

CryoVEx 2014



Deliverable 6: CryoVEx 2014 Final Report

ESA Contract No. 4000110552/14/MP/vb

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1 Executive summary

This document describes the data and results obtained from the various airborne and ground-based measurements performed by York University and collaborators during the CryoVEx2014 field campaign. The document builds on Deliverable 3 (Data Acquisition Report) and is the contractual Deliverable 6: Final Report, submitted to ESA.

Measurements were performed in March 2014 over the Beaufort Sea and north of Greenland, and included airborne EM ice thickness surveying and ground-based drill-hole and snow measurements at four validation sites. Two aircraft were used to perform the surveys, transport personnel and equipment between field sites, and to establish two ice camps. Ground measurements were performed at those two ice camps and at two additional sites nearby. They cover a wide range of different ice and snow conditions typical for various regimes of Arctic multiyear ice.

All measurements were carefully coordinated with the DTU ASIRAS flights and the NASA Operation IceBridge team. Planning of ground-measurements was closely coordinated with Jackie Richter-Menge (CRREL) and Sinead Farrell (UMD). The airborne measurements reported here were carried out by Anne Bublitz (YU) and Alec Casey (YU/UoA). Ground measurements were performed by Christian Haas (YU), Justin Beckers (YU/UoA), Bruce Elder (CRREL), and Christopher Hiemstra (CRREL) (Figure 1).

The CryoVex 2014 field campaign was very successful and met all major objectives outlined in ESA's CryoSat Validation Implementation Plan (CIP).



Figure 1: CryoVEx 2014 ground team; from left: Christopher Hiemstra, Bruce Elder, Christian Haas, Justin Beckers.

2 Purpose And Scope

This document provides a concise summary of measurements performed by York University and several collaborators in the CryoVEx 2014 project, and of the results obtained. Details about project objectives, planning, and coordination can be found in ESA's CryoSat Validation Implementation Plan (CIP).

The European Space Agency ESA operates the CryoSat mission which is dedicated to the measurement of sea ice thickness in the Arctic. Numerous CryoSat Validation Experiments (CryoVEx) have been performed over the past several years. York University has led the CryoVEx 2014 field campaign to obtain ground-truth data from Arctic sea ice to validate the satellite measurements.

CryoVEx2014 has been carried out in March and April 2014, a large, international field campaign in the Arctic to obtain these validation measurements. The campaign involved researchers from Canada, Denmark, the US, the UK, and the Netherlands. It included airborne ice thickness surveys with York University's airborne electromagnetic ice thickness profiler, and in-situ measurements on ice floes visited by aircraft. The campaign was conducted from various locations in Canada (Northwest Territories and Nunavut) and Greenland.

ESA has provided funds for the charter of two aircraft between March 15 and April 5, 2014, a ski-equipped Twin Otter and a Basler BT67. The aircraft were operated by Kenn Borek Air Ltd. from Calgary, AB. Additional funds for small equipment purchases, shipping, travel, and other logistics services required to perform the project were provided as well.

This document is the contractual Deliverable 6: Final Report. The associated data have been delivered as Deliverable 4, 5 (CryoVEx2014 Airborne Ice Thickness Data and Abstract) and 7 (Technical Data Package) and corresponding short report.

CryoVEx 2014 was performed in close collaboration with DTU and NASA, who operated the ASIRAS and Airborne Laser Scanner, or conducted the Operation IceBridge project, respectively. Three researchers from the University College London (UCL) also participated in the ground measurements north of Greenland to perform Ground-Penetrating-Radar measurements. All those activities are reported elsewhere.

3 Logistics

CryoVEX 2014 performed measurements over the Beaufort Sea and Arctic Ocean north of Canada (Ellesmere Island) and Greenland. Airborne surveys and ground-based snow and ice measurements were performed.

In the Beaufort Sea the ground-based measurements were carried out at two ice camps operated by the University of Washington for the Office of Naval Research (ONR) Marginal Ice Zone (MIZ) project. Ice camps were maintained from Sachs Harbour on Banks Island. The ground team had to charter a King Air aircraft operated by Aklak Air in Inuvik to reach Sachs Harbour in a timely fashion.

North of Greenland an ice camp was established by Marc Cornellissen and Petter Nyquist from the Netherlands and Norway. A fourth site 60 nautical miles to the north of that was visited for one day.



Figure 2: Beaufort Sea Camp 2.



Figure 3: CryoEx 2014 main camp north of Greenland.

All flight operations and ice camp locations and time periods are summarized in Figure 4 and Table 1 and 2.

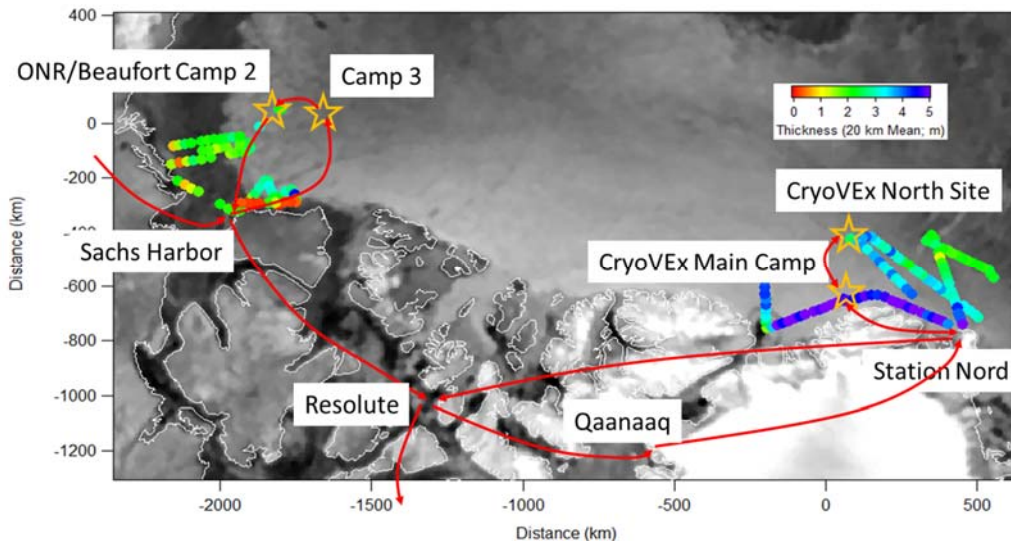


Figure 4: Map of CryoVEx 2014 study area showing location of land bases and ice camps, ice thickness survey profiles with mean thickness of 20 km flight segments, and ground and air team travel route (see Table 1).

A Basler BT67 aircraft (C-GCKB) was used for ice thickness surveying and to transport passengers and equipment between the different locations (Figure 5). Note that the provisions for the AEM system, in particular the winch (see below) could remain in place, thus facilitating quick transition between ferry and survey flights. The EM Bird (see below) was stowed inside the cabin with all other equipment for the ferry flights.

From March 16 to March 22 the Basler was based in Inuvik, carrying our ice thickness surveys. On March 23, it transferred to Resolute Bay. En-route it stopped in Sachs Harbour to pick up personnel and equipment from the CryoVEx/ONR ice camp activity. On March 24 it flew to Qaanaaq in Greenland to pick up four more personnel, the UCL team members and their equipment and Emil Nilsen from DTU. On March 25, the Basler brought all 10 scientists and equipment from Qaanaaq to Station Nord, and continued to Alert on the same day with just the two AEM surveying scientists and equipment. It returned from Alert to Station Nord on March 29, performing an ice thickness survey of the CryoVEx ice camp en-route. On April 2, the Basler returned to Resolute Bay, with six scientists and two ice camp managers.

Between March 24 and April 3, an additional ski-equipped Twin Otter (C-GKGB) was chartered to carry the two ice camp managers and all camping equipment from Resolute Bay to Station Nord. It reached Station Nord on March 25 after a two day journey with strong head winds, requiring an overnight stop at Eureka and a fuelling stop at Alert. The Twin Otter was generally based at Station Nord overnight, and supported the ice camp work during daily flights from Station Nord.

After a blizzard from March 26 to the early hours of March 28, the Twin Otter established a runway at the location of the main ice camp, and left four people to set up the ice camp. On March 29, four more people were brought to the ice camp. On March 30, the Twin Otter brought its own fuel to the main camp to refuel there and carry on to the northern site, with 5 people on board.

Four people were removed from the ice camp on April 1, followed by the remaining party of four and all equipment on April 2. All personnel and equipment returned to Resolute Bay on the same day with the Basler, while the Twin Otter returned on April 3.



Figure 5: A Basler BT67 was used to transport passengers and scientific equipment between study regions.



Figure 6: Twin Otter arriving in Station Nord with two camp managers and all camping equipment on March 26.

4 Methods and Instrumentation

4.1 AEM thickness sounder

Airborne ice thickness measurements were performed with an airborne electromagnetic (AEM) sensor (EM Bird) developed and owned by York University, towed below a Basler BT-67 airplane operated by Kenn Borek Air Ltd from Calgary AB.

The retrieval of sea ice thickness with airborne EM is based on the contrast of electrical conductivity between sea water and sea ice, which can be sensed by low-frequency electromagnetic fields. Because the airplane is a significant conductor, the EM-Bird has to be lowered 70-80 m below the aircraft using a winch installed in the cabin. It is operated 15-20 m above the ice surface. By means of the EM

measurements the height of the EM Bird above the water surface which coincides with the bottom of the ice is determined. The height of the EM Bird above the ice surface is measured with a single-beam Riegl LD90 laser altimeter. Therefore, AEM sea ice thickness retrievals represent the total, snow-plus-ice thickness.

EM measurements are prone to temperature-related electronic drift. To correct for this drift, the EM-Bird is lifted in regular intervals of between 10 and 20 minutes to altitudes higher than 80 m above sea level for zero-level measurements. During these ascends and following descends, no ice thickness data is available.

The general accuracy of airborne EM data is +/- 0.1 m over level sea ice. However, due to the footprint size of the method of more than 3 times the flying altitude the maximum thickness of ridges can be underestimated by as much as 60%. Recent (yet unpublished) studies indicate however, that the mean thickness of longer sections is comparable to the real ice thickness, because deformed features are also overestimated in lateral extent.

The position and ellipsoidal height of the EM Bird is measured with an on-board, Novatel OEM-2 geodetic differential GPS system (DGPS). Note that the data streams of the different sensors deliver data at different sampling frequencies. These are 10 Hz for the EM measurements, 100 Hz for the laser measurements, and 2 Hz for the DGPS measurements.

For more information on AEM sea ice thickness measurements refer to Haas et al. (2009) and Haas et al. (2010).



Figure 7: Basler BT67 C-GJKB parked at Inuvik airport with the EM Bird installed between it's landing gear.

