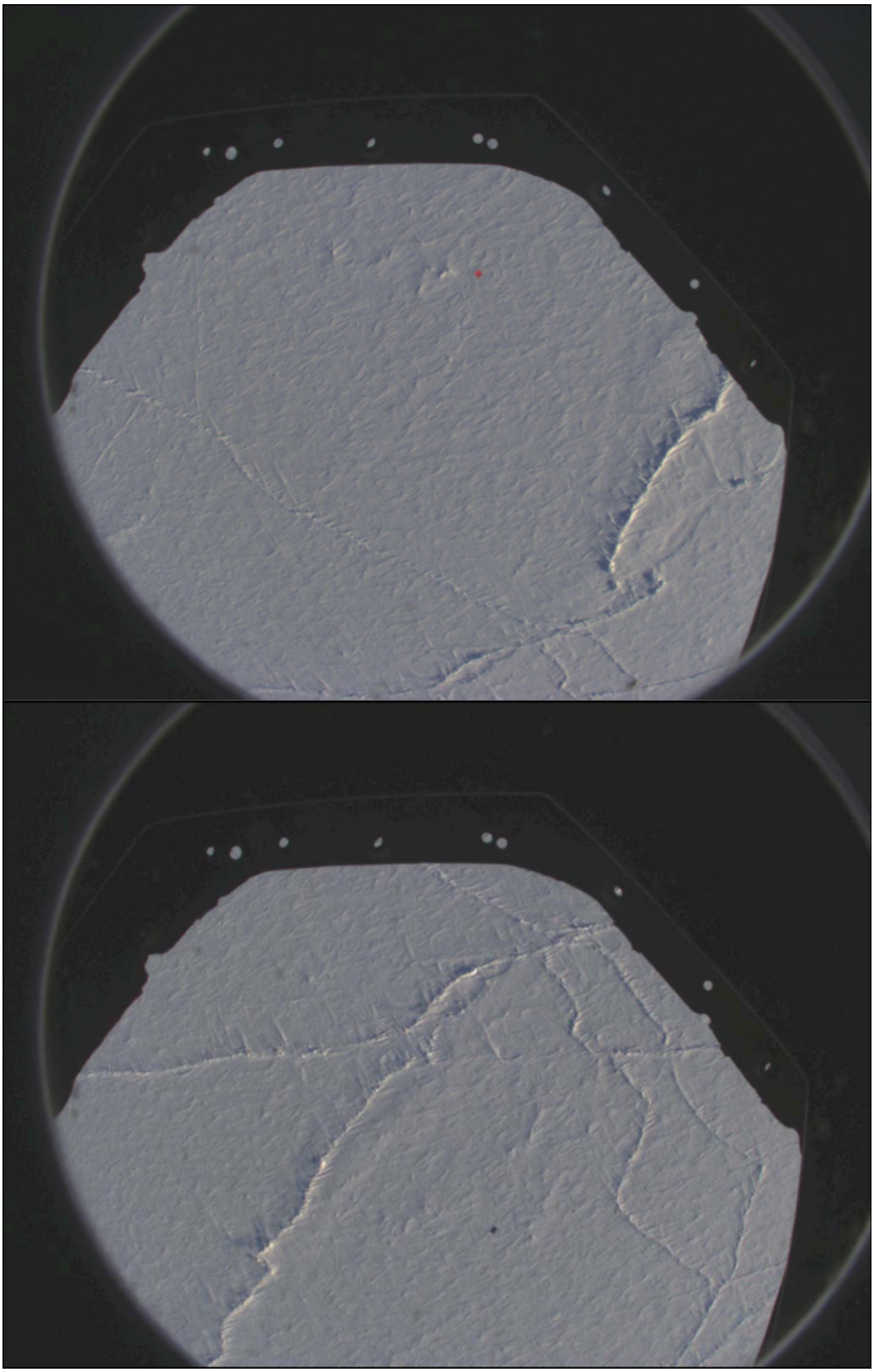


**Figure 7: Webcam footage from Norlandair Twin Otter when over-flying the North site**

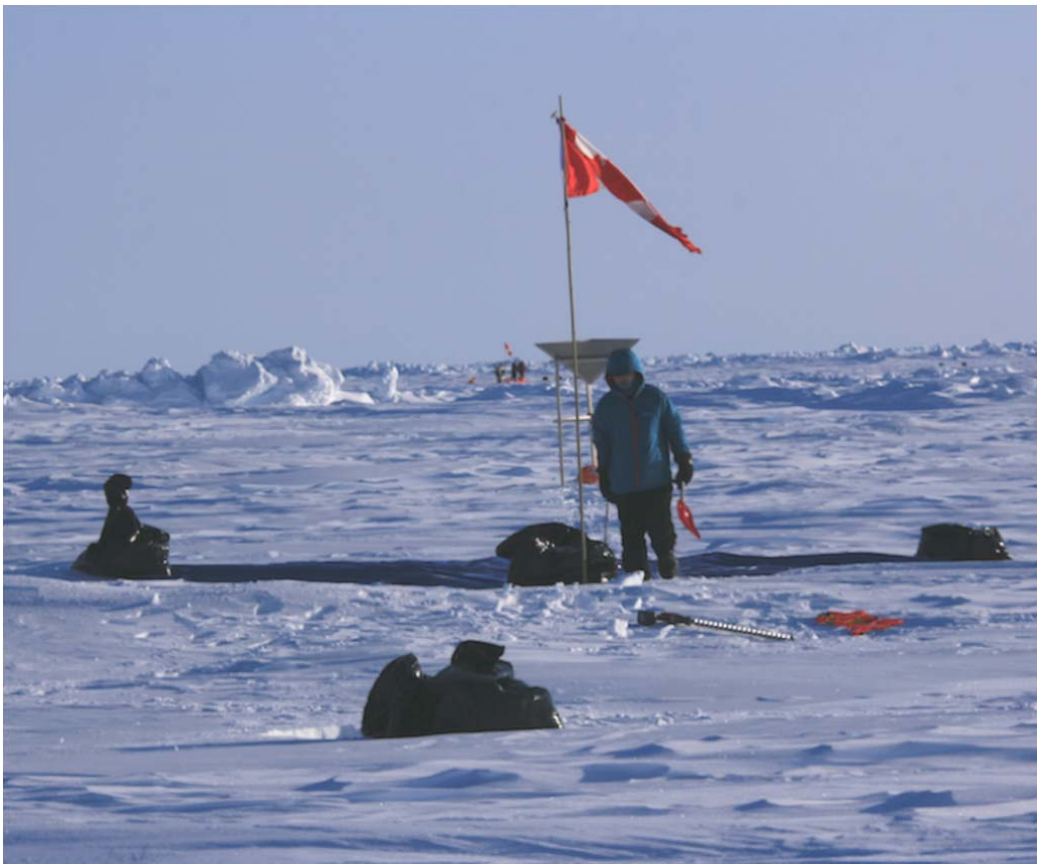


**Figure 8: North site deployment, note the ridge between the CRs: NB (West) in the foreground, NO (East) in the background.**

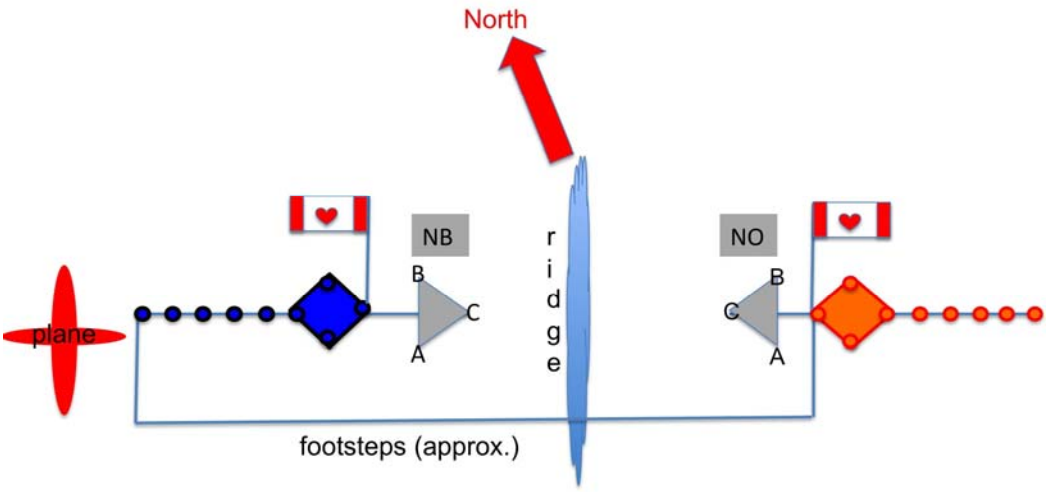



**Figure 9: NO and NB setups, bin bags were laid at 10 m intervals, five after each tarpaulin. Tarpaulin corners 30 m from CRs. Bin bags 10 m apart. NO: Christian, Katharine, Malcolm, Rosie. NB: Seymour, Justin. The blue tarpaulin was approx. 4.5 x 6 m and the orange approx. 4.4 x 5 m.**

## NO (North Orange, East)

Snow description (top surface downwards): hard crust with softer, very dry, loose snow beneath, thick layer of depth hoar. Surface topography around 20cm in height. The site was drifting Eastwards.

Figure 10: North Orange Site Deployment

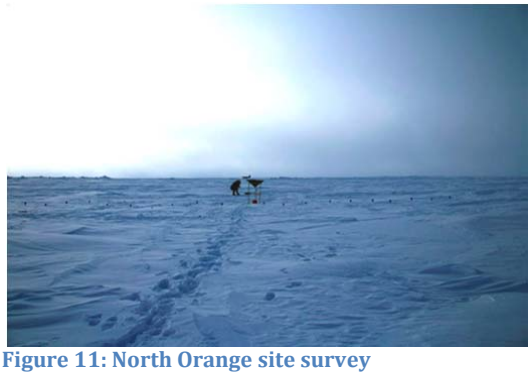


Figure 11: North Orange site survey

### Deployment of NO (East)

Snow depths at CR (cm):

| NOA | NOB | NOC | NO centre (apex) |
|---|---|---|---|
| 16 | 21 | 20 | 19 |

Height of metal CR above snow surface (cm):

| NOA | NOB | NOC | NO centre (apex) |
|---|---|---|---|
| 163 | 160 | 160 | 109-110 cm (measured after buoy deployed, then moved buoy away and guessed snow surface) |

Hand-held GPS Positions:

| | lat (N) | lon (W) |
|---|---|---|
| NO centre | 85.58218 | 69.57596 |

CR Slopes:
Corner C to corner B, 4 degrees down
Corner A to corner C, 0 degrees
Corner A to corner B, 4 degrees down

Surveyed snow depths from flag to CR. 0 is at flag, 30 at CR.
(snow_depth_survey_flag_cr.xlsx)

| Distance (m) from flag | Snow thickness (cm) |
|---|---|
| 0 | 41 |
| 1 | 37 |
| 2 | 38 |
| 3 | 31 |
| 4 | 38 |
| 5 | 32 |
| 6 | 19 |
| 7 | 34 |
| 8 | 26 |
| 9 | 30 |
| 10 | 36 |
| 11 | 31 |
| 12 | 38 |
| 13 | 47 |
| 14 | 39 |
| 15 | 42 |
| 16 | 39 |
| 17 | 40 |
| 18 | 39 |
| 19 | 44 |
| 20 | 40 |
| 21 | 43 |
| 22 | 47 |
| 23 | 39 |
| 24 | 36 |
| 25 | 44 |
| 26 | 39 |
| 27 | 31 |
| 28 | 32 |
| 29 | 23 |
| 30 | 19 |

data in file: crdep_20110414_n_s.doc

## Survey of NO (East)

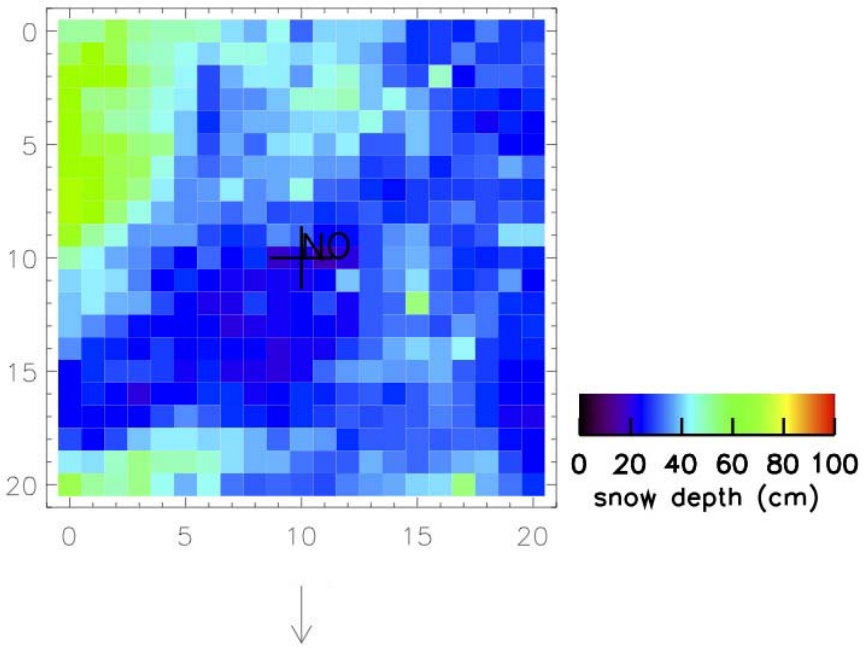



Figure 12: Snow survey at NO (East). The arrow indicates the direction of the other CR, NB.

No GPR data was obtained around NO (East) due to time constraints.

## NB (North Blue, West)

Figure 13: North Blue site deployment

Figure 14: North Blue site survey

### Deployment of NB (West)

Snow has hard wind slab crust, depth hoar layer below.
Topography of snow surface is around 20cm in height.
Laid with corner pointing towards other site (away from tarp; Corner Labelled C)
Sastrugi near CR.

Snow depths at CR (cm):

| NBA | NBB | NBC | NB centre (apex) |
|---|---|---|---|
| 34 | 37 | 36 | 35 |

Height of metal CR above snow surface (cm):

| NBA | NBB | NBC | NB centre (apex) |
|---|---|---|---|
| 172 | 171 | 170.5 | 118 |

Slopes:
Corner C to corner A, inclined (up) 0.5 degrees towards A
Corner C to corner B, inclined (up) 1 degree towards B
Corner B to corner A, 0 degrees

No GPS coordinate taken (have GPS buoy).

### Survey of NB (West)

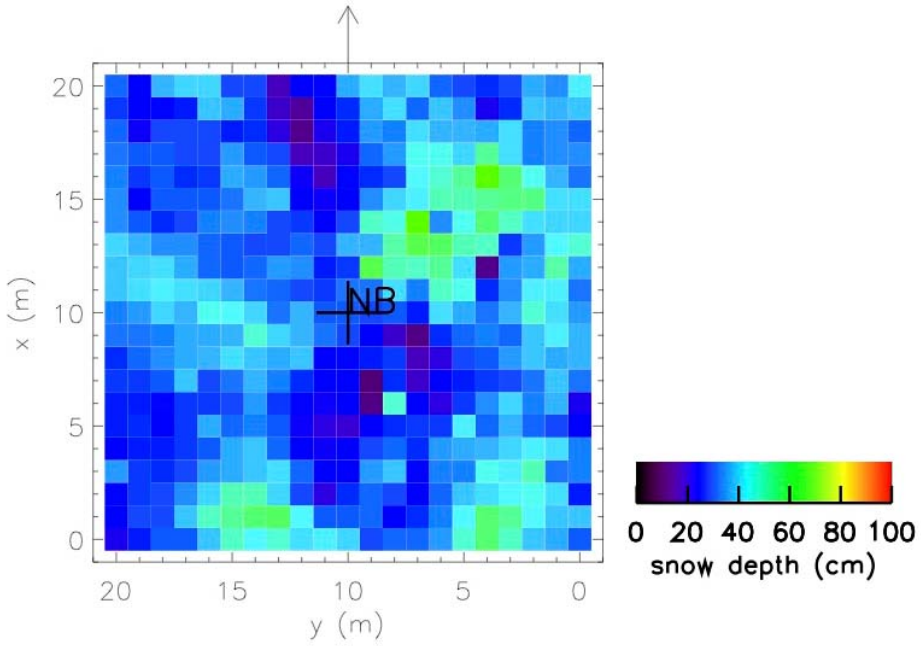



**Figure 15: North Blue site snow survey. The arrow indicates the direction of the other CR, NO**

Three radar shots with coincident snow pits were taken with locations shown in Figure 16.