4.2 Ground-based measurements

Extensive ground-based measurements of snow and ice thickness and freeboard were performed at four sites at various ice camps (see Sections 4 and 5 below). These measurements were performed in close collaboration with Bruce Elder and Christopher Hiemstra from CRREL. Measurements included the following:

- Drill-hole survey of a line profile up to 2 km long. Measurements were performed every 50 m with a Kovacs ice auger. At each drill-hole, ice thickness, snow thickness, and freeboard or draft were measured, providing information about ice thickness and isostatic conditions.
- Snow pit studies of snow stratification and density at the same 50 m points, using standard snow sampling tools.
- Snow thickness and snow freeboard survey along the same line, with point spacings of 5 m. Snow thickness was measured with a so-called Magnaprobe, a computerized, snow ruler probe connected with a GPS receiver and data logger. Snow freeboard was measured with a Leica Rugby rotating construction laser and associated laser receiver and range pole. We also

attempted to gather 2D snow freeboard information with a Leica terrestrial laser scanner. Unfortunately too cold air temperatures severely limited the operability of the scanner such that only few scans could be obtained at the Beaufort Sea ice camp (camp 2).

- Electromagnetic ice thickness measurements along the same line, using portable Geonics EM31 and GSSI EMP400 conductivity sensors. Unfortunately most sensors malfunctioned and only one short profile could be obtained at the Greenland ice camp.
- Installation of two corner reflectors on each line, near the center of the drill profiles, spaced 300-400 m apart. Corner reflectors were located within the coarse and fine resolution snow grids (see below).
- Installation of metocean SVP-B drifting buoys with GPS receivers to monitor the drift of the ice for later correction of other GPS referenced measurements. GPS data were transmitted in real-time to our project partners, such that precise aircraft overflights of the profiles could accurately be planned.
- Snow grid surveys of a 60 m x 400 m snow grid centered about the long drill-hole profile. These were measured with Magnaprobos, with 5 m x 5 m point spacing.
- Nested dense snow grid surveys of 40 m x 40-60 m with point spacings of 1 m x 1 m. These were centered about the corner reflectors.
- Lines and corner reflectors were further marked with orange garbage bags well visible for the pilots overflying the lines. These helped to optimise alignment between overflights and the profiles.

Note that local, Cartesian reference systems in meters were used to position every measurement on the ice, relative to a well-defined point of origin (typically corner of the large snow grid). All positions were established with ruler tapes. This resulted in uncertainties of up to 2% (e.g. 7 m over the length of 400 m of the snow grids) in worst cases, because strong winds or surface undulations prevented truly straight layouts of the tape measures. However, the snow grid layout at the CryoVEx main site was almost perfect.

GPS locations observed by the buoys at the ends of the survey lines can be used to assign true geographical locations to each measurement point at all times.

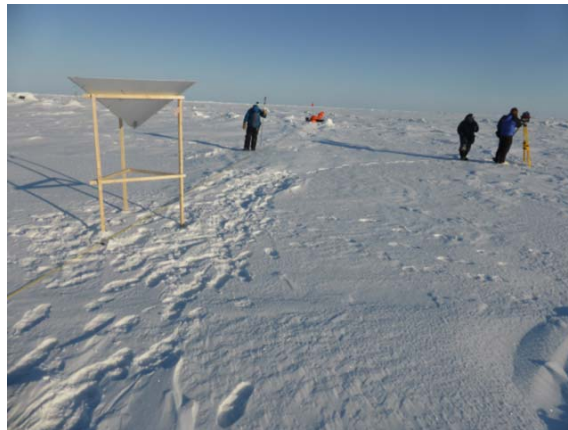


Figure 8: Ground measurements at Camp 2 in the Beaufort Sea. Photo shows Eastern corner reflector, Magnaprobe snow thickness measurement, row of orange garbage bags (background), and terrestrial laser scanner.

5 Results

5.1 Airborne measurements

Seven AEM surveys were carried out between March 18 and 31. Figure 9 shows their regional coverage and mean ice thicknesses, and compares the flight tracks with those of the ASIRAS/ALS and IceBridge overflights. Table 1 summarizes flight dates and regions, and the main purpose and coordination of the flights. Overall data quality was excellent.

Due to a severe blizzard on March 26/27, major damage occurred on the EM Bird. Most components could be successfully replaced such that the next survey could already be performed on March 29. However, the on-board GPS system had failed and could not be replaced or repaired. Therefore only positional data from a handheld GPS inside the aircraft cabin is available. These have been merged with the EM data to georeferenced them. However, their accuracy and synchronization is reduced, leading to uncertainties of approximately 60 m (corresponding to flight distance during 1 s) in the collocation of AEM, ASIRAS, and ground measurements for flights on and after March 29. These time shifts can be corrected by manually shifting the profile data to best correlate with the in-situ or other airborne measurements.

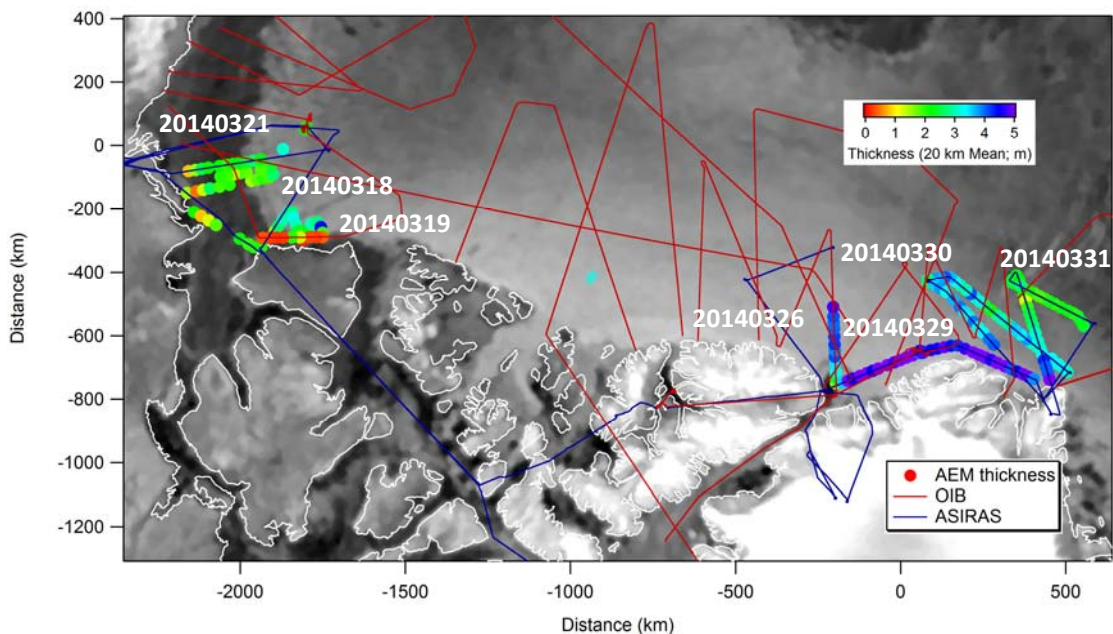


Figure 9: Map of all AEM ice thickness surveys, and ASIRAS and Operation IceBridge (OIB) flight tracks. Background map is ASCAT radar backscatter information on March 26, 2014, obtained from BYU. See data acquisition report (Deliverable 3) for more information.

AEM surveys were performed over three validation sites. The Beaufort ice camp (camp 2) was surveyed on March 21. The main CryoVEx ice camp was surveyed on March 29, and the northern site on March 30.

Table 1: Summary of AEM ice thickness surveys

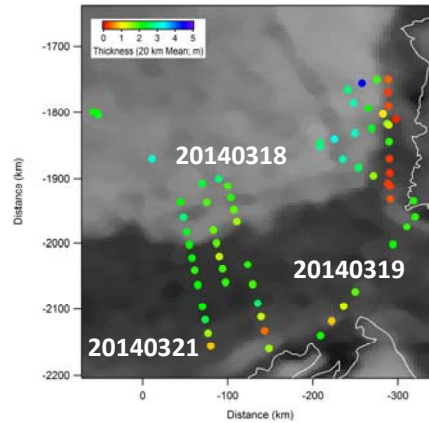
Date (2014)	Region	Purpose / Coordination	Coincident CryoSat orbit
March 18	Beaufort Central	CryoSat & SMOS	20884, 20913
March 19	Beaufort East & Banks Island Polynya	SMOS	
March 21	Beaufort West	CryoSat & SMOS & ASIRAS & ONR ice camp	20942
March 26	Alert, Lincoln Sea, Arctic Ocean	CryoSat & ASIRAS & OIB	21011, 21021
March 29	Alert to Station Nord	Ferry & ASIRAS & CryoVEx ice camp	
March 30	Nansen Basin / North Greenland	CryoSat & ASIRAS & CryoVEx North site	21067
March 31	Nansen Basin / Fram Strait	CryoSat & ASIRAS	21081, 21090

5.1.1 Mean ice thickness distributions

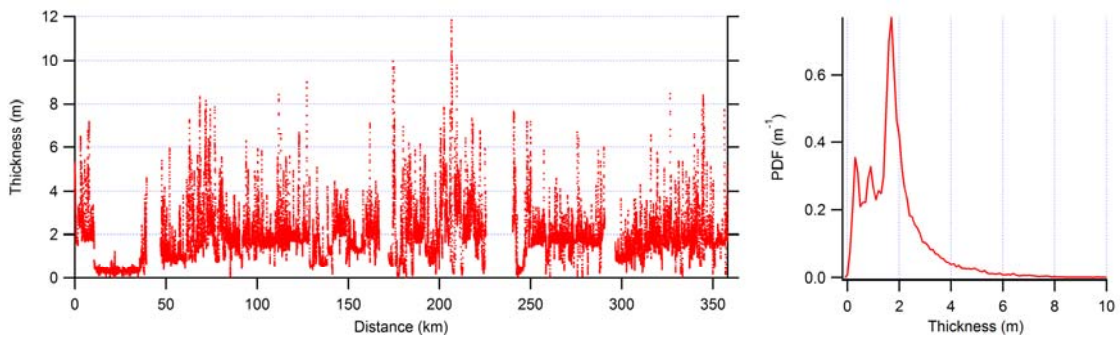
The maps and graphs below summarize the results of all AEM thickness surveys performed during CryoVEx 2014 (see also Table 1 for more information). As can be seen from the ASCAT backscatter maps, a wide variety of different first- and multiyear ice regimes was surveyed. While the Beaufort Sea was characterised by much thin ice located in refrozen polynyas along the shore, the ice north of Ellesmere Island and Greenland was very thick, as expected. Strong thickness gradients have been observed towards the North. Over Fram Strait the ice became remarkably thin, indicating the presence of widespread second- and first-year ice.

The gathered data provided extensive validation data for CryoSat, which will be further exploited in the CryoVal-SI project.