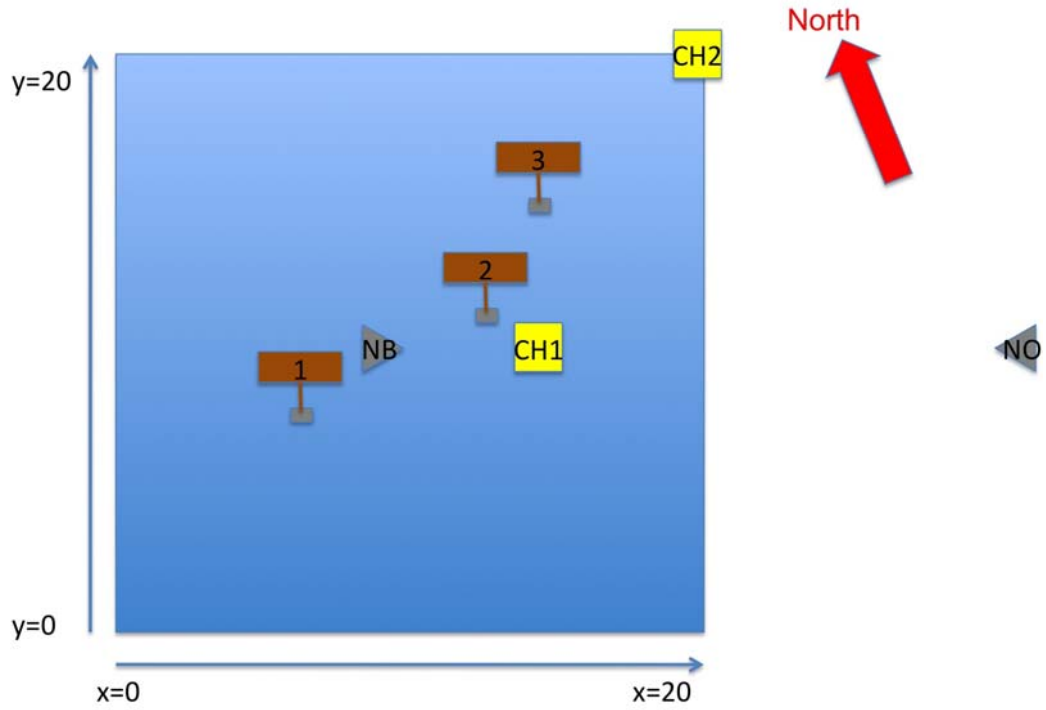



**Figure 16: NB GPR locations. Snow pits by CH where GPR shots were not taken are shown in yellow.**

**Figure 17: NB (West) GPR shot snow pit 1. We were unsure as to whether the bottom surface was really ice.**

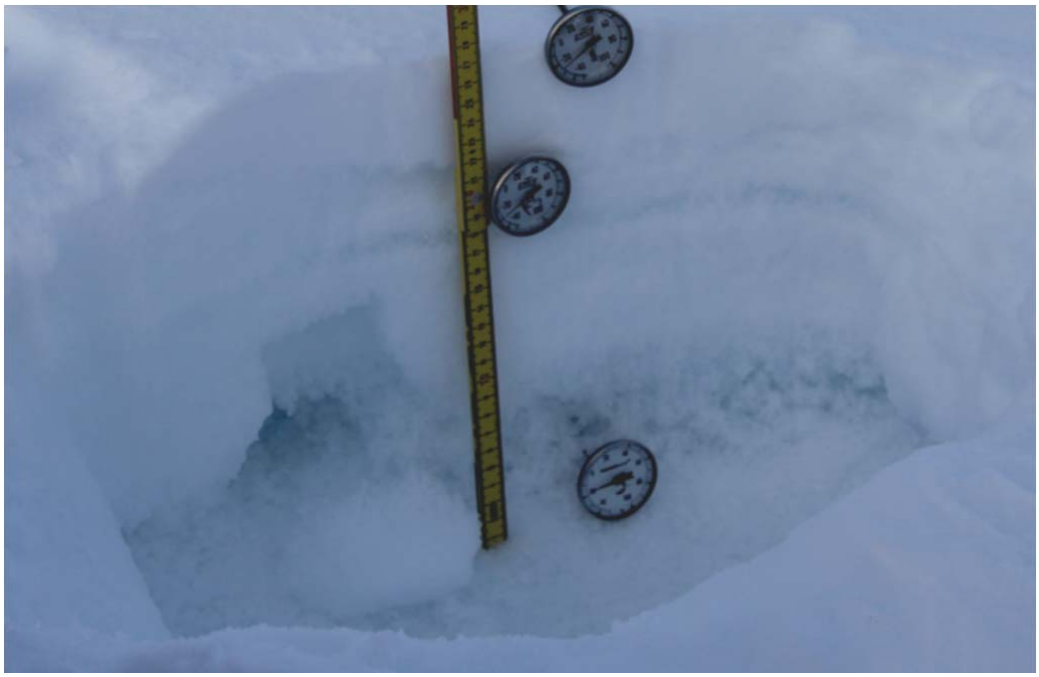


Figure 18: North Blue site snow pit 2.

There is no photograph at NB3.

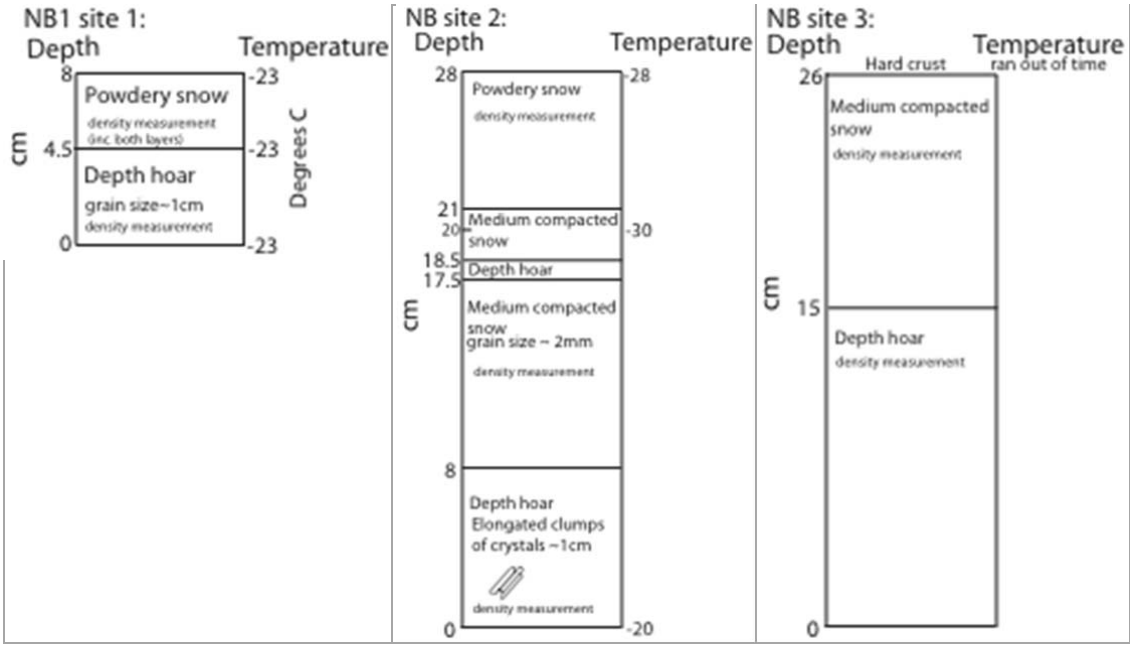



Figure 19: NB (West) snow pit diagrams. In NB1 shown in Figure 17 and here we were unsure as to whether the bottom surface was really ice.

In addition, two snow pits were made near NB with diagrams shown in Figure 20.

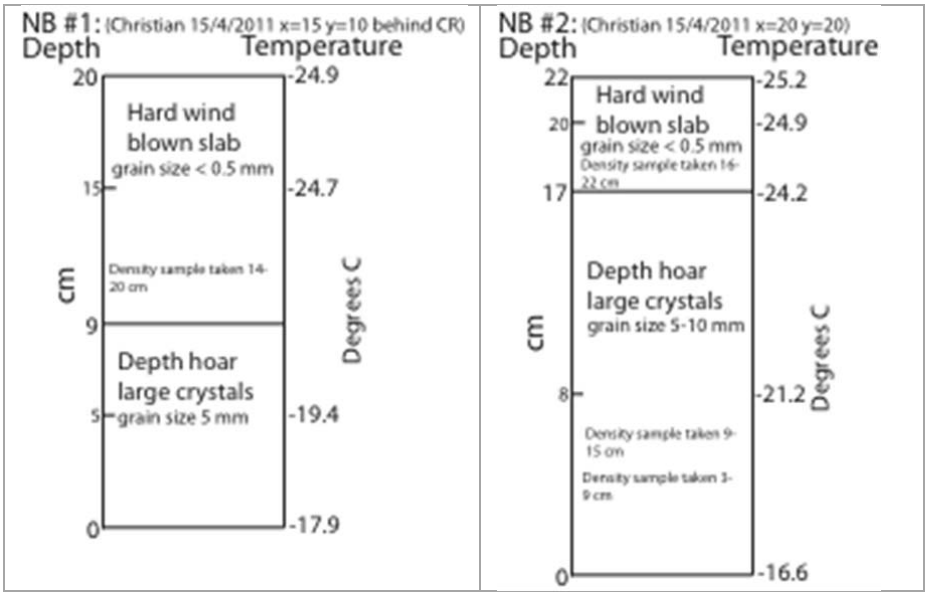



**Figure 20: Two additional snow pits at NB at the coordinates indicated.**

## North Site Transect Survey

Figure 21-23 show the snow depth, ice thickness and ice freeboard measured at the North site.

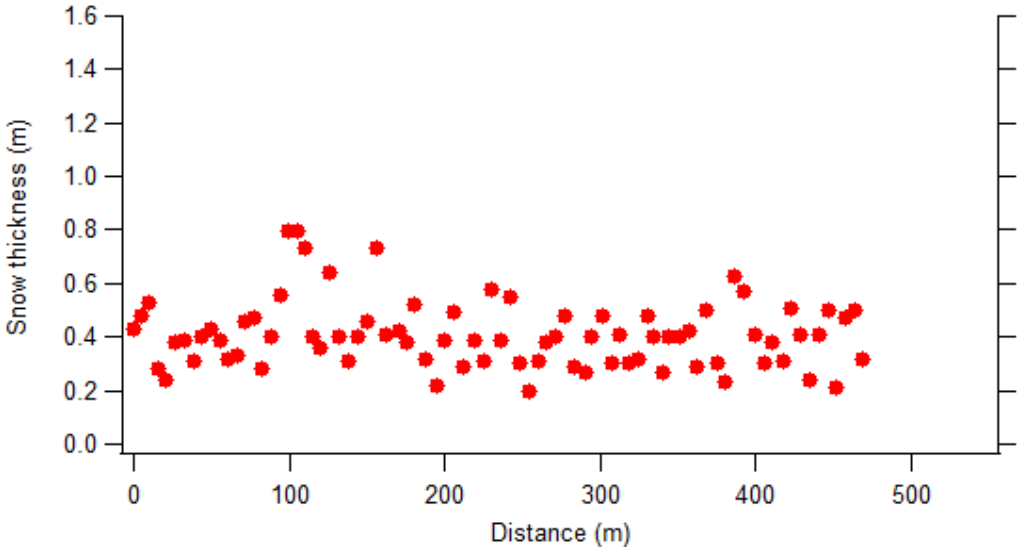



**Figure 21: Snow depth along transect at the North site, with 0m at NB (West).**

Table 2 in Summary of transect measurements p51 provides a summary of the main results from this transect and those at the other sites.

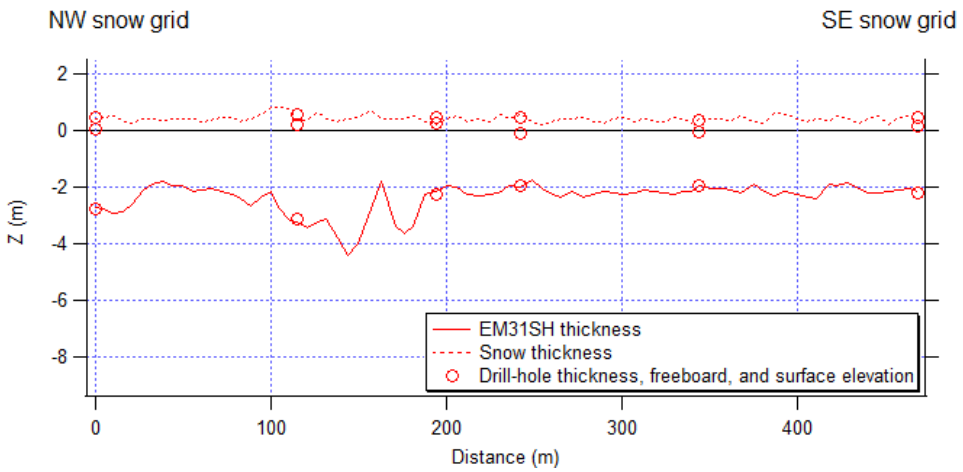



Figure 22: Ice and snow thickness profiles between snow grids.

Table 2 provides a summary of the main results.

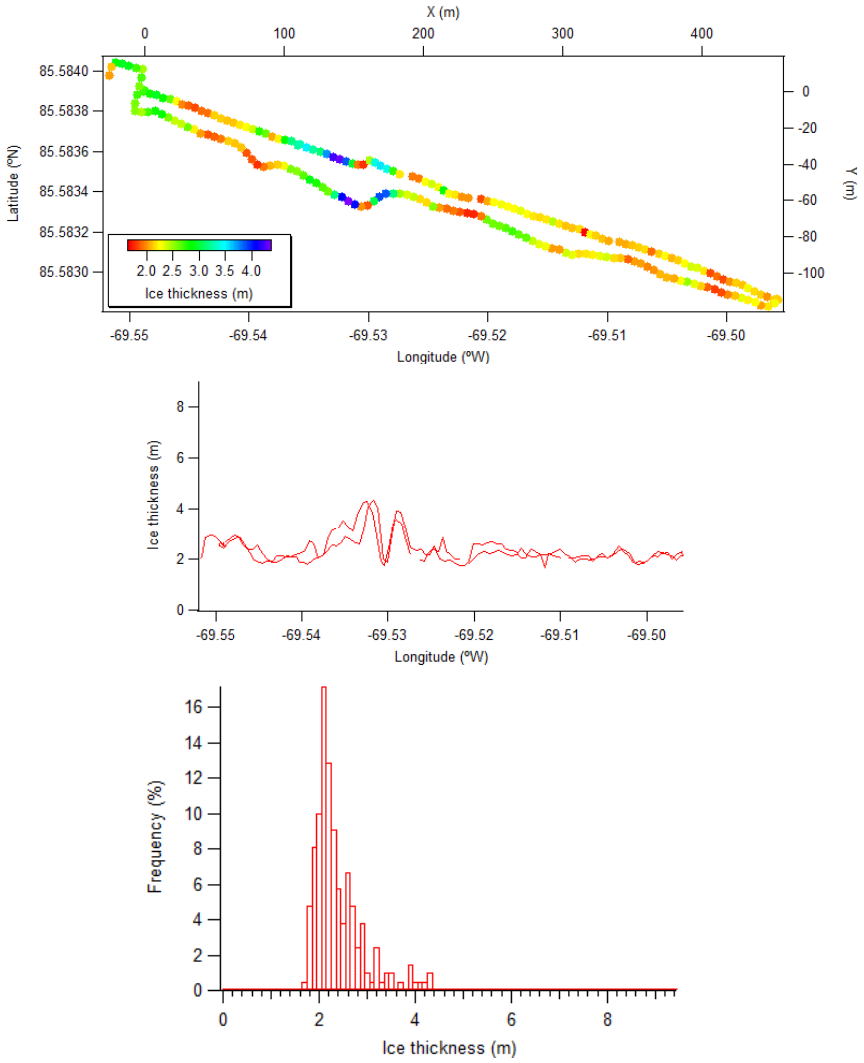



Figure 23: Additional EM ice thickness profiles.

## North site ASIRAS overpasses

ASIRAS overflew the North site on April 14th. Figure 24 shows the ASIRAS over-flights and GPS buoy locations colour-coded with time.

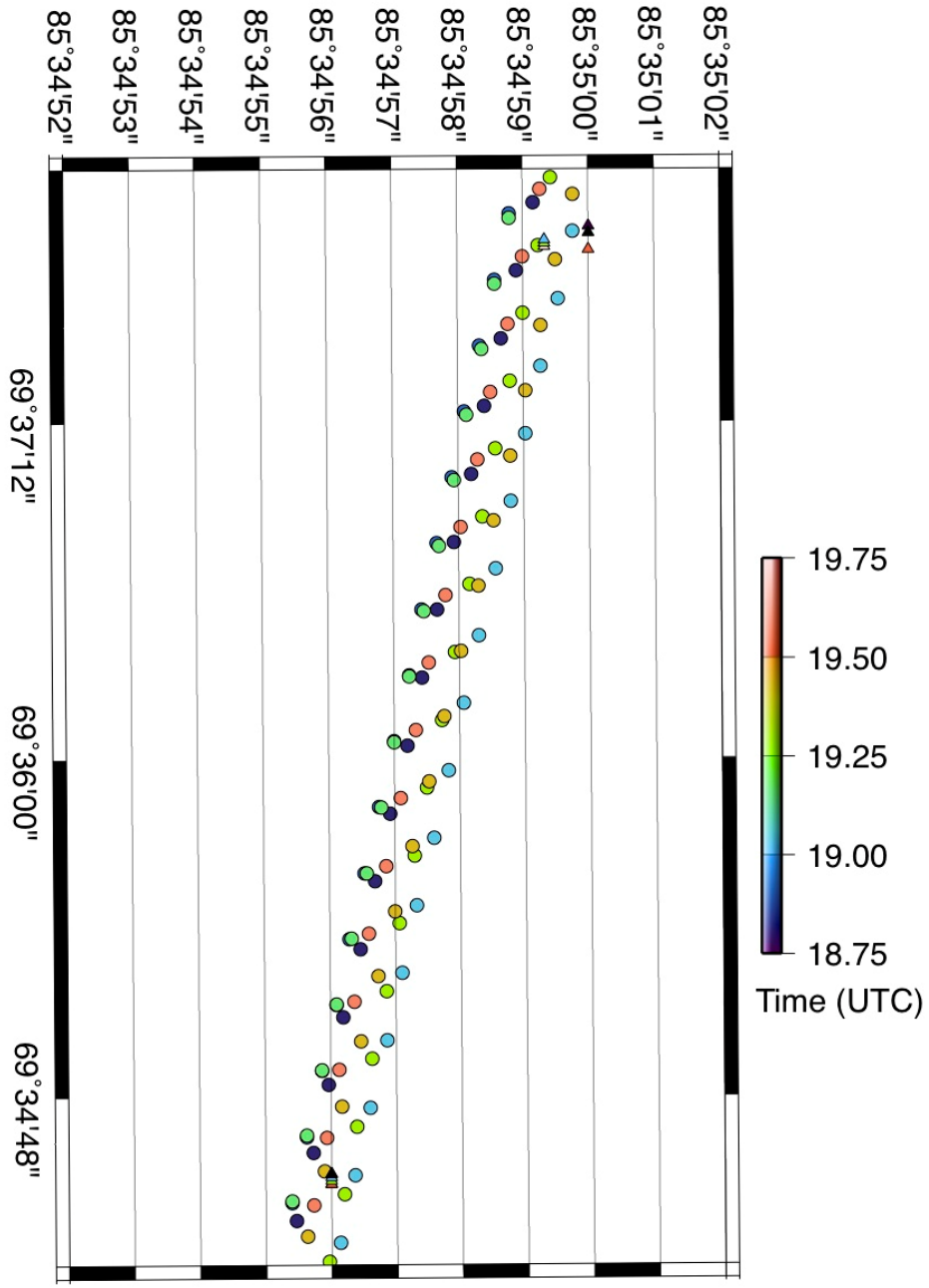



**Figure 24: North site ASIRAS overpasses and GPS buoy locations colour-coded with time.**

## South Site

The South site CRs were deployed on April 14th. The site was over-flown by ASIRAS on April 15th, and the NASA P3 over-flight was also on April 15th. The Polar 5 over-flight was on April 16th, whilst the ground team were conducting the ground survey.

Air temperatures at South site were around -32C and windier than North site, which was around -25C. Snow at SB was ~20cm deep, less than at SO, and harder. There was a ridge between SO and SB. There was another ridge behind SB (see right hand side of Figure 27) where CH dug a hole and found snow depth 2.5 m. There was a large snow depth gradient from this to the smaller snow thickness found at SO. Coordinates of the CRs when they were deployed:

CR1 (Blue/East) on S site: 83° 37.176 ',-62° 52.344‘ (83.6196,-62.8724)
CR2 (Orange/West) on S site: 83° 37.080 ',-62° 54.420 ' (83.618,-62.907)

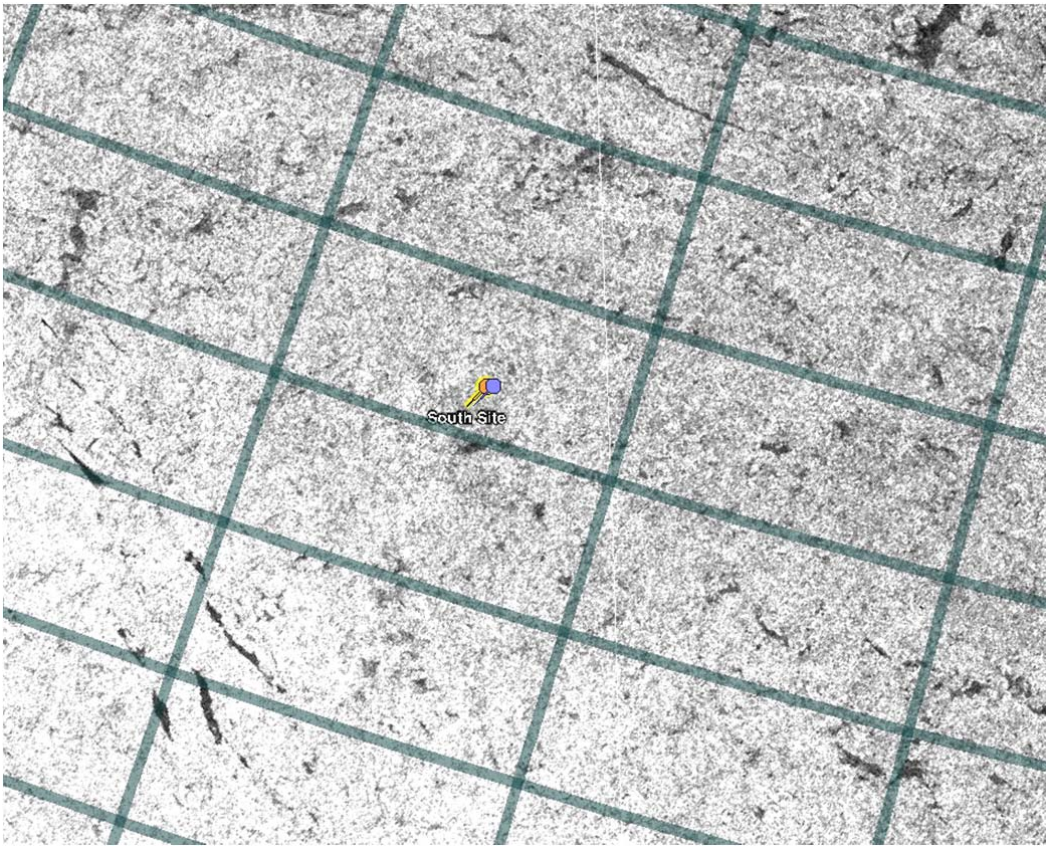



**Figure 25: ASAR Image on 15 April 2011 of south site. The white line shows the CryoSat overpass on 15 April.**

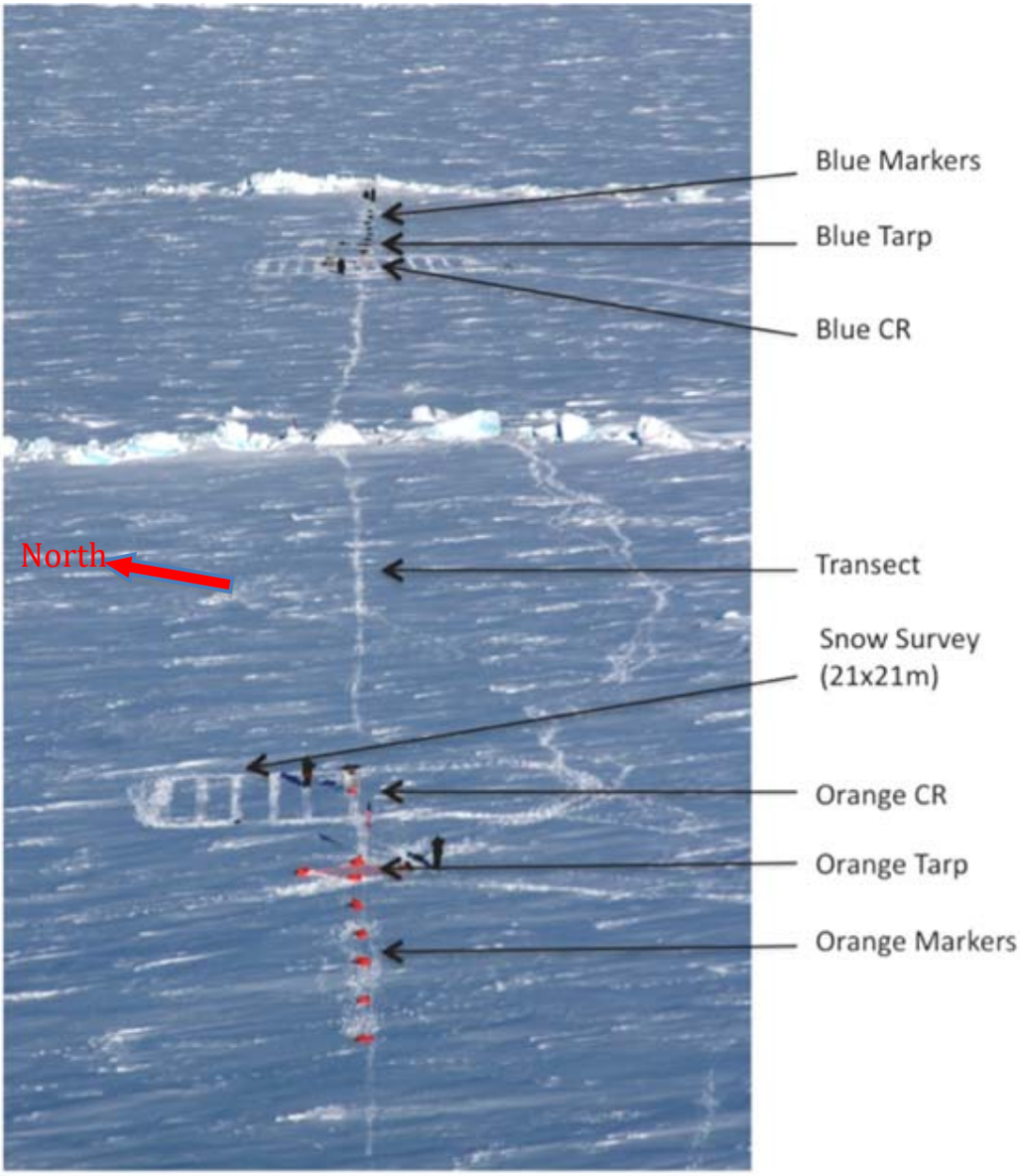



**Figure 26: Aircraft view of South site survey from Polar 5, seen from west to east (Credit: Polar 5 aircrew)**

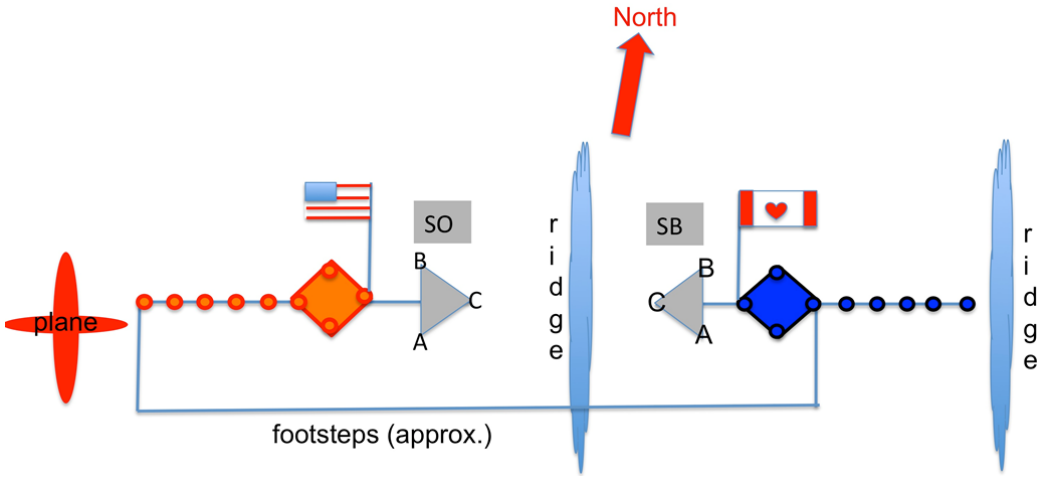



**Figure 27: SO and SB setups, bin bags were laid at 10 m intervals, five after each tarpaulin. Tarpaulin corners 30 m from CRs. Bin bags 10 m apart. Deployment: SO: Katharine, Rosie. SB: Christian, Seymour, Justin, Malcolm. The blue tarpaulin was approx. 4.5 x 6 m and the orange approx. 4.4 x 5 m.**

## SO (West)

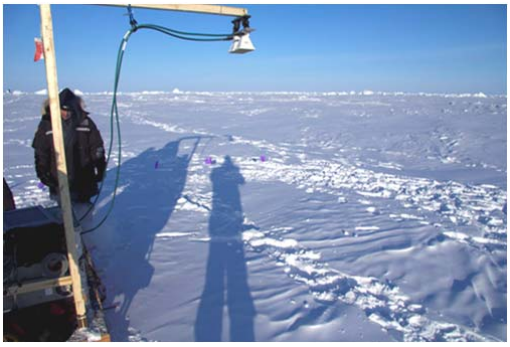


**Figure 28: South Orange site Radar Shot.**

**Figure 29: South Orange site Tarp behind.**

### Deployment of SO (West)

SO was deployed on level snow with sastrugi-type features around, ~10 cm size features ~20 cm high. Top snow at SO sometimes hard, sometimes soft, variability felt when walking. Only GPS buoy data for this CR from 16:30 local time as it was being moved before then. Used American flag at this site. Snow laid on edges of tarp to help weight down as wind picking up (will make tarp look smaller.)

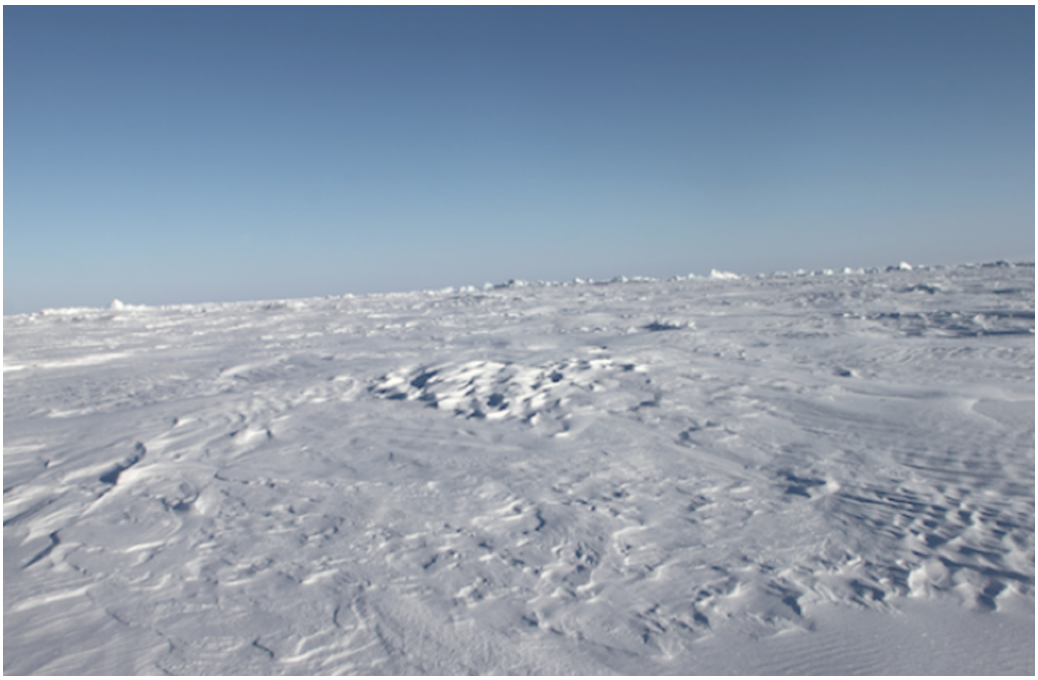


Figure 30: Snow with sastrugi where SO deployed

Snow depths at CR:

| SOA | SOB | SOC | SO centre (apex) |
|---|---|---|---|
| 55 | 50 | 51 | 53 |

Height of metal CR above snow surface (cm):

| SOA | SOB | SOC | SO centre (apex) |
|---|---|---|---|
| 160 | 157 | 161.5 | 106 |

GPS Positions – none, battery no longer functioning.

Slopes:
corner C to corner B, 2 degrees down
corner A to corner B, 2 degrees down
corner C to corner A, level

Other notes about SO:
Only use GPS buoy data for this CR from 16:30 local time.
Snow laid on edges of tarp to help weight down as wind picking up (will make tarp look smaller.)
Used American flag at this site.

### Survey of SO (West)

A grid of snow depth measurements 20 x 20 m around SO (West) is shown in Figure 31.

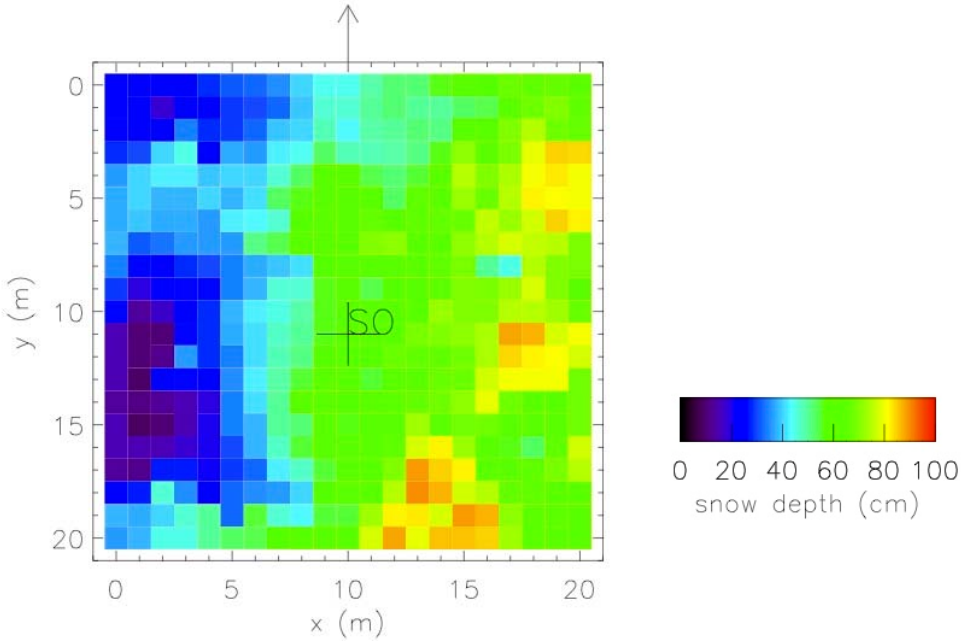



Figure 31: SOCR snow depth (Arrow in direction of SBE).

Two radar shots were taken near SO, at locations shown in Figure 32.