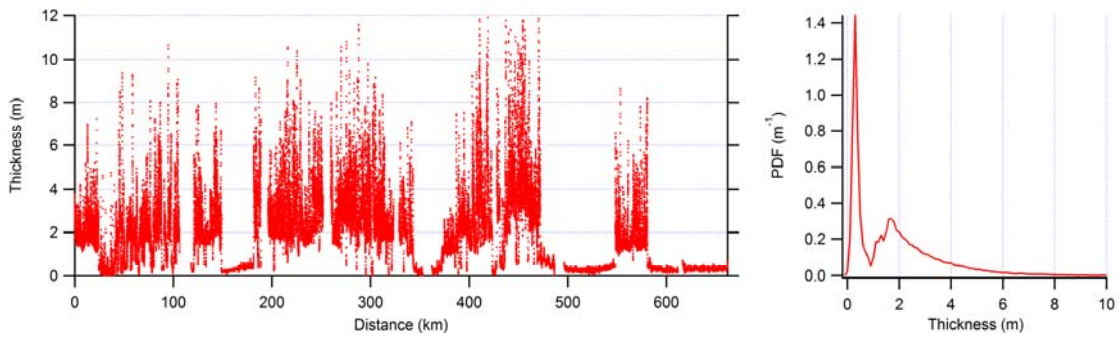
5.1.1.1 Beaufort Sea, March 18-21



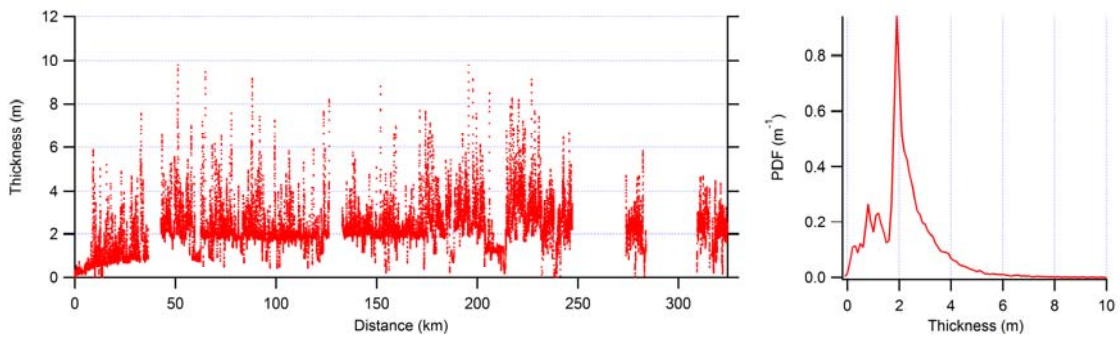
March 18: Beaufort Central



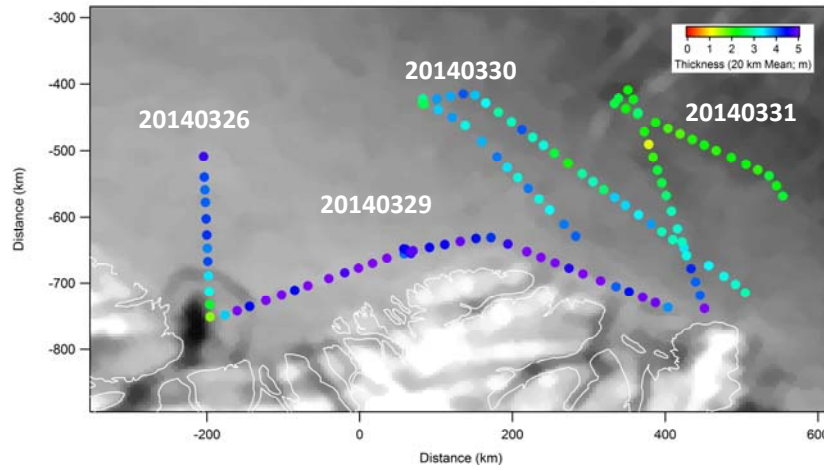
March 19: Beaufort East & Banks Island Polynya



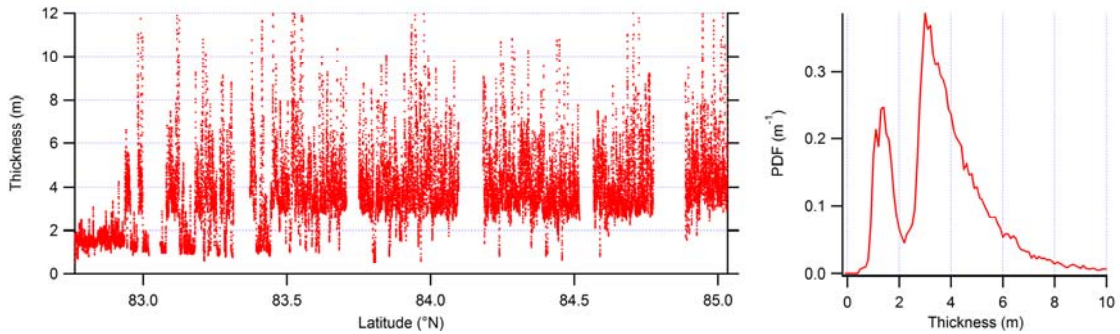
March 21: Beaufort West and ONR ice camp overflight



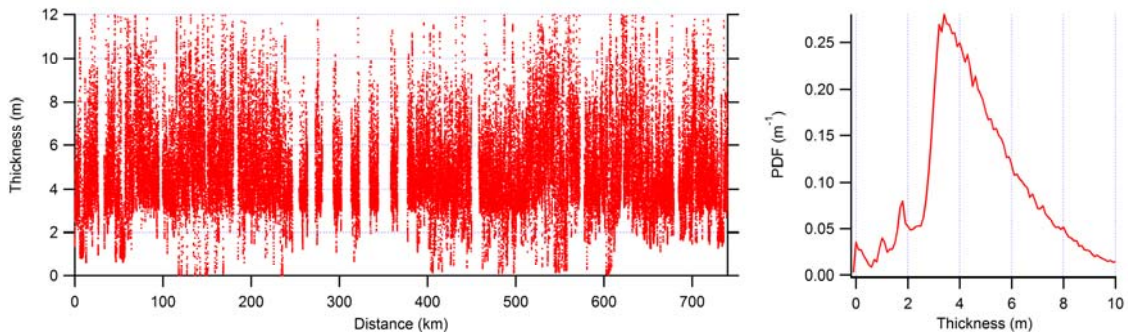
5.1.1.2 Alert and Station Nord, March 26-31



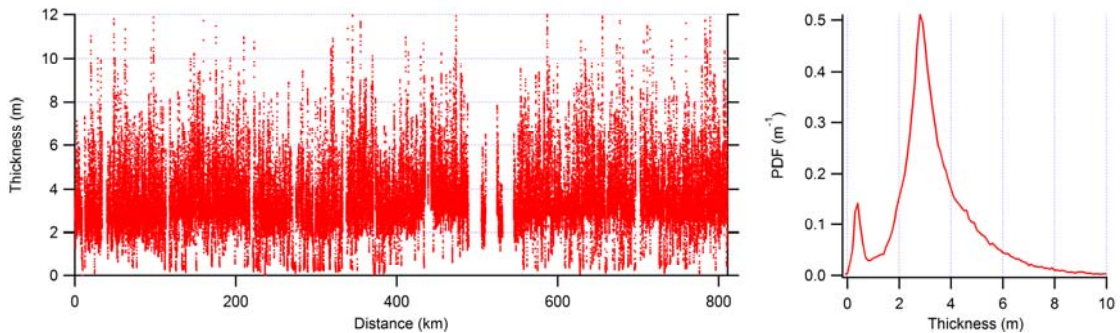
March 26: Alert, Lincoln Sea, Arctic Ocean



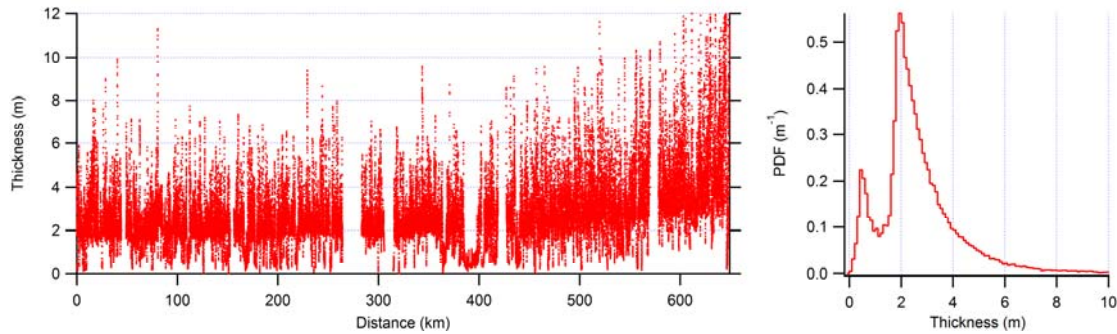
March 29: Alert to Station Nord, and ice camp overflight



March 30: Nansen Basin / North Greenland, and north site overflight



March 31: Nansen Basin / Fram Strait



5.2 Ground-based measurements

All ground validation sites were chosen to be on virtually level ice without pressure ridges. Camp 2 in the Beaufort Sea and the main CryoVEx site north of Greenland were the sites with the complete set of measurements. Table 3 summarizes information about all four sites.

Table 2: Locations and study periods of ice-camp supported ground measurements.

Name	Location	Dates (2014)	Ice characteristics
ONR Camp 3*	Beaufort Sea, 74.4°N, 137°W	March 16/17	FYI/SYI/MYI
ONR Camp 2	Beaufort Sea, 73.5°N 137°W	March 17-22	SYI/MYI
CryoVEx Main Camp	Lincoln Sea, 84°N 40°W	March 28 – April 2	MYI
CryoVEx North Site*	Arctic Ocean, 86°N 34°W	March 30, 2014	SYI/MYI

* Secondary sites

The length of the long 1D profiles was 1929 m in the Beaufort Sea, and 1290 m north of Greenland. At the secondary sites, a 980 m long profile was surveyed at Camp 3 in the Beaufort Sea, and 500 m at 86°N.