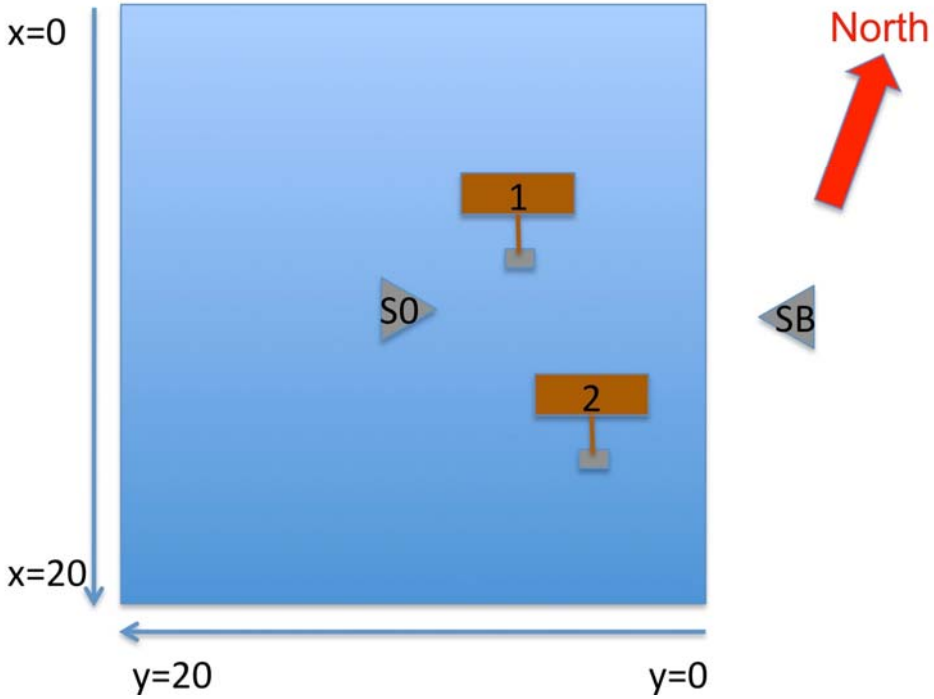



Figure 32: South Orange (West) GPR locations

Figure 33: South Orange Snow pit 1 (SO1) (referred to as site 4 in Figure 35)


Figure 34: Snow at SO2, no snow pit made due to time constraints

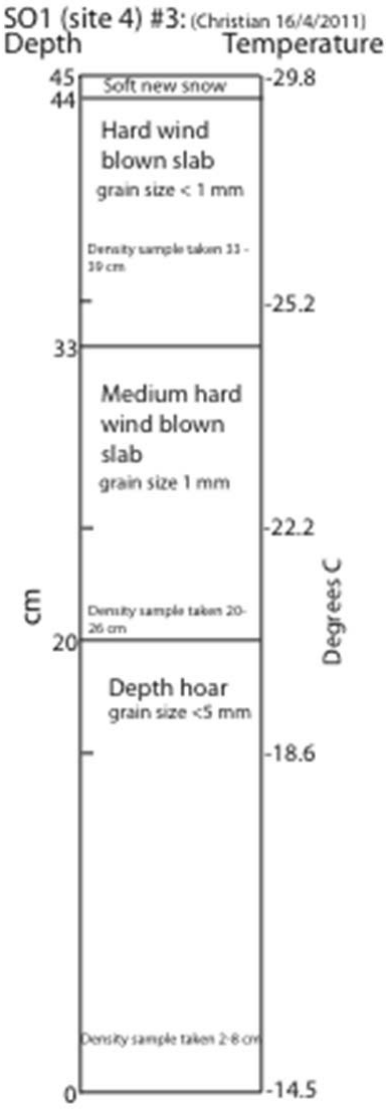



**Figure 35: Diagram of snow in pit SO1 near SO (West). No snow pit at SO2.**

## SB (East)

**Figure 36: South Blue site deployment, plane in background.**

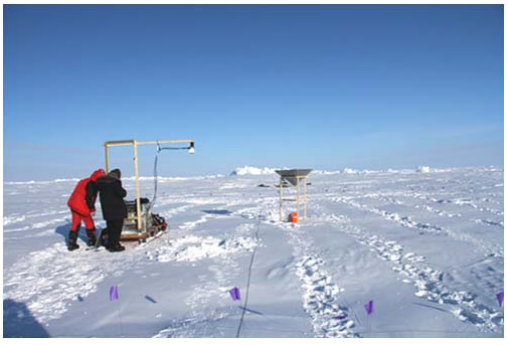


**Figure 37: South Blue site survey.**

### Deployment of SB (East)

Snow depths at CR (cm):

| SBA | SBB | SBC | SB centre (apex) |
|---|---|---|---|
| 20 | 43 | 20 | 23 |

Height of CR above snow surface (cm):

| SBA | SBB | SBC | SB centre (apex) |
|---|---|---|---|
| 162.5 | 165 | 164 | 110 |

Tarp at 33.5 m from CR.

Slopes 0 degrees on each edge – completely level.

Snow depth survey - 0m at CR, to 30 m at flag (m).

| | |
|---|---|
| 0 | 0.23 |
| 1 | 0.38 |
| 2 | 0.3 |
| 3 | 0.1 |
| 4 | 0.1 |
| 5 | 0.11 |
| 6 | 0.08 |
| 7 | 0.12 |
| 8 | 0.38 |
| 9 | 0.38 |
| 10 | 0.37 |
| 11 | 0.37 |
| 12 | 0.37 |
| 13 | 0.36 |
| 14 | 0.2 |
| 15 | 0.13 |
| 16 | 0.08 |
| 17 | 0.11 |
| 18 | 0.14 |
| 19 | 0.16 |
| 20 | 0.3 |
| 21 | 0.38 |
| 22 | 0.35 |
| 23 | 0.3 |
| 24 | 0.21 |
| 25 | 0.2 |
| 26 | 0.21 |
| 27 | 0.2 |
| 28 | 0.2 |
| 29 | 0.2 |
| 30 | 0.2 |

## Survey of SB (East)

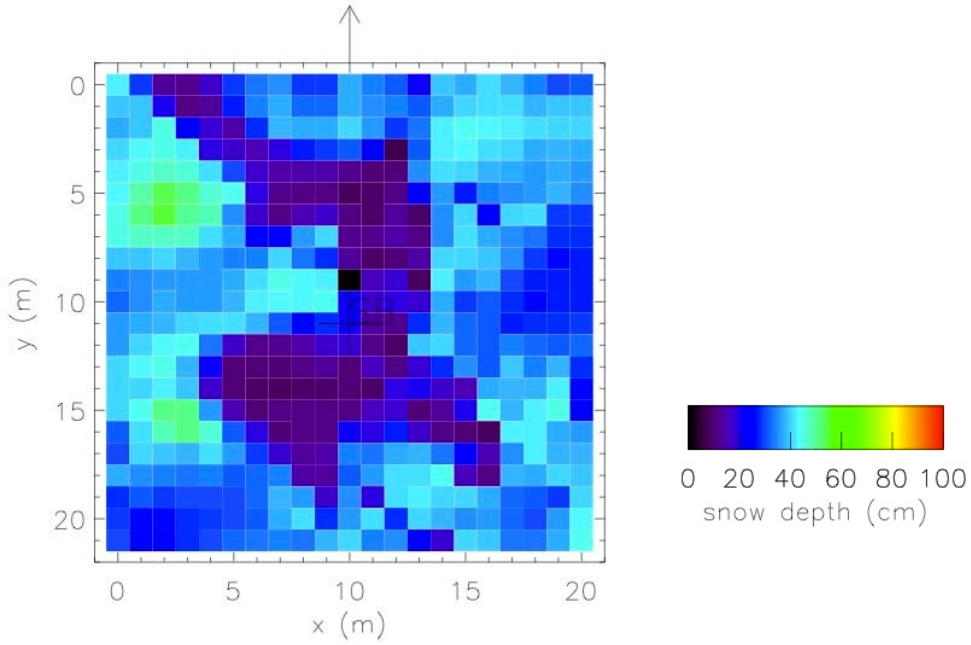



Figure 38: SB CR snow depth (Arrow in direction of SOW).

At SB snow depths were measured on a grid as shown in Figure 38. Three radar shots were fired, at locations shown in Figure 39. From snow pit SB1 we could see that we did not penetrate with the snow depth probe to the snow/ice interface – Justin dug out more, very hard wind blown slab above the ice. Add 12 cm to get more realistic snow depths.

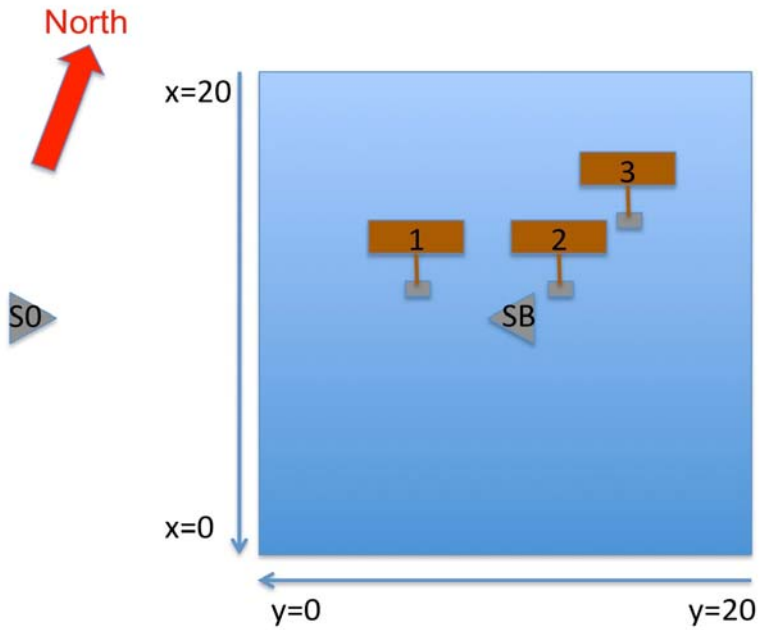



Figure 39: SB (East) radar sampling locations

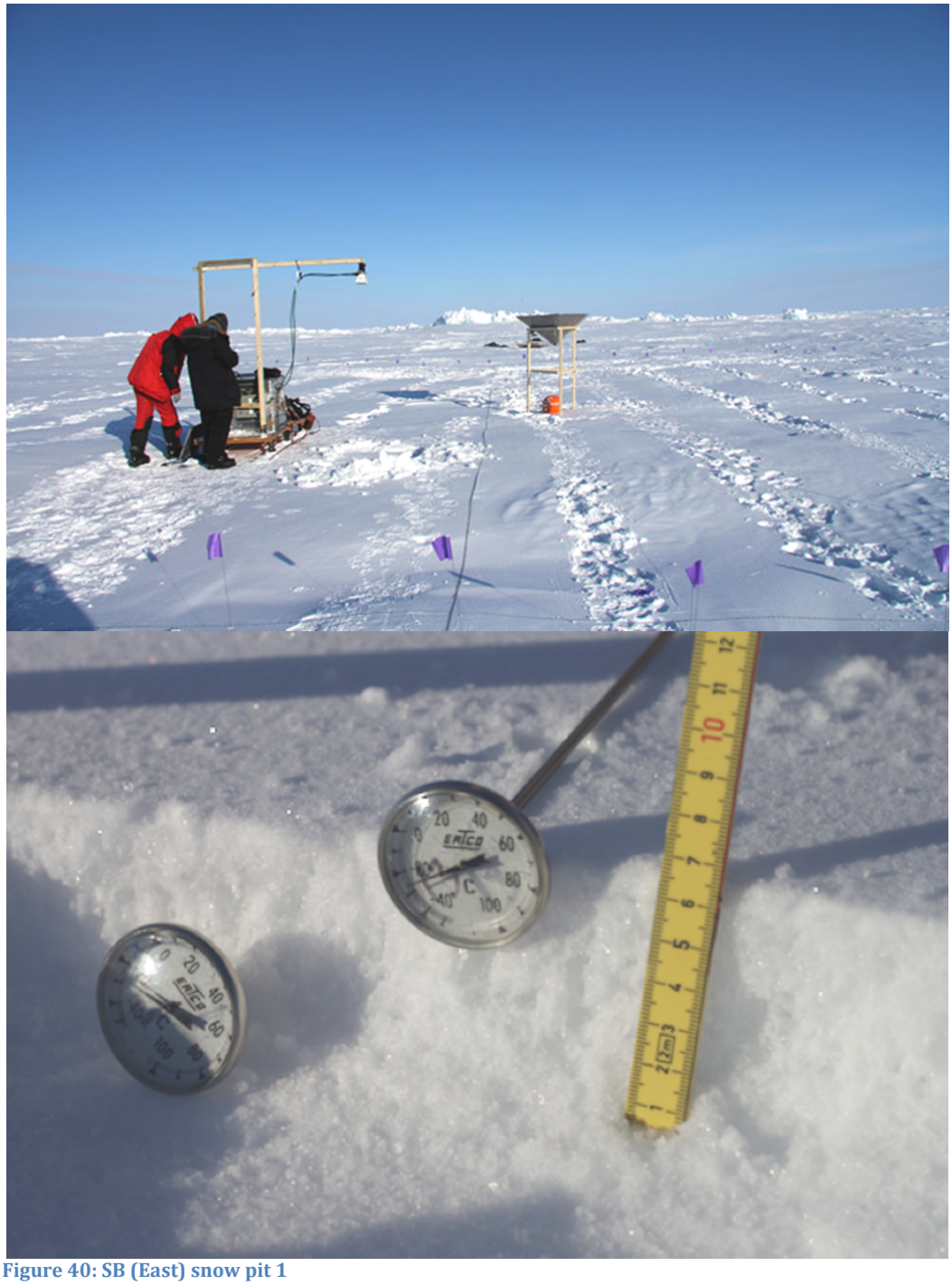


Figure 40: SB (East) snow pit 1

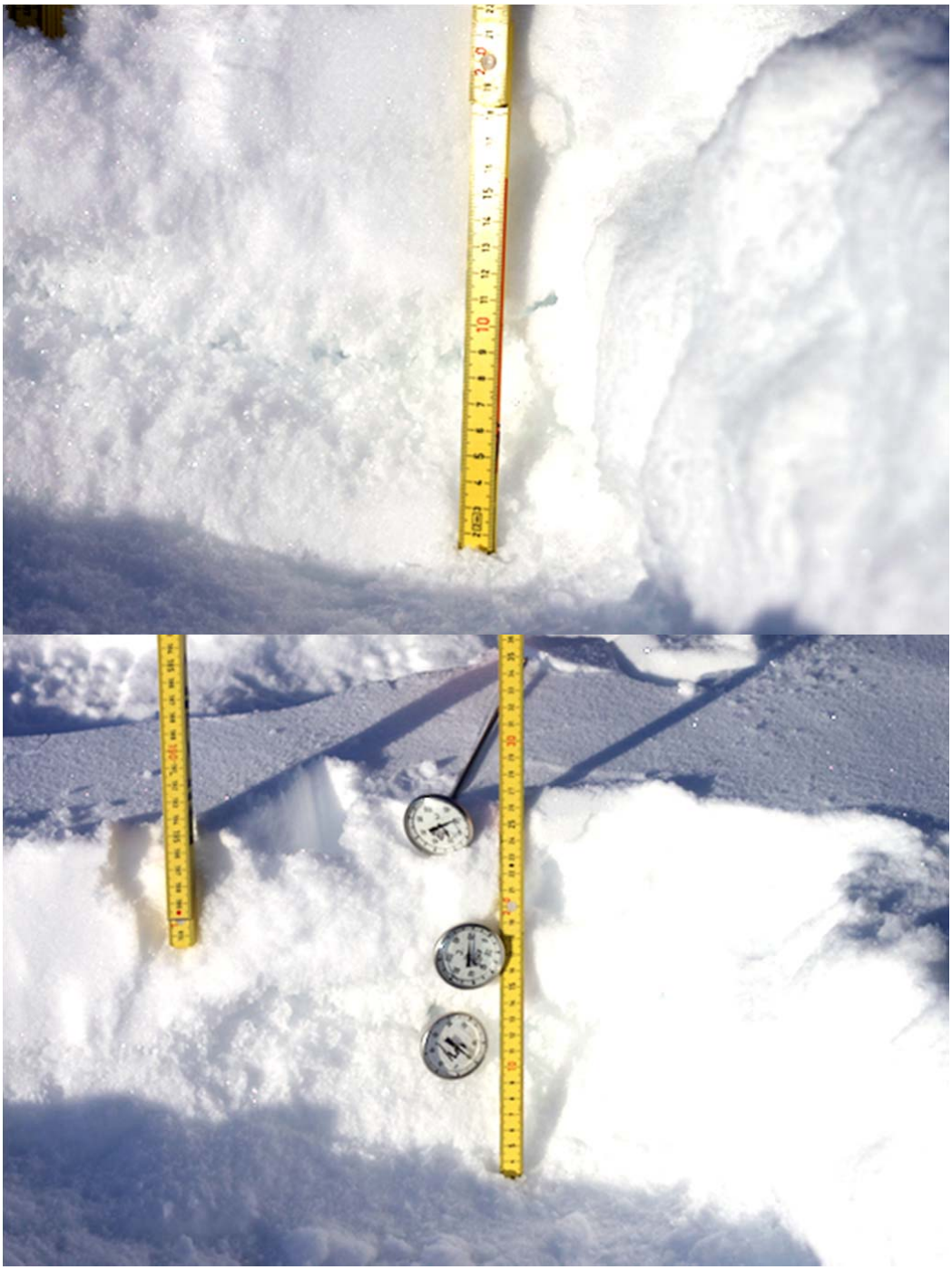


Figure 41: SB (East) snow pit 2.

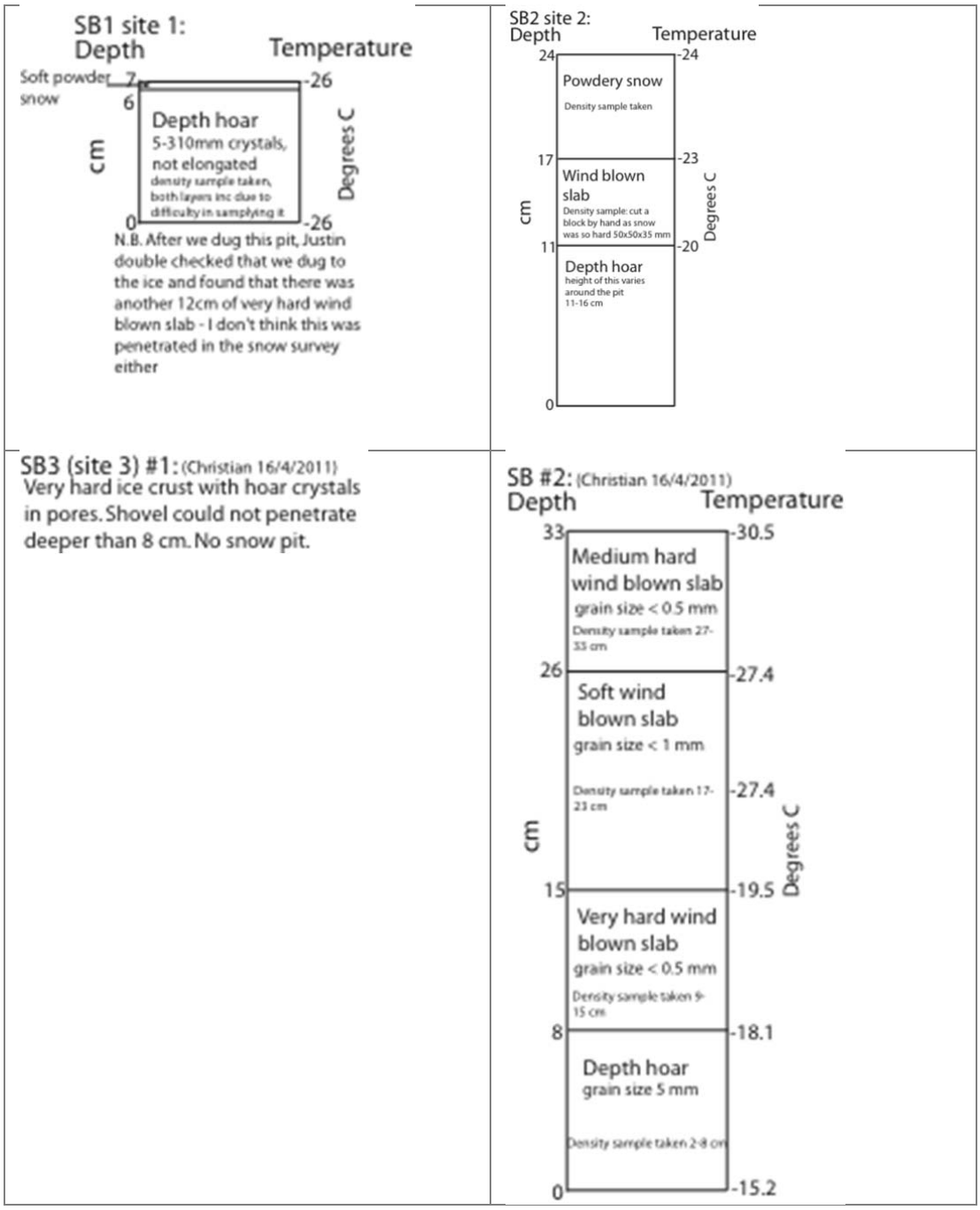



**Figure 42: Diagrams of the snow pits near SB (East).**

## South site transect survey

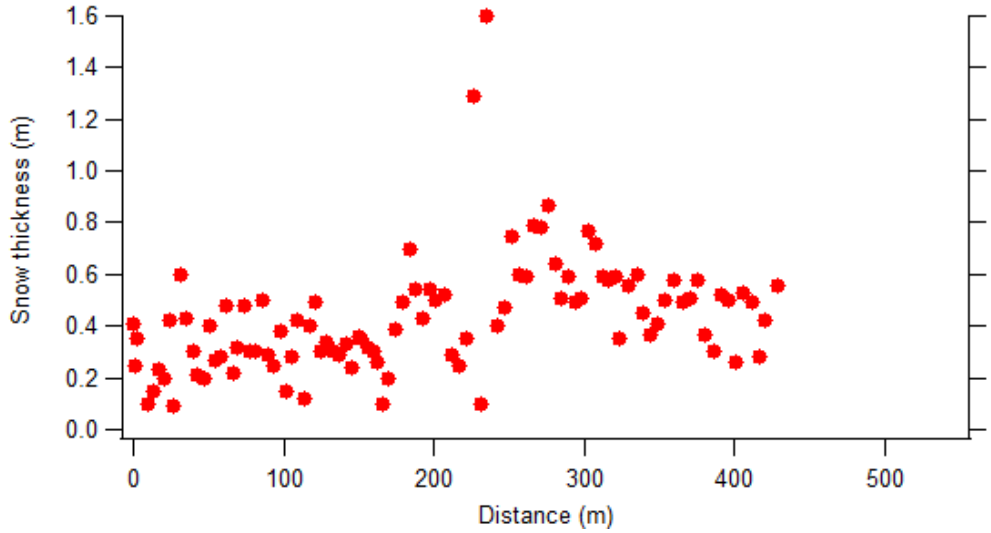



Figure 43: Snow thickness measurements at the South site, 0 m at centre line of Eastern snow grid.

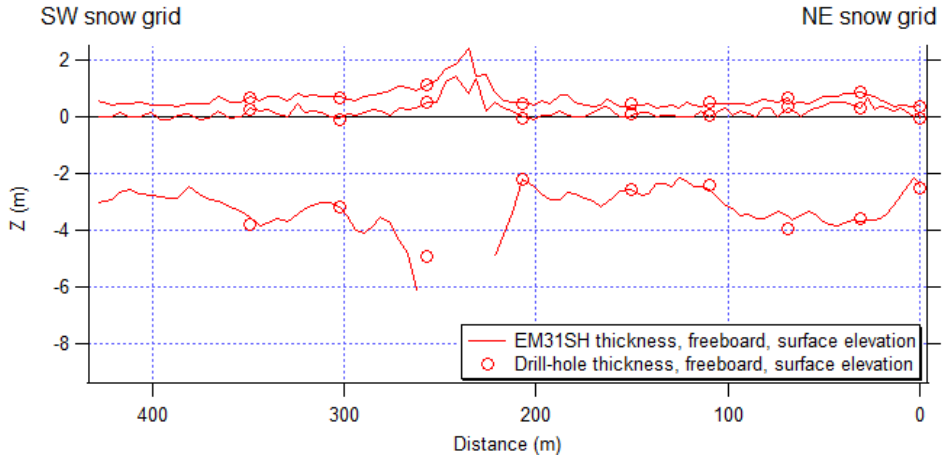



Figure 44: Ice and snow thickness profiles between snow grids.

Table 2 provides a summary of the main results.

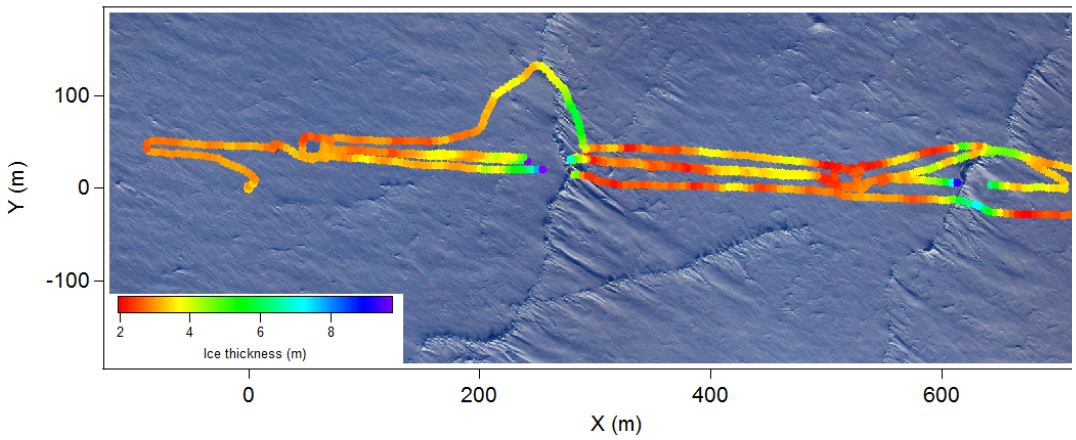



Figure 45: EM ice thickness on South Site, over an aerial photo taken by IceBridge on April 15, 2011.

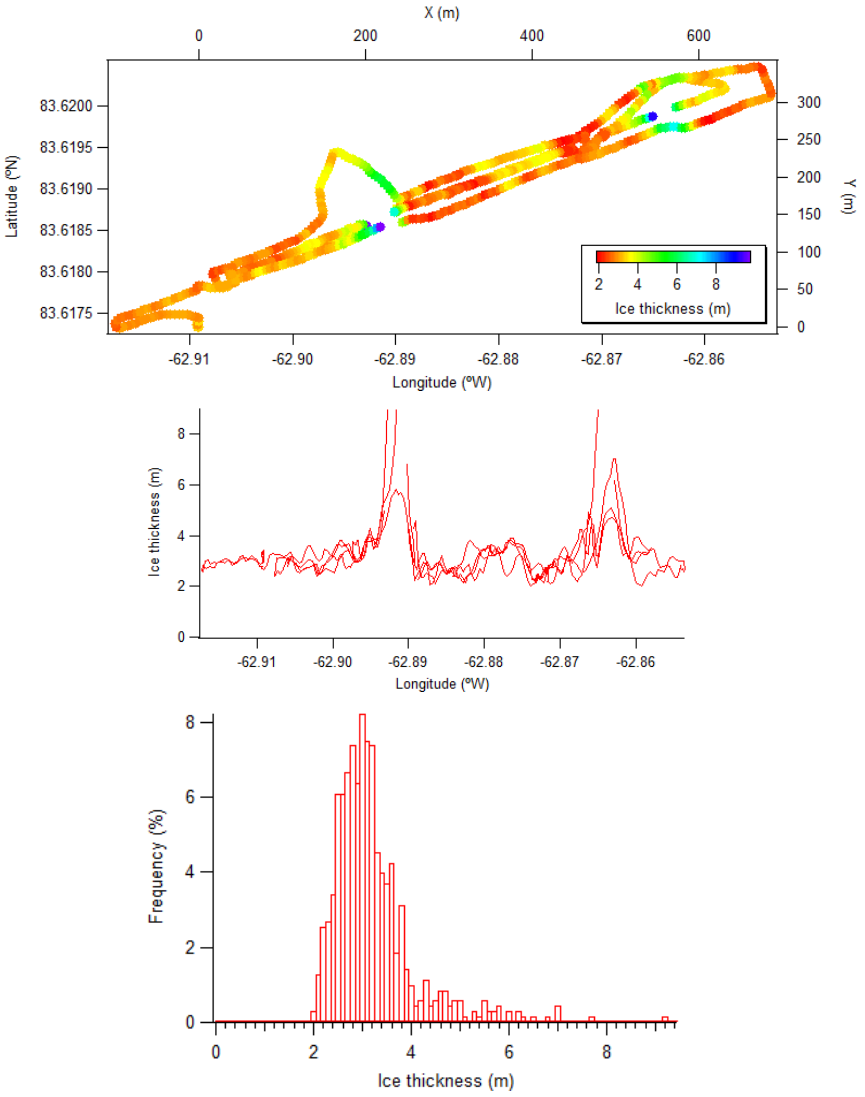



**Figure 46: Additional EM ice thickness profiles.**

Table 2 in Summary of transect measurements (p51) provides a summary of the main results from this transect and those at the other sites.

## South site ASIRAS overpasses

ASIRAS overflew the South site on April 15th. Figure 47 shows the ASIRAS overpasses colour-coded with time and the NASA P3 overpass locations.

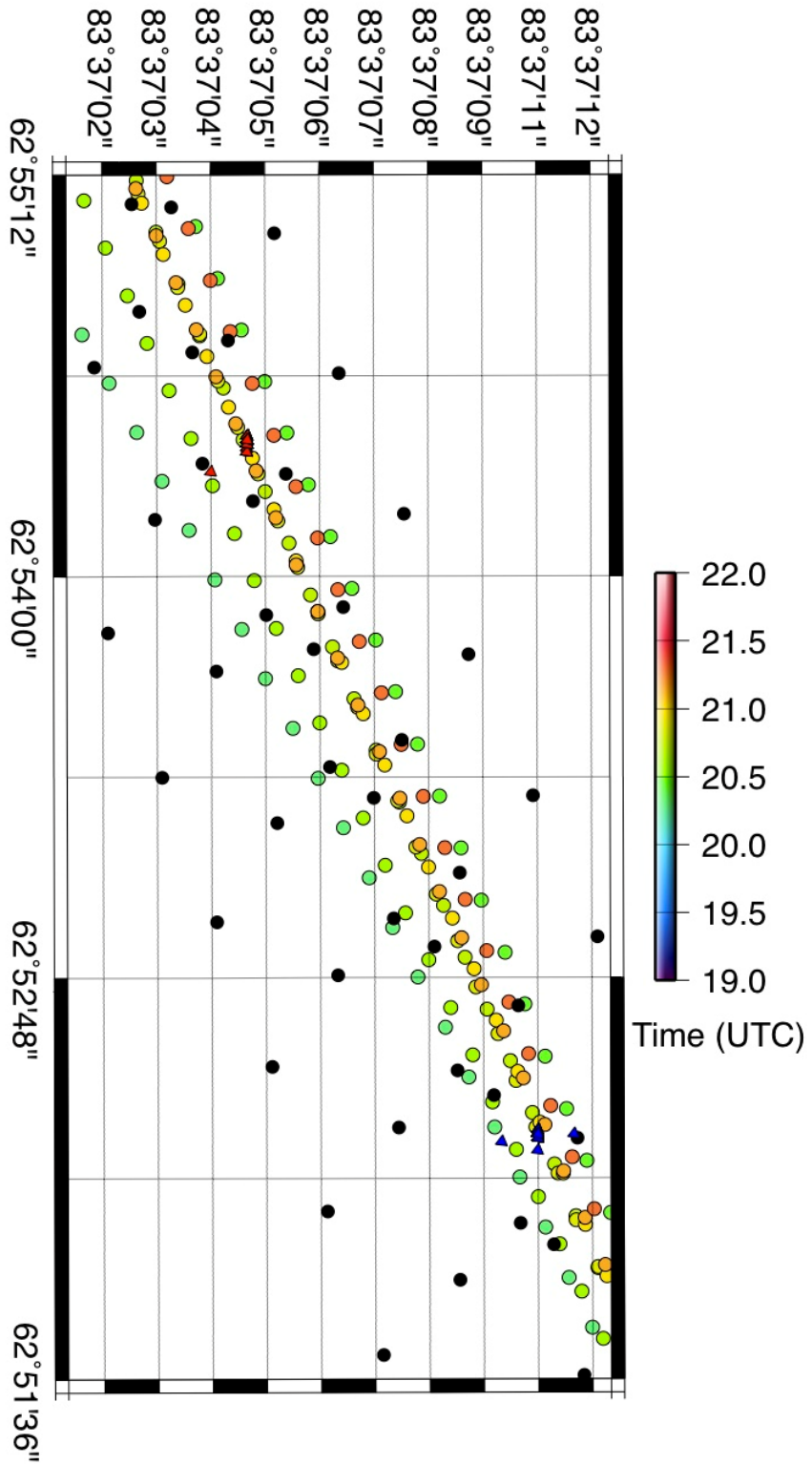



**Figure 47: South site ASIRAS overpasses shown with coloured circles (NASA P3 in black), CRs shown as triangles. The colours indicate the time (UTC.)**

## NASA Survey of the South Site

The NASA P3 aircraft also over-flew the South site on April 15th, as shown in Figure 47. As well as the snow radar, Ku-band radar and laser scanner, the P3 had a DMS camera which captured imagery such as the aerial view of the South site shown in Figure 48.