Figure 10 shows photos of typical surface conditions at three sites, and results of the drill-hole measurements. These show the wide range of conditions encountered typical for the various Arctic ice regimes. Figures 11 and 12 show the snow grids obtained on both main sites. More details are presented in the extensive ground data report by **Beckers et al., CryoVEx2014 - In-situ measurements at MIZ/ONR and NORD (Greenland) ice camps. ESA Ground Team Report at the end of this report.**

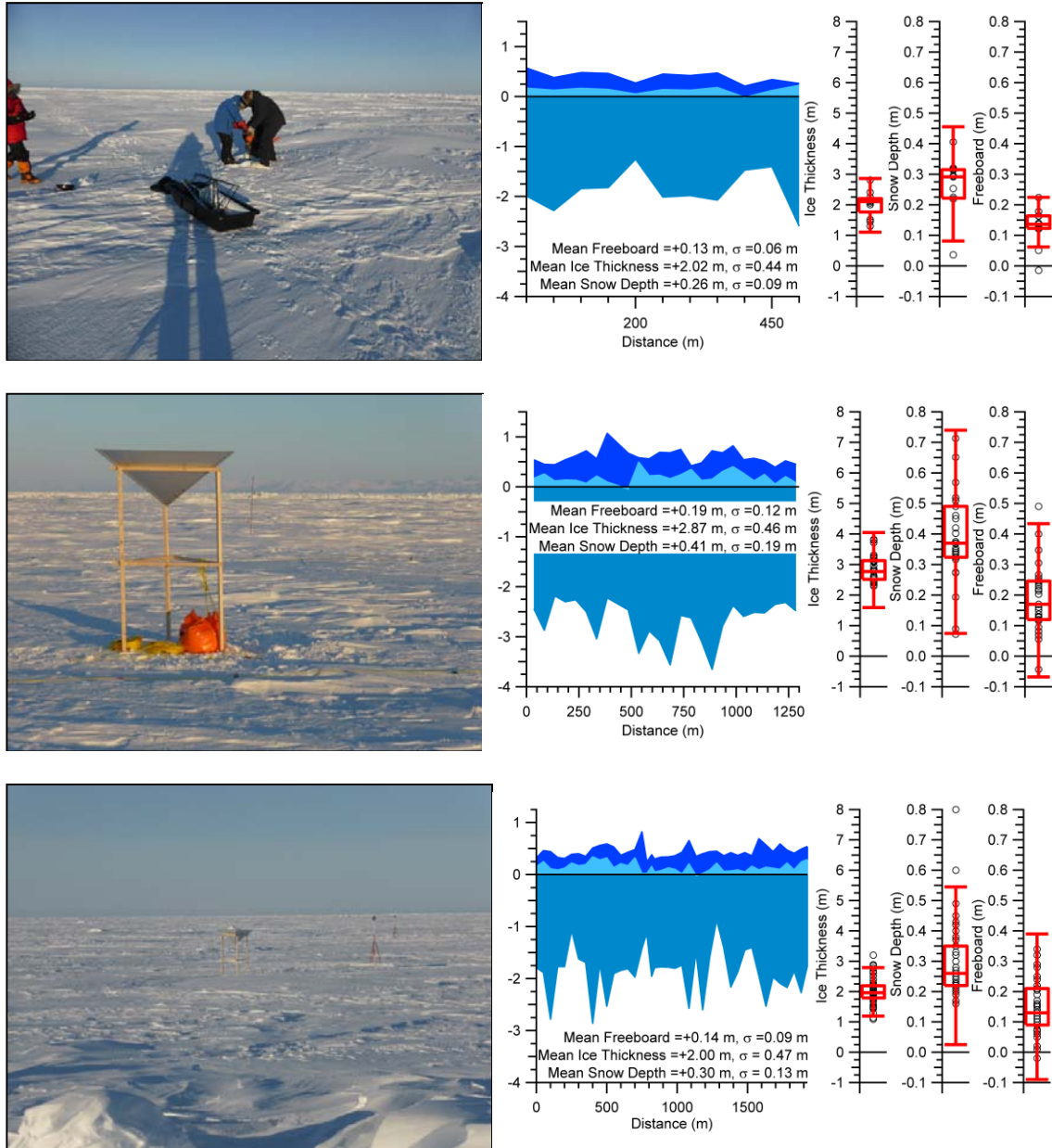


Figure 10: Typical surface conditions at three validation sites CryoVEx North (top), CryoVEx main (center), and Beaufort Camp 2 (bottom), and results of drill-hole measurements.

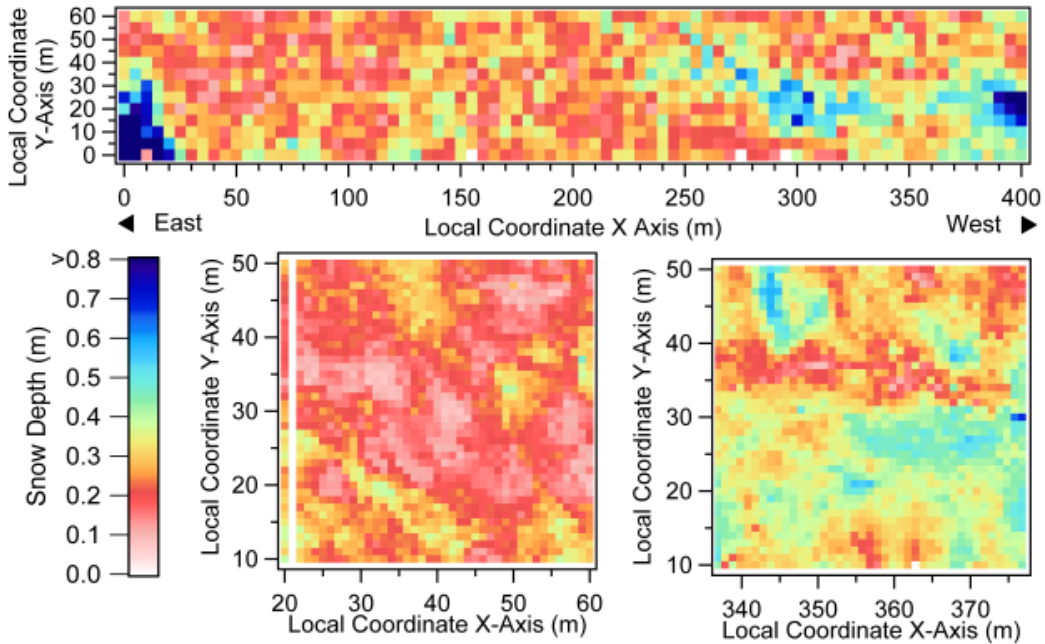


Figure 11: Snow grid measurements at Beaufort Camp 2. Top panel shows complete 400 m x 60 m grid (5 m resolution), and bottom panels show two high-resolution 40 m x 40 m grids centered at corner reflectors.

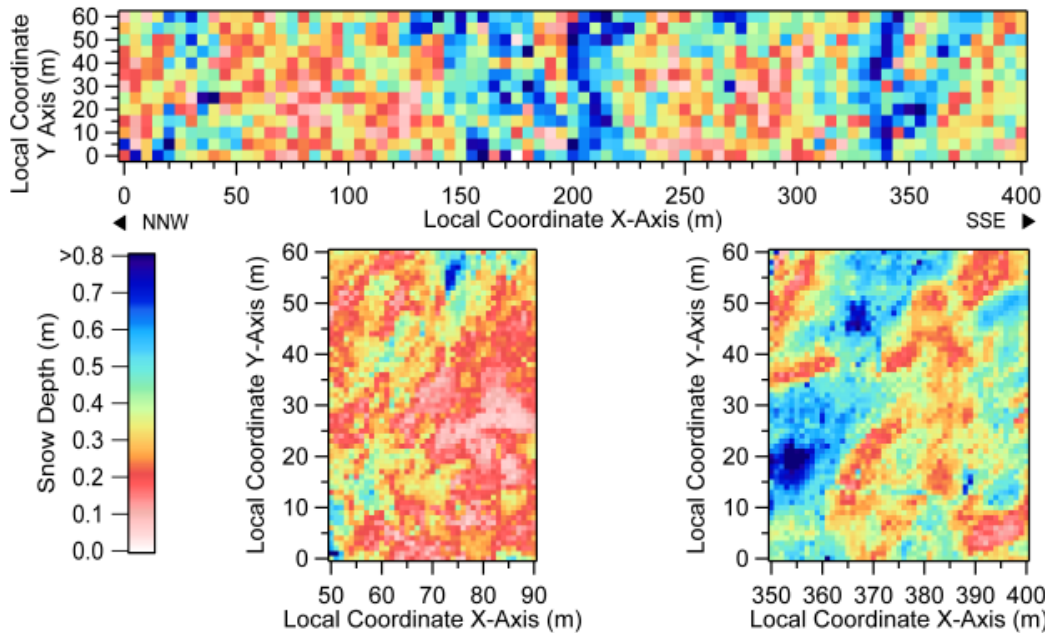


Figure 12: Snow grid measurements at the CryoVEx main camp. Top panel shows complete 400 m x 60 m grid (5 m resolution), and bottom panels show two high-resolution 60 m x 40/50 m grids centered at corner reflectors.

5.3 Comparison of results with OIB quicklook data over validation sites

As described in the Data Acquisition Report (Deliverable 3), all airborne and ground-based activities were closely coordinated with NASA's Operation IceBridge (OIB). Joint activities culminated on March 26 2014 with a tandem flight of CryoSat, the EM Bird, ASRAS, and the OIB instrument suite along the same CryoSat ground track. OIB's P3 aircraft performed multiple overflights of the CryoVex validation site in the Beaufort Sea on March 18, and of the main CryoVEx Greenland site on March 31.

Results of the comparisons are summarized here, and were presented as an invited talk at the AGU Fall Meeting 2014 in San Francisco (Haas et al., 2014; see abstract below).



Figure 13: NASA P3 during overflights of Beaufort Sea ice camp 2, March 18.

AGU FALL MEETING

San Francisco | 15–19 December 2014

SEARCH KEYWORDS

SEARCH SESSIONS

SEARCH CONVENER/AUTHOR

NAME

LOGIN

CryoVEx2014: Observations of Arctic Snow and Sea Ice Properties for Validation of Cryosat and Icebridge Retrievals

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Abstract:

The European Space Agency's (ESA) CryoSat mission and NASA's airborne Operation IceBridge observe large-scale, regional and temporal changes of sea ice thickness in the Arctic by means of radar and laser altimetry. Unfortunately, snow thickness variability and scaling issues at all scales from meters to hundreds of kilometers remain some of the main sources of error for altimetric sea ice thickness retrievals. To address this gap, extensive coincident airborne and in-situ ice and snow measurements were performed as part of the CryoSat Validation Experiment in March and April 2014 (CryoVEx 2014). In-situ ice and snow thickness measurements were performed at four locations representative of various Arctic ice and snow conditions. Two sites were located in first year ice near Barrow, Alaska; one was in the Canadian Beaufort Sea's thin multiyear ice; and one was in thick multiyear ice situated north of Greenland. All four sites were overflown by a number of aircraft equipped with various ice and snow thickness sensors that captured ice and snow property variations. At our field sites, ice thickness, surface roughness, and snow thickness measurements were performed along 2 km transects. Centered on these transects were 60 m x 400 m intensive snow measurement grids with 5 m x 5 m point spacings and nested 60 m x 100 m grids with 1 m x 1 m point spacings. These snow thickness measurements were acquired to study the two-dimensional variability and to provide information on scales comparable to or exceeding the footprint sizes of airborne snow thickness radars operated by NASA and ESA. Here we present results of these snow and ice thickness measurements to shed light on the large- and small-scale spatial variability of these properties across the Arctic. In addition, we present first results from initial comparisons with the airborne and satellite snow and ice thickness retrievals.

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Figure 14 shows the drift track of the ONR ice camp during CryoVEx 2014, and the OIB and AEM flight tracks during their respective overflights. The ice camp drifted significantly (see ground team report by Beckers et al.), which makes direct comparison between the airborne and in-situ data difficult. However, with the help of the buoys (and eventually the OIB DMS photos), the location of the validation transect and snow grids could be accurately reconstructed.