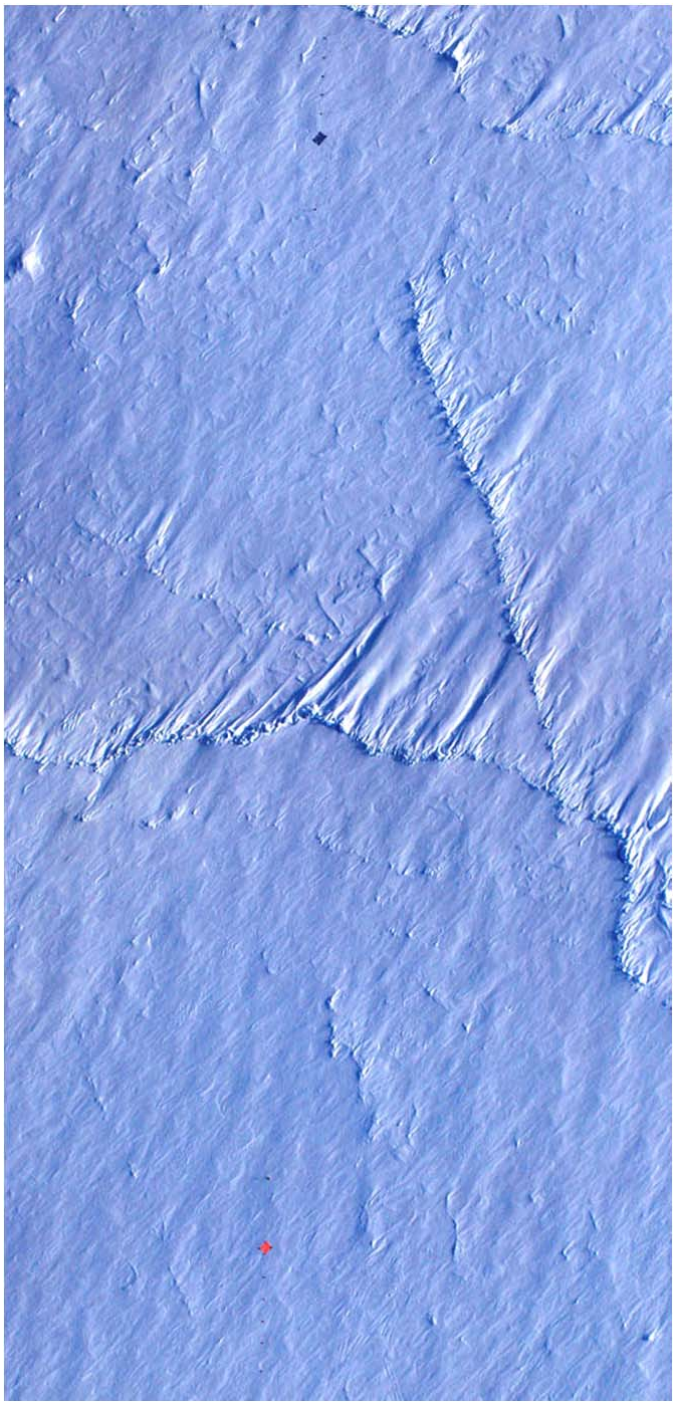


**Figure 48: South site DMS Imagery (Courtesy NASA)**

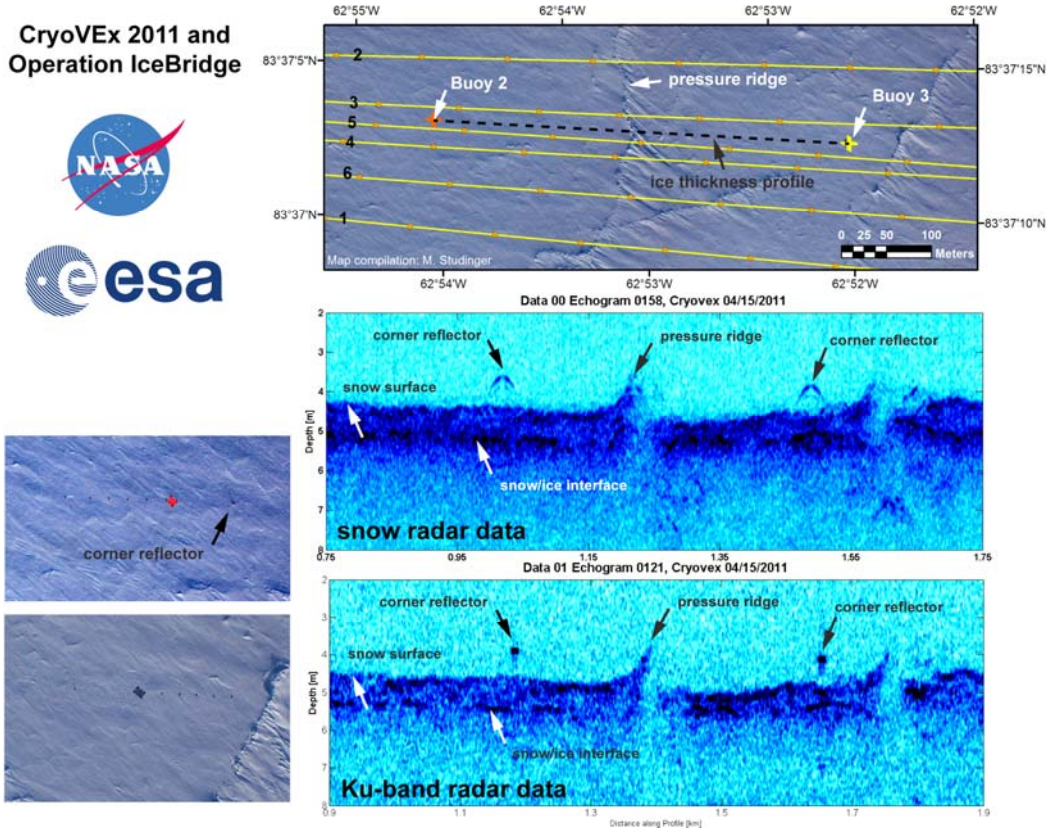



Figure 49: Quick look data from NASA snow and Ku-band radars provided by Michael Studinger.

## Fast Ice

The CRs were set out on April 11th and surveyed on April 17th -18th. The fast ice site was accessed by skidoo. During the ASIRAS and laser scanner over-flights on April 17th the GPR was on the snow grid (so may be visible in the data gathered from the aircraft.)

Fast Ice Orange N82.549048 W062.376847
Fast Ice Blue N82.553368 W062.356424

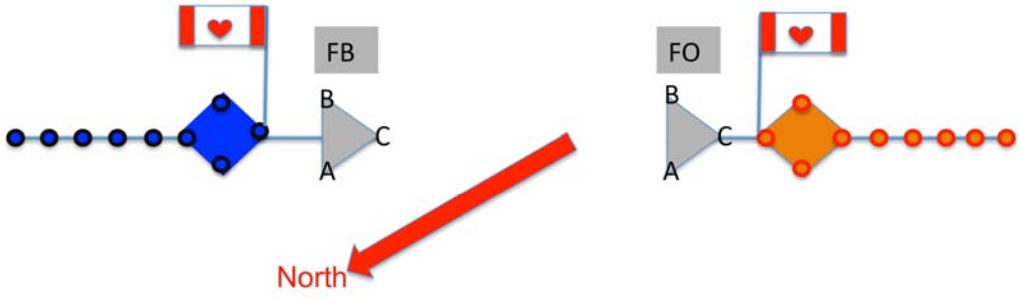



Figure 50: FO and FB setups, bin bags were laid at 10 m intervals, five after each tarpaulin. Tarpaulin corners 30 m from CRs.

## Fast Ice Orange (South)

Figure 51: Fast Orange site deployment

Figure 52: Fast Orange site survey

### Fast Ice Orange (South) Deployment

Laid with corner pointing away from other CR (towards tarp.)
Sides level to within 10 degrees
The distance CR apex to snow surface was 165-170 cm, not measured at legs.

Snow depths at legs (cm):

| FOA | FOB | FOC |
|---|---|---|
| 50 | 47 | 40 |

**GPS Positions**

| | lat (N) | lon (W) |
|---|---|---|
| FO CR | 82.54905 | 62.37685 |
| FO flag (FOF) | 82.54882 | 62.37790 |

### Fast Ice Orange (South) Survey

The snow depth survey around FO (South) is shown in Figure 53, this was done on April 17th. Due to a problem with the generator and with getting the radar up to temperature after it being outside for several hours, only one radar shot was taken on April 17th (number 0) and five more radar shots were taken near FO on April 18th (numbers 1-5), as shown in Figure 55.

Snow on the orange tarpaulin at FO was 15-25 cm deep when we surveyed the site on 17th April, snowfall was on 12th and 13th (for comparison with over-flights.) Fallen snow soft but seems quite dense.

Outside temperature on 17th was around -25 to -30 C but 75% humidity. Very clear, little wind.

The ice surface at the snow ice/interface in snow pits FO1, FO2 and FO3 was very flat.

FO snow depth grid Justin writing, Christian and Malcolm measuring.

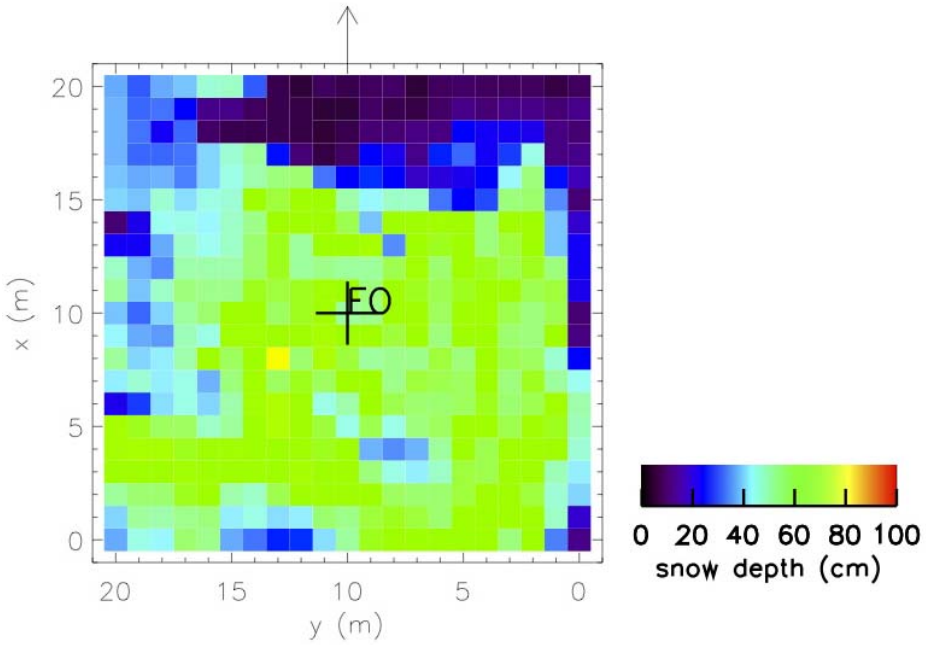



**Figure 53: Fast ice Orange site snow survey. The arrow indicates the direction of the other CR, FB.**

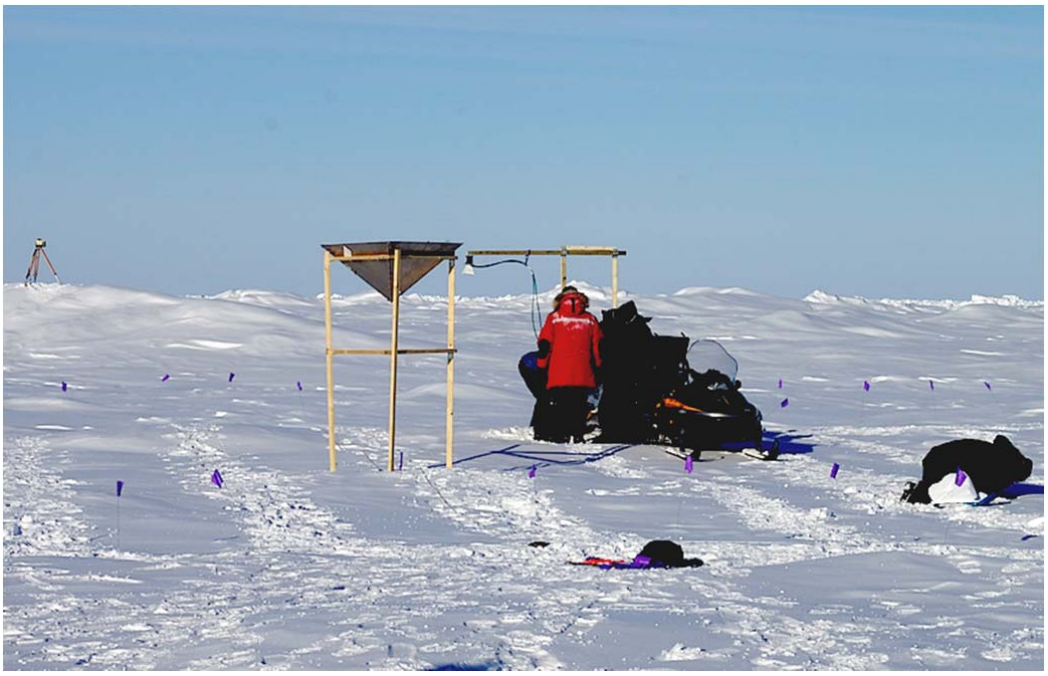


**Figure 54: Figure showing measurements near FO with laser scanner (left), GPR and Katharine digging show pit (right) on April 17th.**

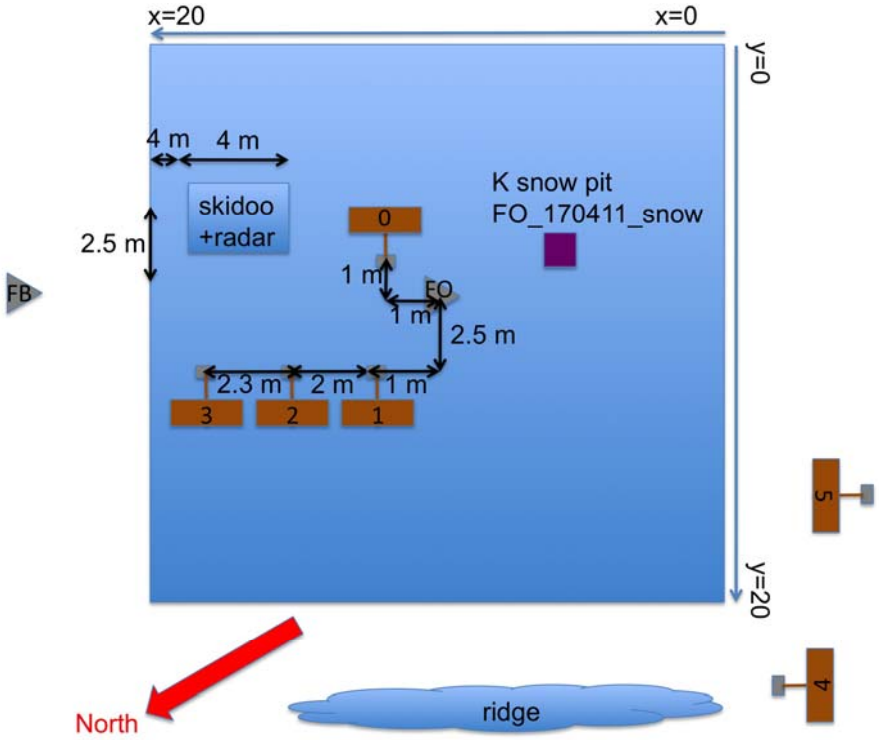



**Figure 55: FO radar sampling locations. Location of skidoo and radar on 17th shown, may be visible in laser scanner data.**

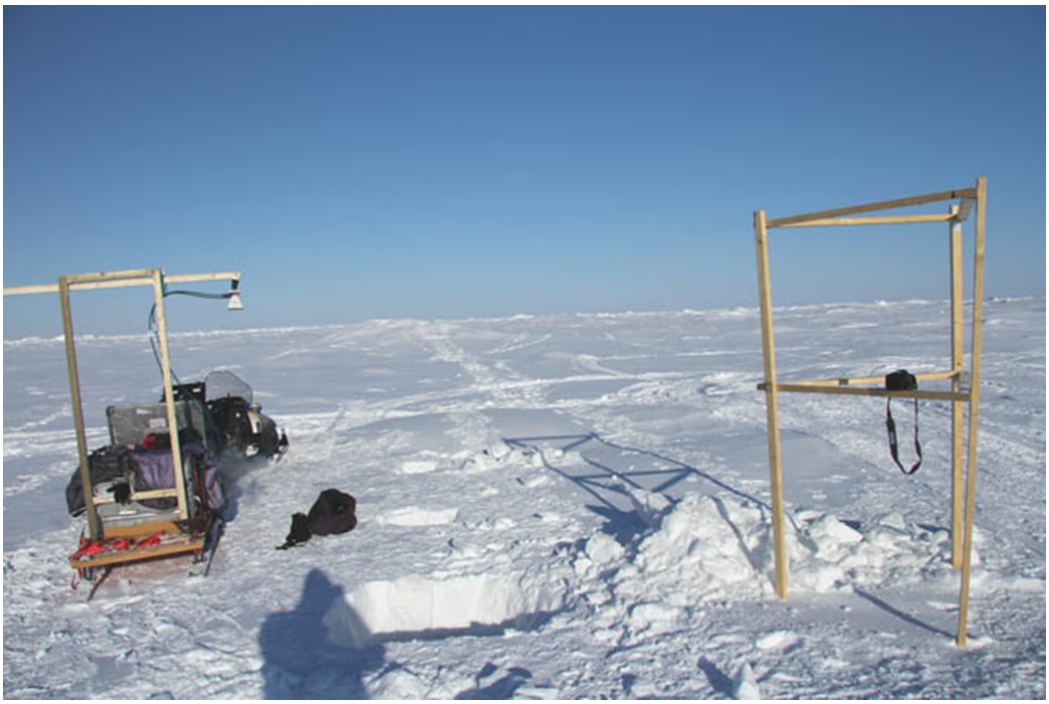


**Figure 56: Fast ice Orange snow pits 1 (foreground) to 3 (background.)**

**Figure 57: Snow pit dug by Katharine on April 17th.**

Figure 58: FO snow pit 1.

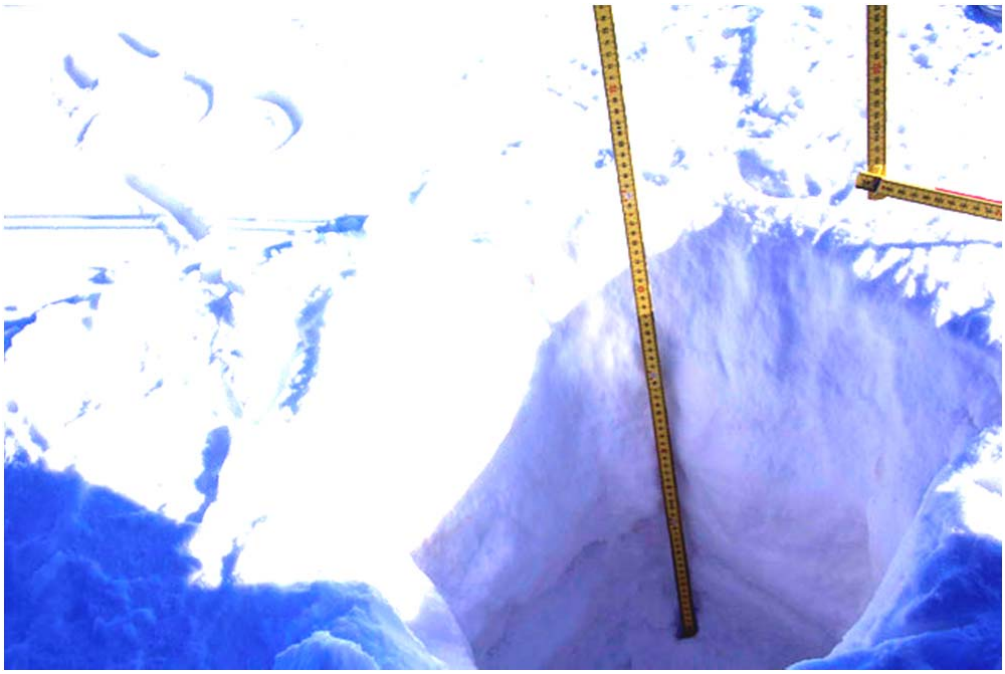


Figure 59: FO snow pit 2.

Figure 60: FO Snow pit 3.

FO1, FO2 and FO3 were within the 20 x 20 m snow depth measurement grid around FO. Some radar shots were then taken outside the grid, FO4 and FO5. FO4 was near a ridge, with deep freshly-fallen snow. When making a snow pit at nadir, we found the bottom but were not sure if it was really ice surface. Stefan drilled – to investigate, it was the ice surface, but the ice was very soft.

Figure 61: Snow crystals from FO 4 snow pit on Seymour's glove (for scale.)

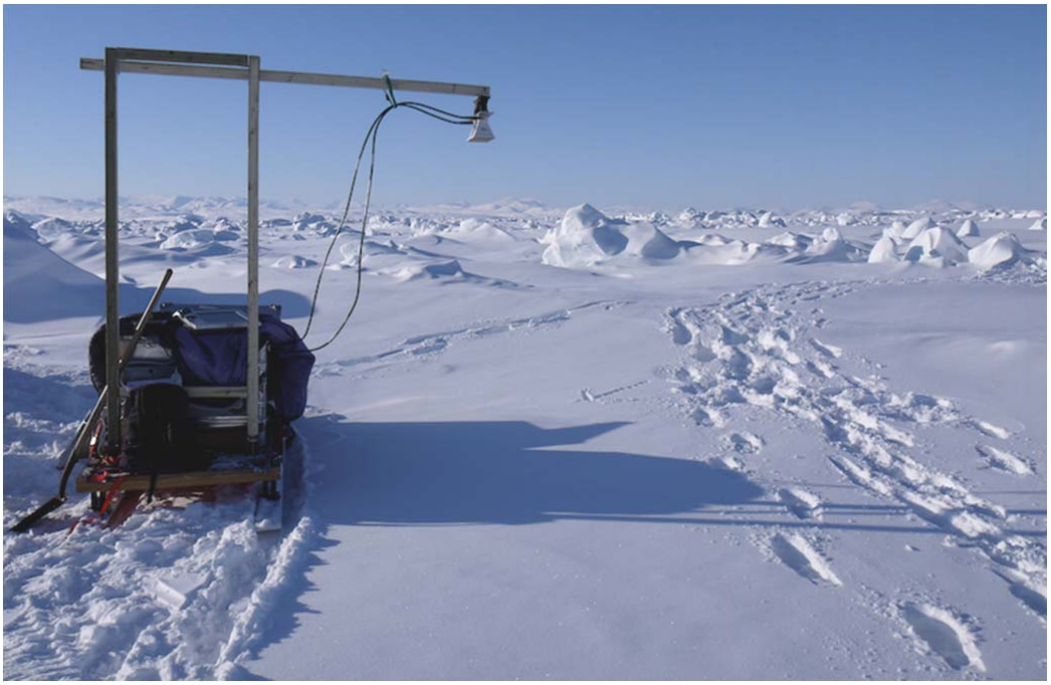
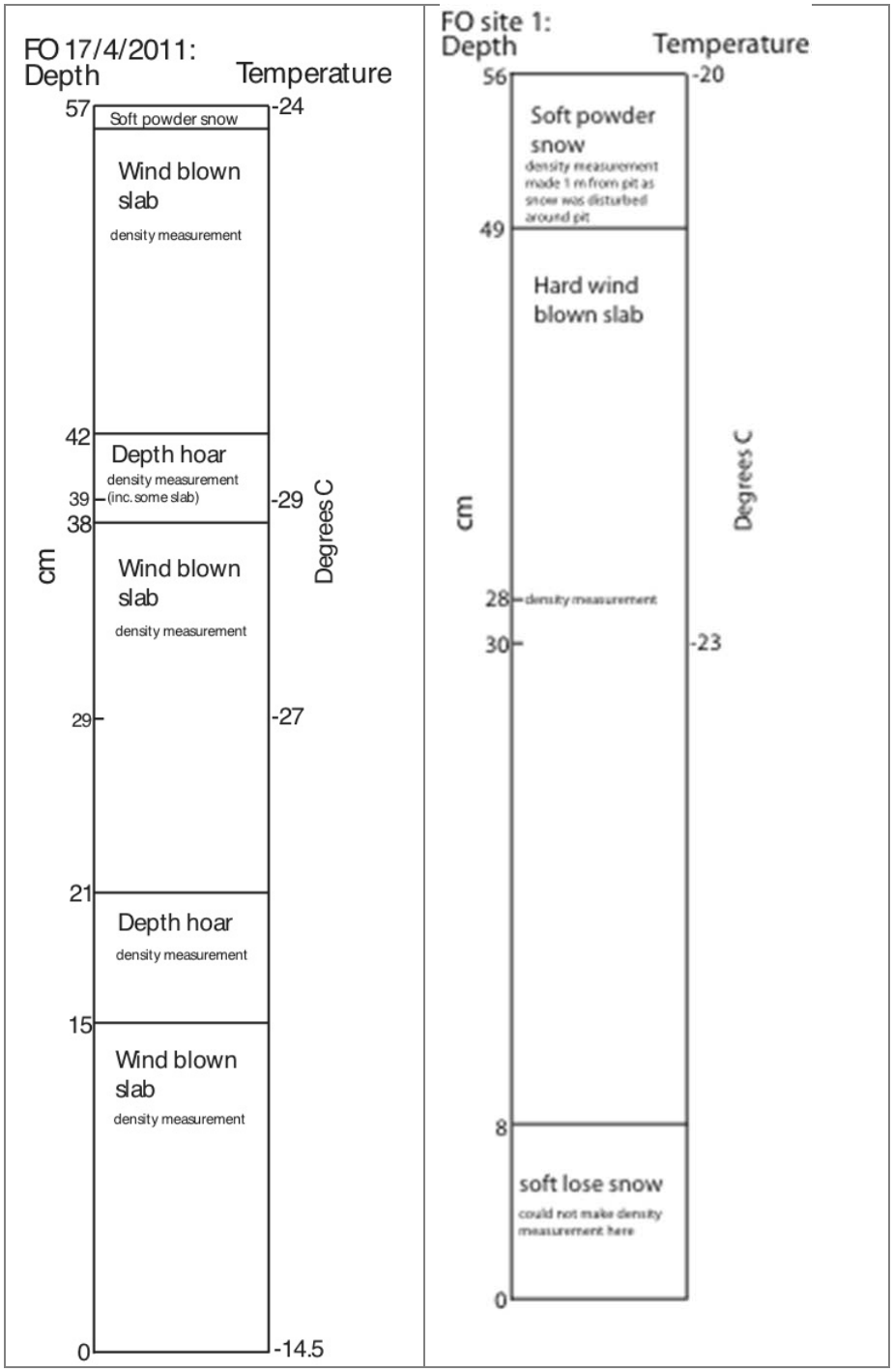
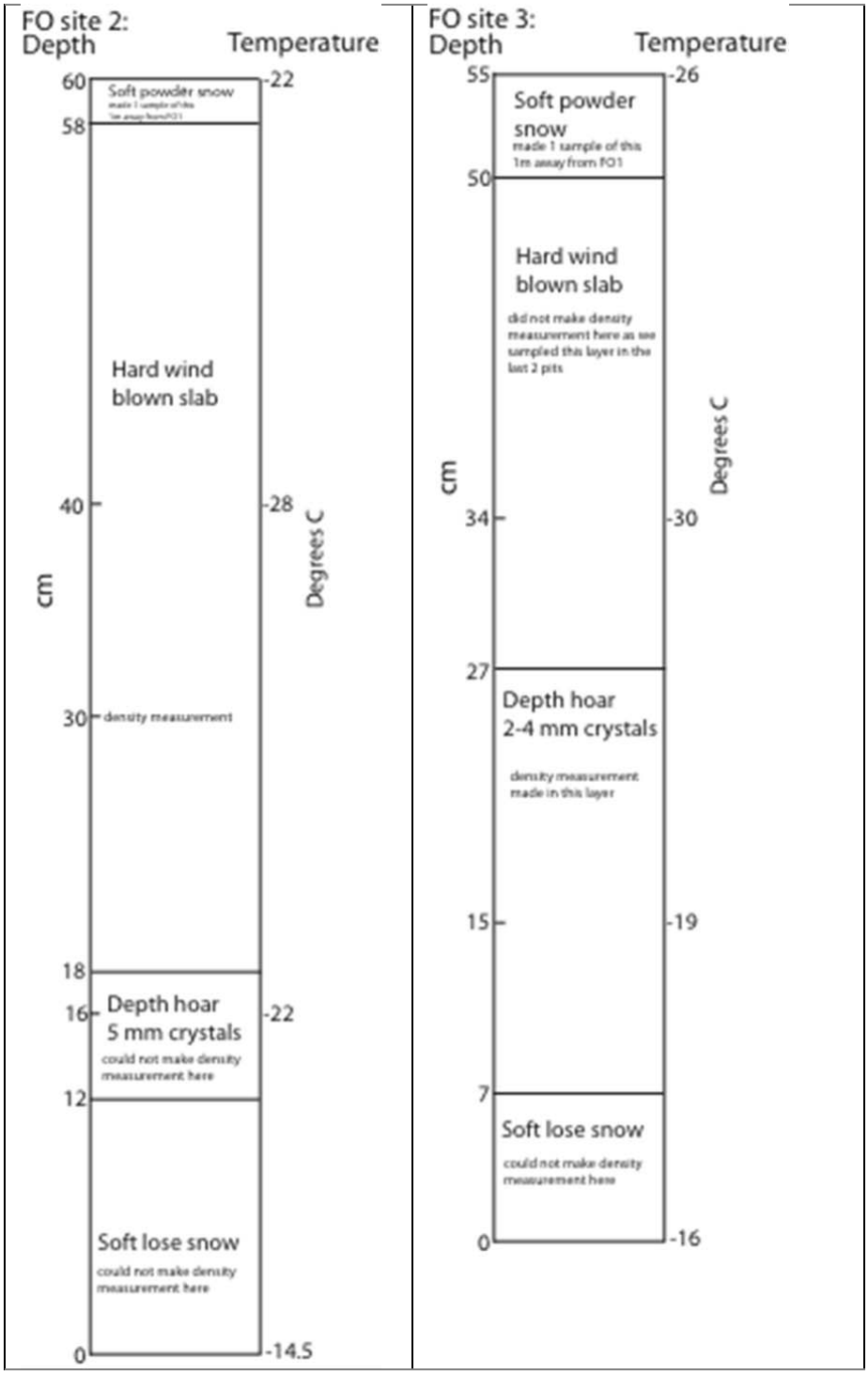


Figure 62: FO radar shot 4.


FO 17/4/2011:
Depth
Temperature
57
Soft powder snow
-24
Wind blown slab
density measurement
42
Depth hoar
density measurement
39
(inc. some slab)
-29
38
Wind blown slab
density measurement
29
-27
21
Depth hoar
density measurement
15
Wind blown slab
density measurement
0
-14.5
cm
Degrees C
FO site 1:
Depth
Temperature
56
-20
Soft powder snow
density measurement made 1 m from pit as snow was disturbed around pit
49
Hard wind blown slab
28
density measurement
30
-23
8
soft lose snow
could not make density measurement here
0
cm
Degrees C


FO site 2:
Depth
Temperature
60
58
40
30
18
16
12
0
-22
-28
-22
-14.5
cm
Degrees C
Soft powder snow
Hard wind blown slab
density measurement
Depth hoar 5 mm crystals
could not make density measurement here
Soft lose snow
could not make density measurement here
FO site 3:
Depth
Temperature
55
50
34
27
15
7
0
-26
-30
-19
-16
cm
Degrees C
Soft powder snow
made 1 sample of this 1m away from FO1
Hard wind blown slab
did not make density measurement here as we sampled this layer in the last 2 pits
Depth hoar 2-4 mm crystals
density measurement made in this layer
Soft lose snow
could not make density measurement here

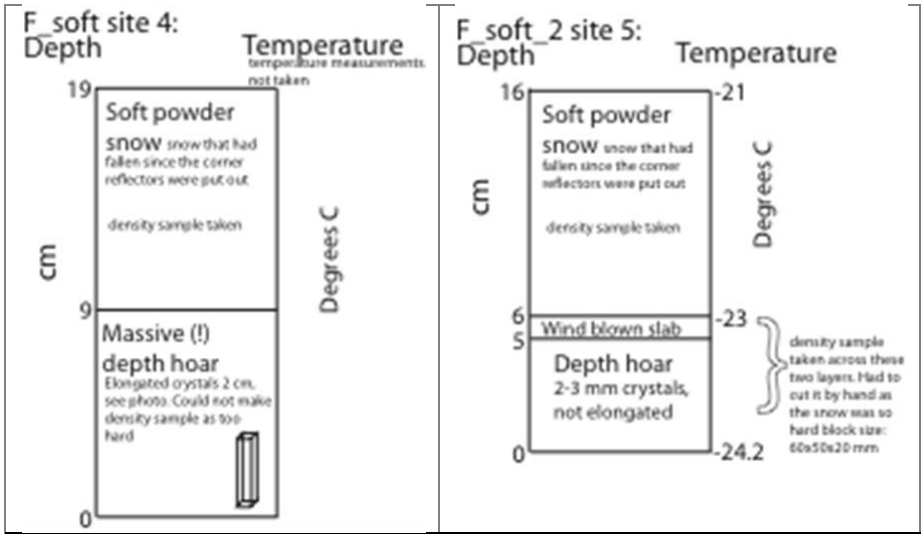



**Figure 63: Diagrams of snow pits near FO**

**Figure 64: Depth hoar in FO4 snow pit.**

## Fast ice Blue (North)

Figure 65: Fast ice Blue deployment.

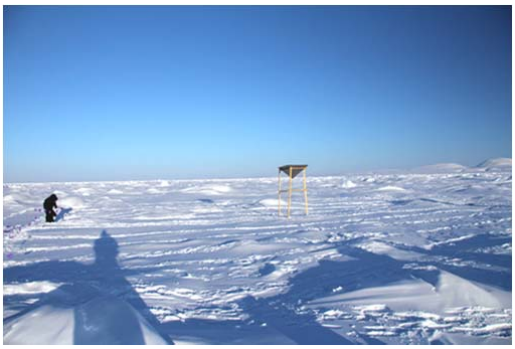


Figure 66: Fast ice Blue survey.

### Fast Ice Blue (North) Deployment

Laid with corner pointing towards from other CR (away from tarp.)
Sides level to within 5 degrees.
Distance CR apex to snow surface: 162 cm.

Snow depths at legs (cm):

| FBA | FBB | FBC |
|---|---|---|
| 44 | 59 | 30 |

Distance from snow surface to metal CR (cm):

| FBA | FBB | FBC |
|---|---|---|
| 220 | 216 | 223 |

**GPS Positions**

| | lat (N) | lon (W) |
|---|---|---|
| FB (1st meas) | 82.55337 | 62.35637 |
| FB (2nd meas) | 82.55337 | 62.35642 |
| FB flag (FBF) (1st meas) | 82.55360 | 62.35530 |
| FB flag (FBF) (2nd meas) (hard to read display) | 82.55360 | 62.35530 |

### Fast Ice Blue (North) Survey

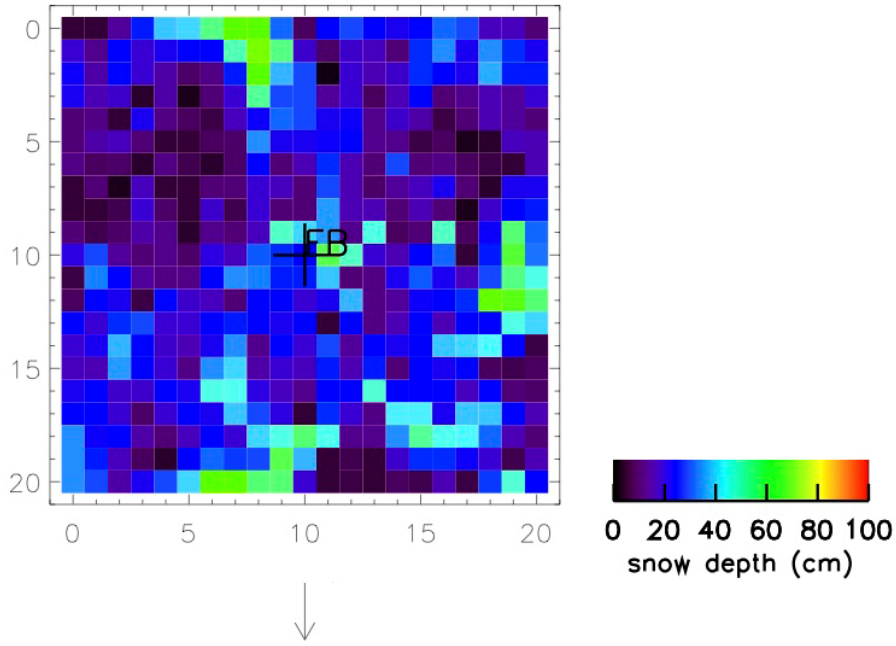



Figure 67: Fast ice Blue snow depth. The arrow indicates the direction of the other CR, FO.