Figure 15 shows a comparison of all coincident in-situ and airborne data thus obtained in the Beaufort Sea. At the Greenland ice camp, there was very little ice drift during our measurements from March 28 to April 2 (few meters). Therefore no drift corrections had to be applied. A comparison of all data is shown in Figure 16.

One of the major CryoVEx 2014 objectives was to obtain extensive snow thickness data to validate snow penetration of CryoSat and the suite of OIB instruments. Figure 17 shows comparisons of the in-situ snow thickness distributions with those from the OIB quicklooks (Version July 2014), and of the AEM and OIB ice thickness distributions. It can be seen that the OIB and in-situ snow thickness distributions agree very well in Greenland, but only partially in the Beaufort Sea. There is a strong mode at thin snow 5-15 cm thick in the Beaufort Sea, which does not appear in the in-situ data. Such spikes have been seen in earlier OIB snow thickness products, and are most likely related to processing artefacts due to the presence of side lobes in the snow radar data (Kwok and Haas, 2015). When the snow is thick as it was in Greenland, these side lobes can be effectively identified and eliminated in the snow thickness retrieval.

Drill-hole and AEM ice thickness distributions are in relatively good agreement both in the Beaufort Sea and north of Greenland (Figure 17). However, the number of samples obtained by the two methods is quite different (i.e. there are many more AEM thicknesses). As might be expected by the poor OIB snow thickness retrievals in the Beaufort Sea, the OIB ice thickness distribution does not agree well with the in-situ and AEM estimates. Due to the underestimation of snow thickness, ice freeboard is overestimated, leading to too thick ice retrievals. However, over the Greenland ice camp the agreement is quite good.

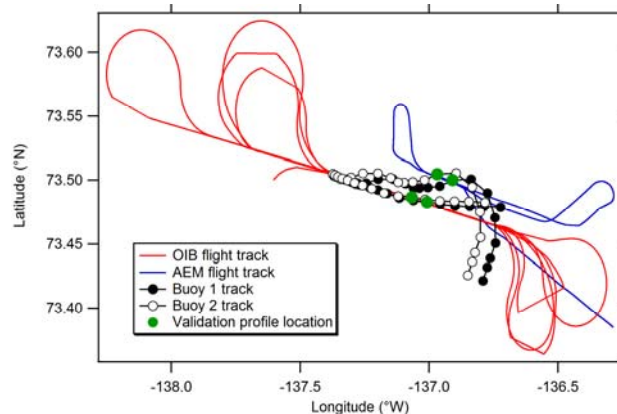


Figure 14: Map of OIB (March 18) and AEM (March 21) flight tracks over ONR ice camp in the Beaufort Sea during CryoVEx2014. Black markers show the drift of the ice camp between March 17 and 22, as observed by two SVP GPS beacons located at each end of the long validation transect. Green markers show the location of the validation transect during the respective aircraft overflights.

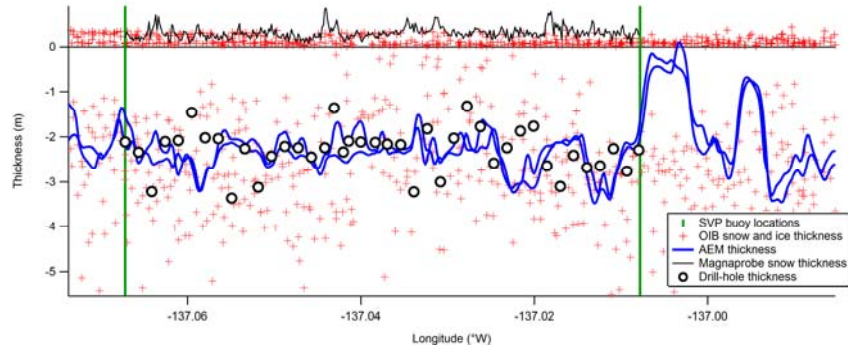


Figure 15: Comparison of all coincident in-situ, OIB, and AEM data (2 overflights) obtained over the CryoVEx 2014 Beaufort Sea ice camp. Ice thickness is shown with negative values to resemble ice draft, and snow thickness is shown with positive values. Data have been drift corrected using data from the SVP buoys located at the end of the long in-situ transect.

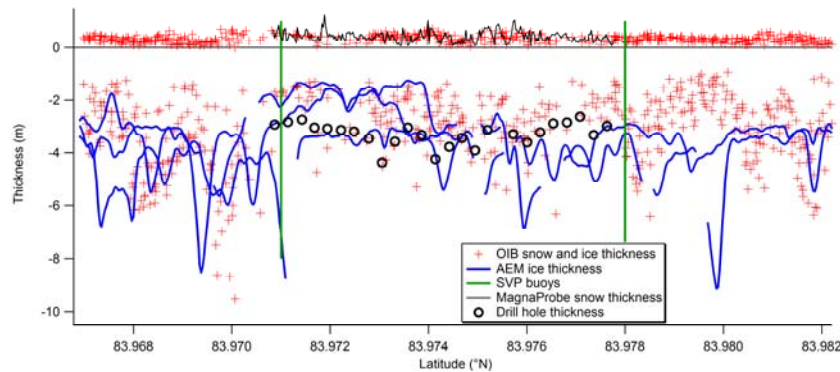


Figure 16: Comparison of all coincident in-situ, OIB, and AEM data obtained over the CryoVEx 2014 Greenland ice camp. See Figure 15 for further explanations.

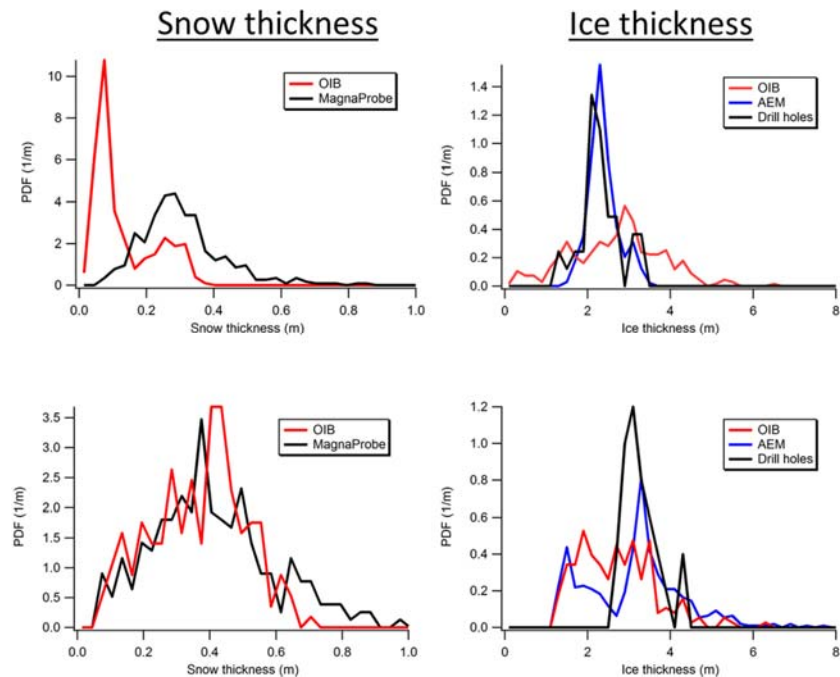


Figure 17: Comparisons of in-situ snow and ice thickness distributions with those from AEM and the OIB quicklooks (Version July 2014). Top row: Beaufort Sea camp; Bottom row: Greenland ice camp.

6 Data delivery and formats

All airborne EM and in-situ data gathered during CryoVEx 2014 have been processed and delivered to ESA for posting at the ESA Earth Observations Campaigns Data web site at <https://earth.esa.int/web/guest/campaigns>. Data are used by the CryoVEx, CryoVal, and SMOSIce projects. The data content and formats have been described in Deliverable 4 of this contract:

Haas, C., J. Beckers, A. Bublitz & A. Casey, 2014, CryoVEx 2014 Airborne and In-situ Ice and Snow Thickness Data; Internal Report, ESA Contract No. 4000110552/14/MP/vb, Deliverable 4.

Below is a description of file contents and data formats:

6.1 AEM ice thickness surveys

The ice thickness data include all data acquired by the EM bird operated under the Basler aircraft. 7 data files were delivered containing all ice thickness data of the seven flights performed (D4AEMThicknessData.zip). These are:

20140318_allfinal.dat
20140319_allfinal.dat
20140321_allfinal.dat
20140326_allfinal.dat
20140329_allfinal.dat
20140330_allfinal.dat
20140331_allfinal.dat

Figure 18 shows the geographical coverage of each flight. Please refer to the Data Acquisition and Final Reports for more information.

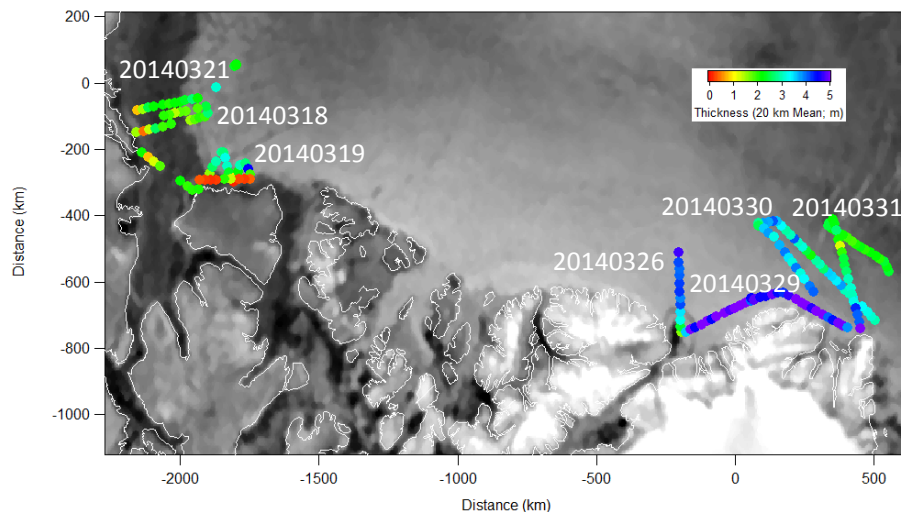


Figure 18: Map of all EM ice thickness flights carried out with the EM bird operated by the Basler aircraft. Background map is ASCAT radar backscatter information on March 26, 2014, obtained from BYU. See data acquisition and final reports (Deliverable 3 & 6) for more information.

6.1.1 Data format

Files are named according to the date of flight: YYYYMMDD_allfinal.dat, with

YYYY: Year of flight (e.g. 2014)

MM: Month of flight (e.g. 03)

DD: Day of flight (e.g. 18)

The file format is ascii, tab delimited. There are 10 data columns in each file, separated by a tabulator character:

- Year
- Month
- Day
- GPSseconds: Time of measurement in seconds of the day, GPS time.
- Fid: Fiducial number, a measurements index referencing to all other measurements performed by the EM ice thickness sensor
- Lat: Latitude of measurement
- Lon: Longitude of measurement
- Distance: Distance along flight track in m. Note that this parameter is reset to 0 after every new file created during a complete survey.
- Thickness: Total (ice-plus-snow) thickness computed from the EM and laser measurements (see Haas et al., 2009 & 2010) for more information on data processing.
- Height: Laser-measured height of EM ice thickness sensor above the snow surface.

6.2 In-situ measurements

A wide range of ice and snow thickness measurements were performed with different spatial scales (long line transects and snow grids) and resolutions (50 m, 5 m, 1 m), and using different methods (Magnaprobe, drill-holes, laser surveying, snow pits, bulk density tubes, EM sounding, drifting buoys, DGPS base station, corner reflector installations). These are described in detail in the Final Report (Beckers et al., 2015; see Appendix below). Accordingly, numerous different data formats and files had to be chosen to properly provide and archive these data. The delivered data (**D4CRYOVEX2014_SEAICE_GROUNDDATA_V1.ZIP**) include the complete directory structure with data files and additional descriptions of meta data and data formats. These are summarized and introduced in the **README.README.txt** file:

```
README FOR CRYOVEX2014_SEAICE_GROUNDDATA_V1.ZIP
```

```
AUTHOR:
```

```
JUSTIN F. BECKERS
```

```
AUTHOR CONTACT:
```

```
JUSTIN.BECKERS@UALBERTA.CA
```

```
NOTES:
```

```
THIS DIRECTORY AND SUBDIRECTORY CONTAINS THE DATA COLLECTED DURING THE 2014 CRYOVEX CAMPAIGNS PERFORMED IN THE BEAUFORT SEA AND THE CENTRAL ARCTIC OCEAN NORTH OF GREENLAND IN MARCH AND APRIL 2014.
```

```
ALL DATA ARE PROVIDED IN HUMAN READABLE COMMA-DELIMITED (CSV) FILES THAT INCLUDE HEADERS.
```

```
A README FILE IS INCLUDED FOR EACH DATASET.
```

```
OVERVIEW DIAGRAMS OF THE SITES ARE PROVIDED AS PORTABLE DOCUMENT FORMAT (PDF) FILES.
```

CHECKSUM VALUES FOR ARCHIVE FILE:

SHA-256:
 1C4F3085F0B954A7DAC41BCC243142300258EB865DB3E05C86F94F0E28AB89AA
 SHA1: 7B3D9E88809D1B66CA6CA35CA131F32F05B49CFF
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DIRECTORY LISTING:

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./CryoVEx2014_CR_METADATA.csv
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./DGPS_DATA/MIZONR_CAMP2_DGPS/NRCANCSRS_PPP_KINEMATICSOL/MIZONR_CAMP2_DGPSREF_0770.sum
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./NORD_CAMP_TRANSECT.csv
./NORD_NDAYSITE_OVERVIEWMAP.pdf
./NORD_NDAYSITE_TRANSECT.csv