No snow pits or radar shots were taken near FB due to time constraints.

### Fast ice site transect

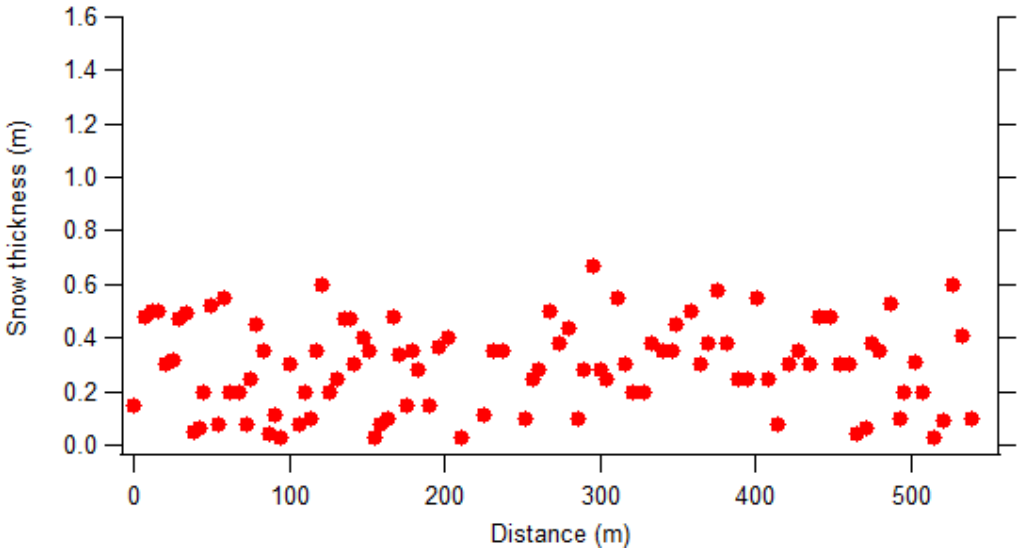



Figure 68: Snow depth measurements along transect with 0 m at southern snow grid edge.

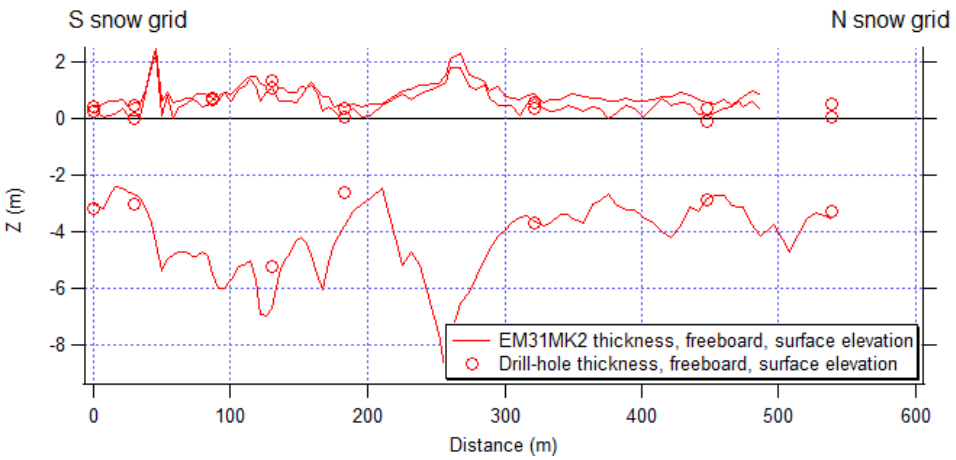



Figure 69: Ice and snow thickness profiles between snow grids.

Table 2 provides a summary of the main results.

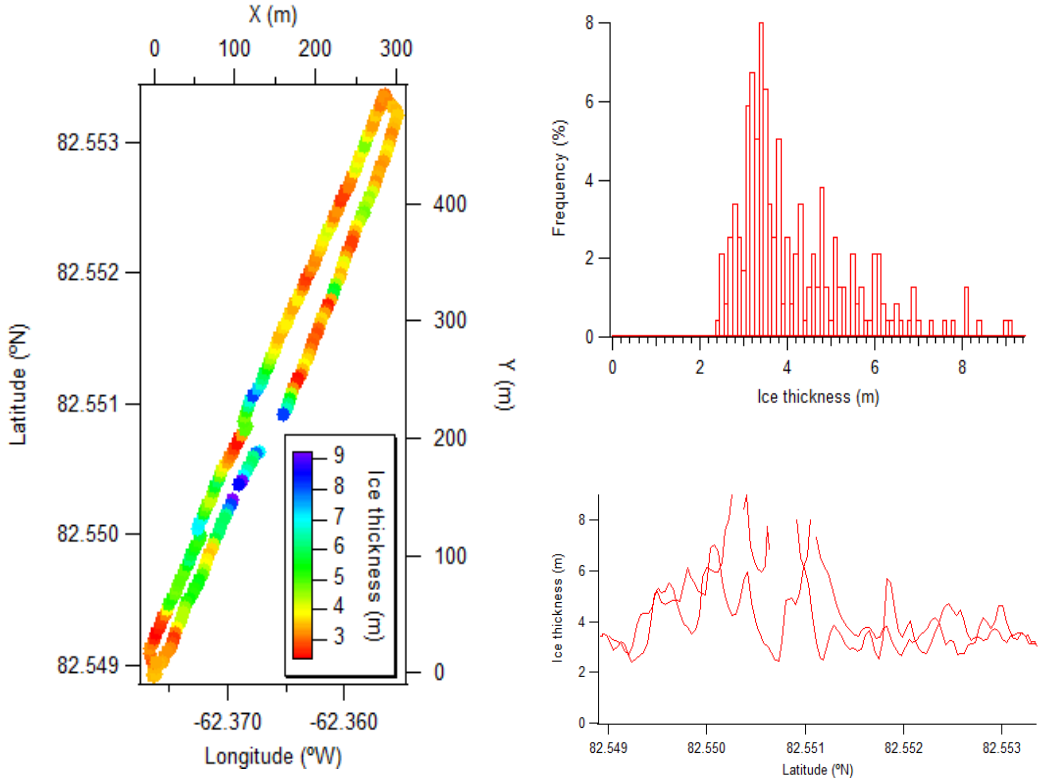



Figure 70: Additional EM thickness profiles.

Table 2 in Summary of transect measurements (p51) provides a summary of the main results from this transect and those at the other sites.

## Fast ice site ASIRAS overpasses

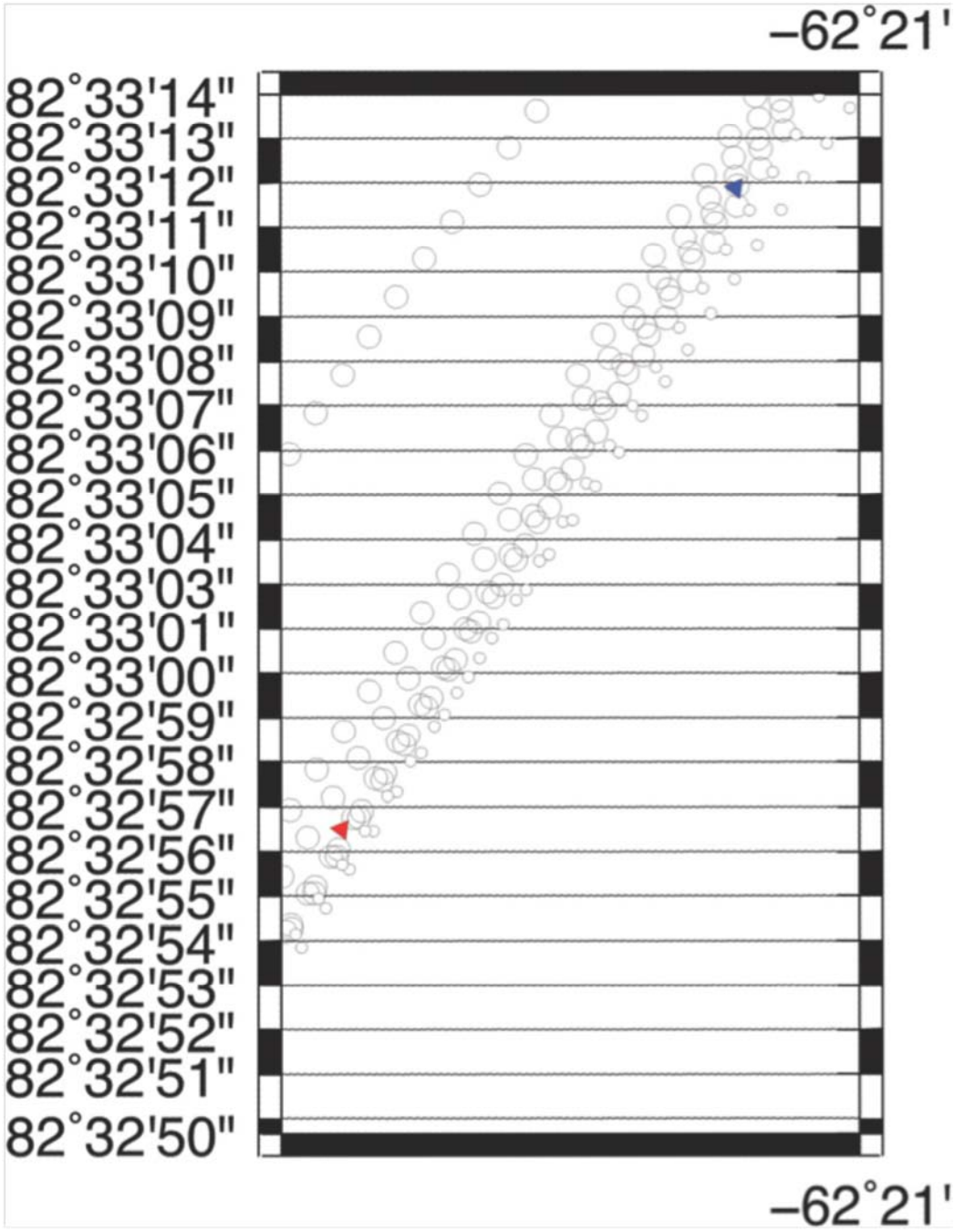



**Figure 71: Fast site ASIRAS overpasses shown with circles, CRs shown with triangles.**

## Summary of transect measurements

Table 2: Results of all ground measurements on long profiles between snow grids / corner reflectors

| **Main profile along center line between snow grids** | **North Site** | **South Site** | **Fast Ice** |
|---|---|---|---|
| Mean EM thickness (snow plus ice; m) | 2.37 ± 0.53 (N = 82) | 3.18 ± 0.65 (N = 92) | 4.25 ± 1.29 (N = 101) |
| Modal EM thickness (m; bin width 0.1 m) | 2.1 | 3.4 | 3.6 |
| Mean snow thickness (m) | 0.41 ± 0.13 (N = 82) | 0.43 ± 0.22 (N = 99) | 0.29 ± 0.16 (N = 101) |
| Modal snow thickness (m; bin width 0.05 m) | 0.30 & 0.40 (bimodal) | 0.25 & 0.50 (bimodal) | 0.35 |
| Mean freeboard (m) | ND | 0.20 ± 0.27 (N = 99) | 0.58 ± 0.44 (N = 92) |
| Modal freeboard (m; bin width 0.05 m) | ND | 0.00 & 0.25 (bimodal) | 0.60 |
| **Complete EM thickness profiles parallel to and including main profile** | | | |
| Total length (m) | 1110 | 3690 | 1235 |
| Mean EM thickness (snow plus ice; m) | 2.44 ± 1.68 | 3.22 ± 0.90 | 4.19 ± 1.35 |
| Modal EM thickness (m; bin width 0.1 m) | 2.1 | 3.0 | 3.4 |

## Density Sample Measurements

Table 3: Density samples

| **Site** | **Notes** | **Volume (cc)** | **Total Mass (g)** | **Salinity (ppt)** | **Bag Weight (g)** | **Sample Weight (g)** | **Density (kg/m3)** |
|---|---|---|---|---|---|---|---|
| FO1 | Powder surface. 1 m away from pit. | 100 | 38.3 | | 11.4 | 26.9 | 269 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| FO1 | Wind blown slab 28 cm | 442 | 196.2 | | 11.4 | 184.8 | 418 |
| FO2 | Wind blown slab 30 cm | 442 | 216.2 | | 11.4 | 204.8 | 463 |
| FO3 | Depth hoar, loose dry crystals | 100 | 22.4 | | 7.3 | 15.1 | 151 |
| FO4 f_soft | Powder snow | 100 | 36 | | 7.3 | 28.7 | 287 |
| FO5 f_soft_2 | 6-16 cm powder snow | 100 | 32.8 | | 7.3 | 25.5 | 255 |
| FO5 f_soft_2 | 0-6 cm. Wind blown slab and depth hoar | 60 | 34 | | 7.3 | 26.7 | 445 |
| CH1 FO | top slab | 442 | 204.5 | 0 | 7.3 | 197.2 | 446 |
| CH1 FO | top hoar+slab | 442 | 157.8 | 0 | 7.3 | 150.5 | 340 |
| CH1 FO | mid slab | 442 | 192.1 | 0 | 7.3 | 184.8 | 418 |
| CH1 FO | bott depth hoar | 442 | 114.9 | 0 | 7.3 | 107.6 | 243 |
| CH1 FO | bott slab | 442 | 190.1 | 0 | 7.3 | 182.8 | 414 |
| NB1 | x=8.5, y=13 depth hoar | 100 | 25.4 | 0 | 11.4 | 14 | 140 |
| NB1 | x=8.5, y=13 across both layers | 100 | 31.6 | 0 | 11.4 | 20.2 | 202 |
| NB2 | x=14.5, y=7 med. compact 8-17.5 cm | 100 | 36 | 0 | 11.4 | 24.6 | 246 |
| NB2 | x=14.5, y=7 dh 0-8 cm | 100 | 23.6 | 0 | 11.4 | 12.2 | 122 |
| NB2 | x=14.5, y=7 soft 22-28 | 100 | 34.8 | 0 | 11.4 | 23.4 | 234 |
| NB3 | top layer | 100 | 45.8 | 0 | 11.4 | 34.4 | 344 |
| NB3 | depth hoar | 100 | 22.6 | 0 | 11.4 | 11.2 | 112 |
| CH1 NB | slab | 442 | 175.7 | 0 | 7.3 | 168.4 | 381 |
| CH2 NB | depth hoar | 442 | 82.2 | 0 | 7.3 | 74.9 | 169 |
| CH2 NB | depth hoar | 442 | 115.7 | 0 | 7.3 | 108.4 | 245 |
| CH2 NB | wind slab | 442 | 172.9 | 0 | 7.3 | 165.6 | 375 |
| SB1 | v thin snow layer + depth hoar | 100 | 29.3 | 0 | 11.4 | 17.9 | 179 |
| SB2 | 11-17 cm depth 50x50x35mm (cut by hand) | 87.5 | 53 | 0 | 11.4 | 41.6 | 475 |
| SB2 | 24-19 cm | 100 | 27.2 | 0 | 11.4 | 15.8 | 158 |
| CH2 SB | hoar | 442 | 106.3 | 0 | 11.4 | 94.9 | 215 |
| | hard slab | 442 | 206.2 | 0 | 11.4 | 194.8 | 441 |
| | soft slab | 442 | 113.6 | 0 | 11.4 | 102.2 | 231 |
| | intermediate hard slab | 442 | 129.2 | 0 | 11.4 | 117.8 | 267 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| SO1 | 33-39 | 442 | 200.4 | | 11.4 | 189 | 428 |
| SO1 | 20-26 | 442 | 156.8 | | 11.4 | 145.4 | 329 |
| SO1 | 2-8 | 442 | 154.8 | | 11.4 | 143.4 | 324 |

## Lessons

Tasks to be completed in future experiments:

- Record snow hardness at depths during survey
- Hot water bottle for GPR
- Photos at fixed reference point for each CR.
- Photos of grid with location of each Snow pit indicated.

It would be very advantageous to have the airborne radar altimeter data and flight paths from the ASIRAS and NASA planes over the validation sites available to the ground team before they start their surveys. Both the information on exactly where the planes over-flew and the radar echoes over the sites should be passed to the ground team before execution of the ground work. This would allow the ground survey to be adapted for better comparisons between data from ground-based and airborne instruments.

The constraints on people and time schedules should be revisited, future surveying strategies should be modified in light of the experience gained in 2011. For example, the snow depth surveys took a large proportion of the time, and one or two extra people in the survey team would have been very valuable.

## Acknowledgement

This work was funded by the UK Natural Environment Research Council and the flights were funded by the European Space Agency, through Duncan Wingham and Malcolm Davidson. We would like to acknowledge Jim Milne at Alert whose logistical support made our work on the ice possible. Also our pilots Troy and Derek, and the engineer Iain, who flew us in the Twin Otter to sample sea ice which would have been unreachable by other means. Thank you to the Norlandair twin otter team for their communication and for bringing the GPR to Alert. Thanks to NASA for their collaboration, especially to Michael Studinger for his communications. CH and JB thank the Alberta Ingenuity Fund and the Canadian Circumpolar Institute for significantly supporting this activity.