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./README_5MGRIDS.txt  
./README_CR.txt  
./README_DGPS.txt  
./README_SNOWPITS.txt  
./README_SVPGPS.txt  
./README_TRANSECTS.txt
```

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- Kwok, R., and C. Haas (in press), Effects of radar sidelobes on snow depth retrievals from Operation IceBridge. *J. Glac.*, 2015.

APPENDIX: CryoVEx2014 - In-situ measurements at MIZ/ONR and NORD (Greenland) ice camps

ESA Ground Team Report

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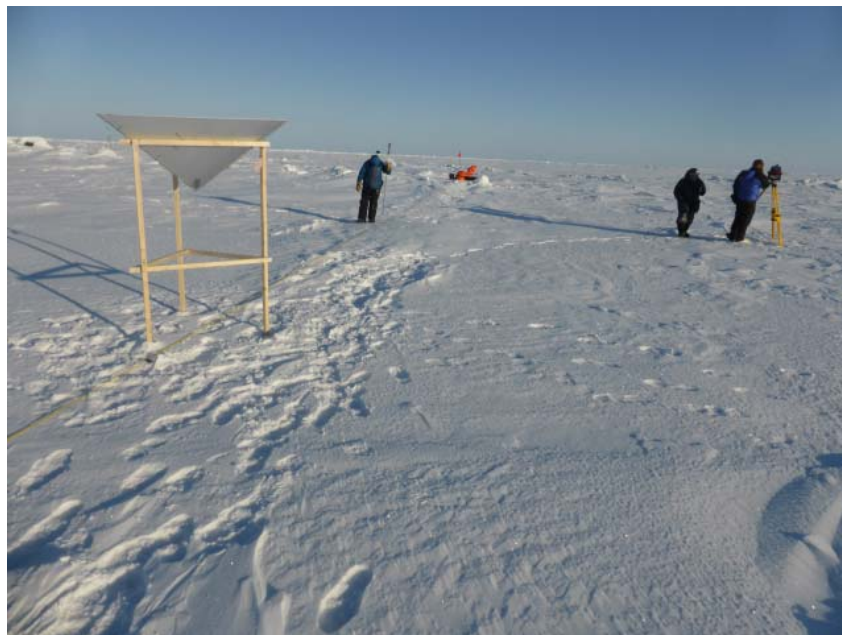
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CryoVEx2014 - In-situ measurements at MIZ/ONR and NORD (Greenland) ice camps ESA Ground Team Report



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Acronyms and Abbreviations

AEM - airborne electromagnetic induction sensor

ASIRAS –Airborne Synthetic-Aperture, Interferometric Radar Altimeter System

CFS Alert - Canadian Forces Station Alert

CryoVEx - CryoSat Validation Experiment

DTU - Danish Technical University

EM – electromagnetic induction sensor

ESA - European Space Agency

FYI - First year sea ice

GPR – Ground Penetrating Radar

KBAL – Kenn Borek Air Ltd.

MIZ - Marginal Ice Zone Project

MYI - Multi-year sea ice

NASA - National Aeronautics and Space Administration

NU - Nunavut

OIB - Operation Ice Bridge

ONR - U.S. Office of Naval Research

YU - York University

DMS - Digital Mapping System, a NASA OIB instrument.

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Executive Summary

Continuing the work of the 2011 and 2012 post-launch CryoSat-2 Validation Experiments (CryoVEx; Willat and Haas, 2011), the European Space Agency (ESA) initiated a third validation campaign carried out in March 2014 for further calibration and validation of CryoSat-2 data products. The 2014 campaign was modeled after CryoVEx 2011 and thus included both airborne and ground based measurements. The main purpose of CryoVEx 2014 was to acquire data along long transects of CryoSat-2 ground tracks and overflying measurement sites of a ground-based field team with airborne sensors. Furthermore, CryoVEx 2014 included sampling at multiple locations in the Arctic Ocean to better capture regional variability in the snow and ice properties and to sample different ice types and surface roughness features. CryoVEx 2014 was a major coordinated effort involving multiple aircraft and a large group of European, Canadian, and US scientists representing numerous universities, research institutes, and both ESA and NASA's Operation Ice Bridge (OIB).

The CryoVEx 2014 experiment was performed in two regions: the Beaufort Sea, and the Lincoln Sea / Arctic Ocean. A summary of the data and results acquired by the ground team at each measurement site is presented. A brief day-to-day summary of activities is followed by a short introduction into the measurement philosophy at the main measurement sites and for the auxiliary sites measured in each region. A detailed description and presentation of the data and statistics follows. This report is meant to accompany the final data delivered to ESA. A summary of the coincident airborne measurements can be found in the CryoVex 2014 Airborne Data Acquisitions Report (Haas, 2014).

In the Beaufort Sea, the ground team collected measurements between March 16 and 22 at two camps, the Marginal Ice Zone Project/ Office of Naval Research (MIZ/ONR) Camp 3 and Camp 2. Camp 3 was an auxiliary site where measurements of snow depth, ice thickness, and snow surface elevation were acquired along two 500 m long transects. ONR/MIZ Camp 2 was the main survey site. At Camp 2 a 400 m by 60 m snow depth grid was established near the center of a 1.98 km transect survey. The 400 m by 60 m snow depth grid was measured with 5 m spacing. Two 40 m by 40 m snow depth grids with 1 m spacing were also established around each of two corner reflectors located within the 400 m survey grid. Measurements performed along the transect included snow depth, ice thickness, ice freeboard, ice draft, snow freeboard, snow density.

The second phase of the campaign was out of a camp on the sea ice in the Arctic Ocean near 84N and 40W, near Cape Morris Jessup, Greenland, from March 28 to April 2. The main survey site consisted of a 1.3 km transect survey with a 400 m by 60 m snow depth survey grid at its center. Once again the 400 m grid was sampled at 5 m spacing and two, 50 m by 60 m and a 40 m by 60 m, grids were measured at 1 m spacing around the two radar corner reflectors placed within the 400 m grid. The measurements conducted along the transect included snow depth, ice thickness, ice freeboard, ice draft, snow freeboard, snow density. Measurements of snow depth and ice thickness were also conducted at an auxiliary site at approximately 86N, 34W.

Airborne measurements were made over each of the grid sites by ESA's Airborne Synthetic-aperture, Interferometric Radar Altimeter System (ASIRAS), York University's Airborne EM (AEM) ice thickness sounder, and the NASA Operation IceBridge (OIB) laser altimeters data and snow radars. Each aircraft made multiple passes over the site in order to ensure that sufficient coincident data were collected over the validation sites. For the NASA OIB P3 and ASIRAS multiple passes also aimed to ensure measurements were taken of both corner reflectors.

Day to Day Summary

- March 15, 2014 Arrival in Sachs Harbor
- March 16, 2014 Ground team arrives at MIZ Camp 3. Measurements of ice thickness, ice freeboard, draft, snow freeboard and snow depth performed along two transects, FYI and MYI.
- March 17, 2014 Ground team transfers to MIZ Camp 2. 400 m by 60 m snow survey grid, 2 km transect, drifting buoy, and corner reflectors setup.
- March 18, 2014 Snow depth and density, ice thickness/freeboard/draft, snow surface elevation measurements along the 2 km transect. NASA OIB P3 over flight
- March 19, 2014 Snow depth, ice thickness/freeboard/draft, snow surface elevation measurements along snow survey grid centerline. Terrestrial LIDAR measurements of first 100m of snow survey grid. Deployment of seasonal ice mass balance buoy.
- March 20, 2014 Snow depth measured in 400 m survey grid with 5 m spacing over entire grid and two 40 m by 40 m grids with 1 m spacing centered around each corner reflector.
- March 21, 2014 York University DC-3 AEM and DTU ASIRAS over flights. Snow pits at corner reflectors and at 100m intervals of snow survey grid.
- March 22, 2014 Team returns to Sachs Harbor.
- March 23, 2014 Team transfers from Sachs Harbor to Resolute Bay with YU DC-3. DTU ASIRAS re-surveys measurement transect and grid at MIZ ONR Camp 2 before transfer to Resolute Bay.
- March 24, 2014 Team transfers to Qaanaaq, Greenland with YU DC-3. KBAL Twin Otter has not arrived on schedule. Overnight in Qaanaaq.
- March 25, 2014 Team arrives at Station Nord, DC-3 departs to CFS Alert, NU, Canada.
- March 26, 2014 Weather Day/KBAL Twin Otter has not arrived in Station Nord.
- March 27, 2014 Weather Day/KBAL Twin Otter arrives in late evening
- March 28, 2014 Weather Day/Twin Otter departs late afternoon with four members of ground team to deploy camp. Corner reflectors deployed, transect and grid established.
- March 29, 2014 Remaining members of ground team shuttled to camp. Snow depth measured in 400 m survey grid with 5 m spacing and started 1 m spacing centered around each corner reflector (50 m by 60 m and 40 m by 60 m). Over flight of site by YU DC-3 and DTU ASIRAS
- March 30, 2014 Measurements of snow depth, ice thickness/freeboard/draft at northern site (86N, 34W). Over flights of northern site by DTU ASIRAS and YU DC-3. Deployment of snow depth buoy at N site. Completion of 5 m and NNW 1 m snow survey grid at main site.
- March 31, 2014 Snow depth, snow density, ice thickness/freeboard/draft, and snow surface elevation measurements along extended transect and centerline of snow grid. Snow pits at corner reflectors and at 100 m intervals of snow survey grid. Deployment of snow buoy. NASA OIB P3 over flight.
- April 01, 2014 Demobilization of camp. CRREL IMB deployment. Four team members back to Nord
- April 02, 2014 Remaining ground team back to Nord, and all members depart. End of Campaign.

Introduction

This report details the measurements performed and data collected by the sea ice ground team during the CryoVEx 2014 experiment between March 16 and April 1, 2014. This document accompanies the ground team data and metadata files. The information presented here is meant to summarize the data collected, the instruments and methods used as well as highlight key measurements.

As in previous years, the aim of the experiment was to characterize the snow and ice properties of Arctic sea ice and its snow cover during winter and to examine how these properties affect Ku-band radar penetration into the snow, and the radar altimetric freeboard retrievals. Unlike previous years, measurements were performed at multiple sites and over multiple days to characterize regional differences and to examine different mean snow and ice conditions. Furthermore measurements were designed to fulfill requirements for both ESA CryoVEx/CryoSat and the OIB airborne measurements.

The tasks to be completed by the ground team at each of the main study sites were as follows. Before airborne measurements occurred:

- Set up a two km transect line marked by drifting GPS buoys and marked for visualization from the air. The transect line would be used to put the grid in context of the ice floe and area. The drifting buoys allow for drift correction and allow aircraft to find and survey the site.
- Set up a 400 m long by 60 m wide grid at the center of the two km long transect line. The 400 m by 60 m grid would be measured at 5 m point spacing to cover the footprint of the ESA's Airborne Synthetic-aperture, Interferometric Radar Altimeter System (ASIRAS), and the OIB snow radar and to examine two dimensional variability in snow and ice properties.
- Set up a corner reflector 30 m to 40 m in from each end of the 400 m X 60 m grid. The corner reflectors provide a vertical height reference for ASIRAS and the OIB snow radar.

Once airborne measurements had been completed over the survey line and grid the ground team was to:

- Measure snow depth at 5 m spacing over entire 400 m X 60 m grid.
- Measure snow depth at 1 m spacing over a subset grid around each corner reflector, minimum of 40 m by 40 m.
- Measure snow depth and snow surface elevation along the 2 km survey transect at 5 m spacing. Drill hole measurements of ice thickness, freeboard, and draft were performed at 50 m spacing. Combined with the snow depth and snow surface elevation data, the ice thickness data can be used to determine ice freeboard at 5 m point spacing. Bulk snow density was sampled at 100 m spacing.
- Measure snow properties (grain size, hardness, density, salinity) via snow pits along the center of the grid at 100 m spacing and near corner reflectors.

Additional sites of opportunity would include measurements of snow depth, ice thickness, ice freeboard, ice draft along 500 m long (or greater) transects marked by drifting GPS buoys.

In addition to the standard aforementioned suite of ground measurements, the University College London Ground Penetrating Radar was utilized at the camp north of Greenland to assess the influence of snow properties on radar penetration.

Study Site Locations

Measurements were performed in two regions, the Beaufort Sea west of Banks Island and in the central Arctic Ocean north of Cape Morris Jessup, Greenland (Figure 1). In each region, a main site was established and measurements performed along a transect and over a snow depth survey grid. Furthermore, measurements were also performed at one auxiliary site in each region.

In the Beaufort Sea, the CryoVEx ground team performed measurements at the MIZ/ONR ice camps. The CryoVEx ground team in the Beaufort Sea consisted of Christan Haas (York U), Justin Beckers (U of Alberta), Bruce Elder (USACE CRREL), and Chris Hiemstra (USACE CRREL). On March 15 the team arrived in Sachs Harbor, NWT. Instruments and equipment that had been shipped in February were located, charged, checked and packed for deployment. As initial plans were to conduct measurements at the auxiliary site at MIZ/ONR Camp 3 first, space and weight considerations limited us to essential measurements with additional equipment to come the following day or to be delivered to MIZ/ONR Camp 2.

Measurements were performed at the auxiliary site, MIZ/ONR Camp 3 on March 16 - March 17, 2014. The main survey site was established at MIZ/ONR Camp 2 and measured from March 17 to March 22, 2014. The MIZ/ONR camps experienced rapid drift. From March 17 to March 19, drift was westwards at up to 1.2 kmhr^{-1} ; on March 20 the drift direction changed and the ice began to drift eastwards. The CryoVEx ground team demobilized from MIZ/ONR Camp 2 on March 22, 2014 and transited to Resolute Bay Greenland on March 23, 2014 with the York U DC-3.

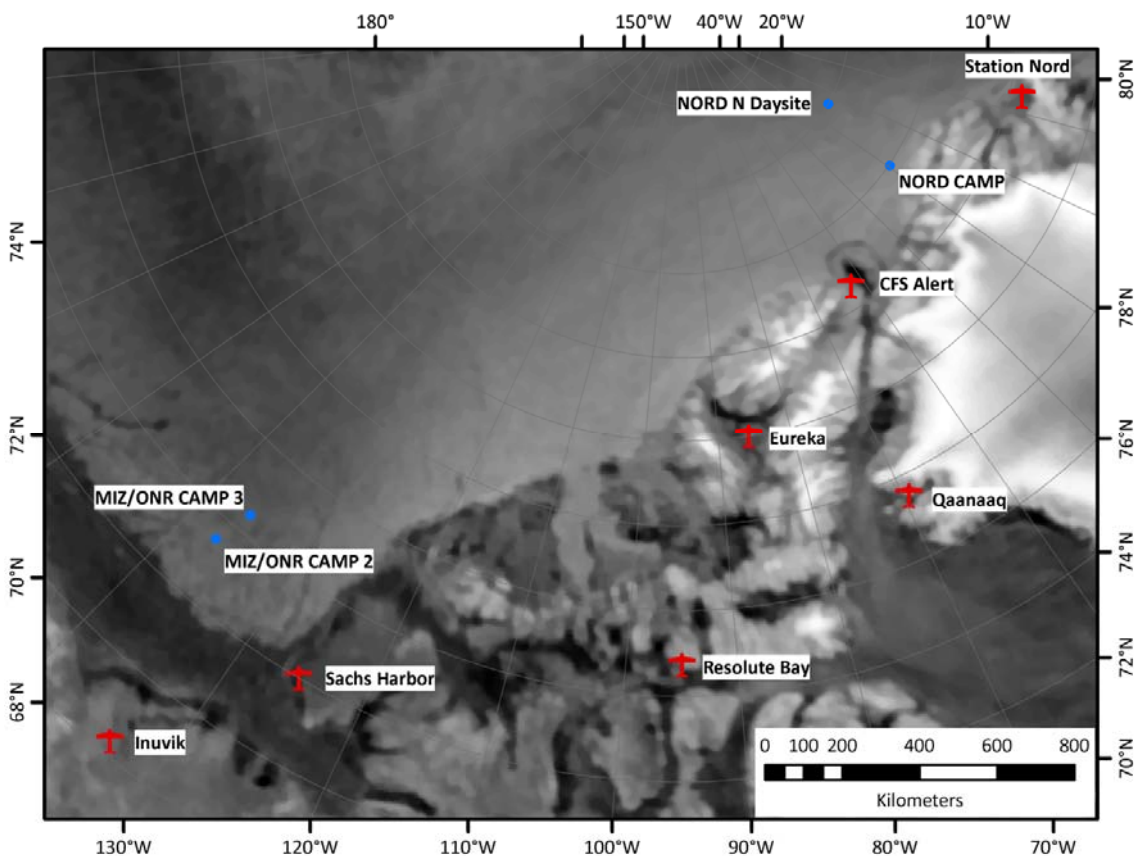


Figure 1: Map of the location of measurement sites (blue dots) and utilized airfields (red airplanes) overlain on an ASCAT scatterometer image from March 22, 2014. Low backscatter (dark) indicates smooth, first-year ice and or open water (black). Brighter gray tones are associated with multi-year ice due to its greater surface roughness and volume scattering.

On March 24, the CryoVEx ground team and the York U DC-3 AEM team left Resolute Bay, NU for Station Nord Greenland. Weather delays resulted in a late departure and forced an overnight stay in Qaanaaq. On March 25, the DC-3 continued to Station Nord. C. Haas, B. Elder, M. Cornelissen and P. Nyquist deployed the camp on March 28 using the Twin Otter that had arrived late on March 27 after repair and weather delays. The camp was setup to the north of Greenland and due to safety, aircraft range, and ice drift considerations the camp was deployed far to the west of Station Nord at roughly 84N, 40W. The rest of the team deployed to the camp with the remaining equipment on March 29.

The CryoVEx ground team now consisted of the Beaufort Sea CryoVEx team (C. Haas, J. Beckers, B. Elder, C. Hiemstra), Tom Armitage and Rachel Tilling from the University College London, and the camp managers, Marc Cornelissen and Petter Nyquist.

The DTU/ESA Twin Otter carrying ASIRAS and the YU AEM system flew over the Nord camp survey line on March 29 and measurements of the snow grids were conducted. Measurements at the NORD NDaysite, an auxiliary site at 86N 35W, were performed on March 30, 2014. The NASA P3 carrying the Operation Ice Bridge sensor suite flew over the survey line on March 31, 2014. On March 31, 2014 the remaining measurements of snow and ice properties along the grid and transect were completed. Measurements at the main camp were concluded on April 1, 2014 with the installation of an ice mass balance buoy and a snow depth buoy. Ice drift at the Nord camp was minimal and temperatures were below -20°C for the duration of the experiment. On April 1, 2014 four members of the ground team returned to Station Nord. The four remaining team members returned to camp on April 2, 2014 and the team departed Station Nord.

Data Description

In this section we briefly describe the sensors and methods used to collect the data.

Two corner reflectors were deployed in each of the grid survey sites. The corner reflector panels had dimensions of 1.0 m by 1.0 m by 1.4 m. Three panels are joined to form a triangular pyramid and placed in to the stand so that the open base faces the sky. The stands were inserted into the snow layer by drilling into the snow with a 0.05 m Kovacs Drill Equipment ice auger.



Figure 2: Christian Haas standing next to the East corner reflector at MIZ/ONR Camp 2.

Snow depth was measured along the transect and grid with a Snow Hydro MagnaProbe. The MagnaProbe stores snow depth and GPS position in a data logger at the push of a button. Snow depth is measured with a steel rod and an external plastic basket with a metal ring. An electric signal is used to determine the distance from the top of the probe to the plastic basket and is converted to snow depth. Extreme care was taken to ensure that the probe completely penetrated the snow to the ice surface.

Snow surface elevations (snow freeboard) were measured using a Leica Rugby 100, a self-leveling, rotating laser. The Rugby 100 creates a laser plane that is then detected by a detector placed on a graduated telescoping rod and the detector is raised or lowered until the laser plane is sensed. Measurements are relative and were therefore referenced to the drill hole freeboard. With an effective range of some 200 m to 400 m, the laser was placed approximately 100 m to 200 m ahead of the section to be sampled and set up on a survey tripod so as to be higher than any feature along the transect. Measurements were taken every 5 m along the transect until the laser unit was approximately 100 m to 200 m behind the point of measurement, or detection became too difficult. Then the laser unit was moved another 100 m to 200 m ahead. The last measurement of the first section was repeated as the first measurement of the new section,

in order to cross-reference the new height of the laser plane. Using the MagnaProbe snow depth data and the drill hole data as reference points, the laser can provide snow and ice freeboard.

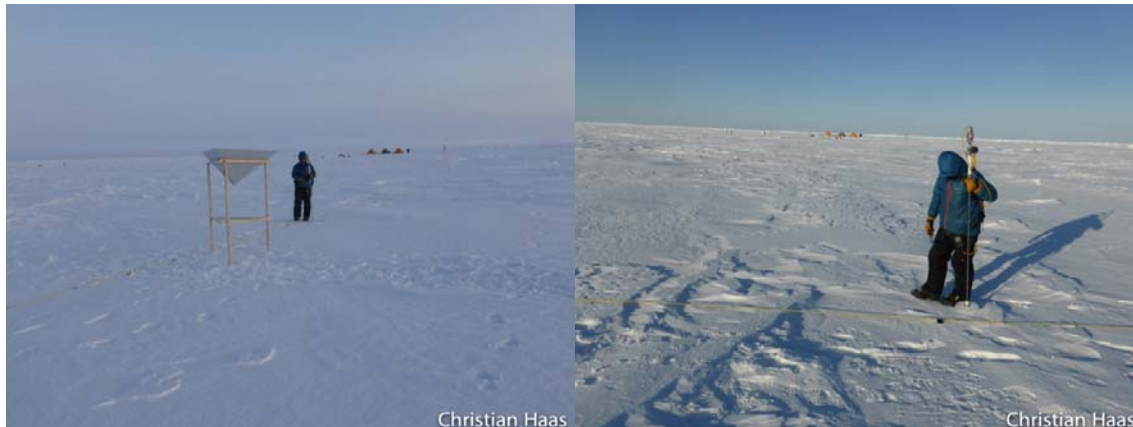


Figure 3: (Left) Corner Reflector at MIZ Camp 2. (Right) Justin Beckers measuring snow depth with the MagnaProbe.

Ice thickness was measured manually using an electric drill and 0.05 m diameter augers from Kovacs Ice Drilling Equipment Ltd. Ice thickness, ice draft, ice freeboard, and snow freeboard (elevation of the snow surface above the water) were measured using a ruler tape. Snow depth at the drill hole was either measured with a steel graduated probe or using the MagnaProbe. Ice thickness was also measured at the two sites north of Greenland using a GSSI EMP-400 after the failure of two Geonics EM-31 instruments in the Beaufort Sea. The EMP-400 collected data at a sampling rate of 2 Hz and operated at 5, 10, and 15 KHz and includes GPS measurements. The EMP-400 was placed on a sled and pulled. EMP-400 data were re-sampled to a consistent 5 m sample spacing to remove variability in walking speed.



Figure 4: (Left) Marc Cornelissen towing the GSSI EMP-400. (Right): The GSSI EMP-400.

Bulk snow density measurements were made using a Federal Snow Sampler. Properties of the snow layers measured in the snow pits were measured using a custom kit supplied by C. Hiemstra. The kit included SIPRE sampler, Snow Hydro 100cc sampler, Snow Metrics 250cc sampler, a digital weigh scale, a Test 925 Digital Thermometer and various other brushes, grids and tools for examining snow grains. For more detailed information on the snow pit measurements see README_SNOWPITS.TXT provided with the data distribution.



Figure 5: (Left): Surveying snow surface elevation with the Leica Rugby 100 rotating construction laser. (Right): Chris Hiemstra measuring snow layer properties.

The outer ends of the transect were marked with several large orange garbage bags filled with snow arranged in a line (visually) with the corner reflectors. MetOcean Surface Velocity Profiler (SVP) buoys were also placed at each end of the transect, and buoy positions were available on-line in real time and used by the ESA and NASA aircraft to locate the survey lines and to plan precise overflights. The beginning and end of the centerline of the 400 m by 60 m survey grid (aligned with the transect) were also marked with orange garbage bags arranged in a line with the corner reflectors and transect ends. A Trimble 5700 GPS base station with a Zephyr geodetic antenna (DGPS) was deployed at one end of each of the 400 m by 60 m survey grid. At MIZ/ONR Camp 2, the DGPS was setup at (0,30) of the 400 m by 60 m grid. At NORD Camp, the DGPS was set up at (400,30) of the 400 m by 60 m grid. A handheld Garmin GPSMap 76 unit was also set up to log positions within the main camp.

Beaufort Sea MIZ/ONR Camp 2 (Main)

Site Description and Timeline

The main CryoVEx study site in the Beaufort Sea was located at the MIZ/ONR Camp 2. The camp was located on a large, smooth, multiyear ice floe. The site was very smooth with limited hummocks and ridges (Figure 7). The main 400 m by 60 m survey grid was set up to the south of camp, parallel to the bagged runway established for the camp (Figure 8). A ridge ran perpendicularly across the East edge of the measurement grid. The east end of the transect was on thin first year ice near the edge of a lead.

The north edge of the grid and the transect end points were established on March 17, 2014 and marked using 3 m bamboo poles. The two corner reflectors were also placed within the grid. The remaining outer edges and centerline of the grid were marked with bamboo poles on March 18, 2014. Both ends of the transect were measured/placed using a handheld GPS unit with the aim of being 800 m past the ends of the survey grid. On the west end, the high drift speed of the floe resulted in the transect leg being 745 m long (Figure 6, Figure 8).

The drift speed of the floe remained high throughout the measurement campaign and at times was over 0.8 kmhr^{-1} . Drift was generally westward between arrival on 01:43UTC March 18 2014 and March 20 at 00:53UTC, whereupon the drift switched to eastwards (Figure 9).

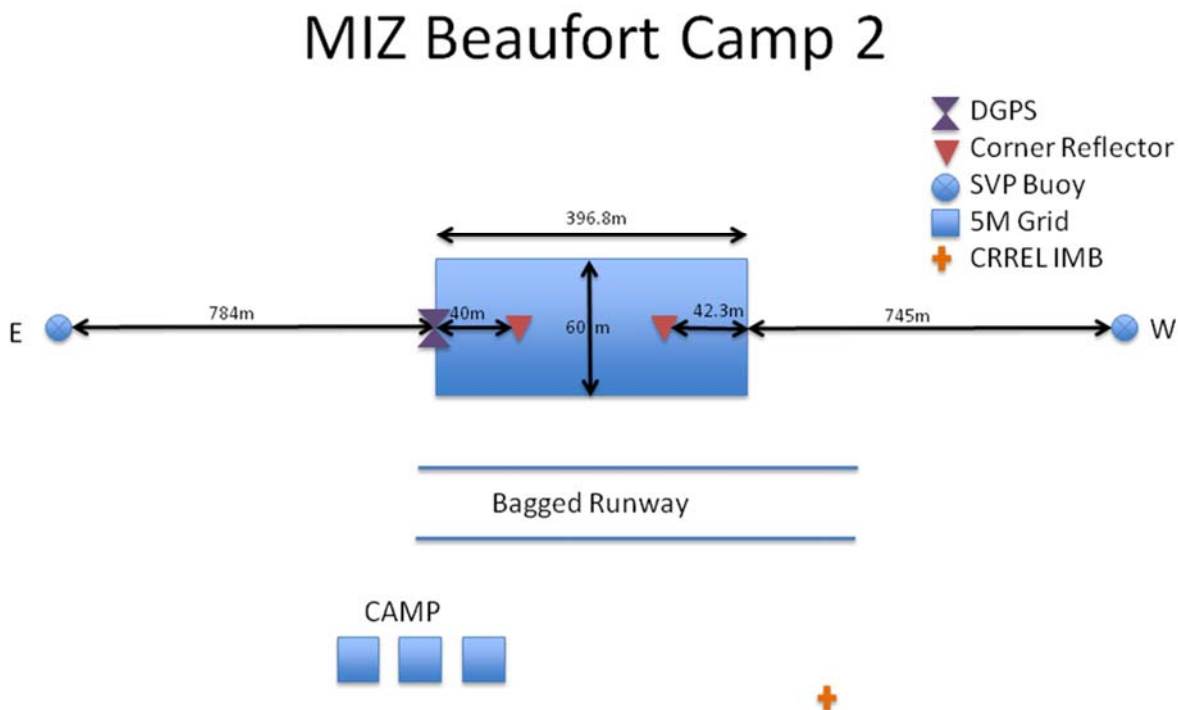


Figure 6: Overview map of Beaufort Sea MIZ/ONR Camp 2 measurement site.

Measurements were completed in an order designed to limit disturbance of the main measurement grid by limiting measurements of the grid until after the aircraft over flights. Thus, on March 18, snow depth and snow surface elevation were measured along the transect at 5 m spacing using the MagnaProbe and Leica laser; ice thickness, freeboard and bulk snow density were sampled at 50 m spacing using the Kovacs 0.05 m ice auger. Measurements along the section of transect from 0 m to 784 m were performed in the morning,

before the NASA OIB P3 flew over the site. The NASA OIB P3 flew over the survey site between 19:12 UTC to 20:33 UTC, making a total of 9 passes along the transect and grid. Measurements of the snow depth, snow surface elevation, ice thickness, freeboard, and bulk snow density along the transect line from 1180.8 m to 1925.8 m were conducted after the NASA OIB P3 completed the survey of the site.



Figure 7: Photographs of the MIZ/ONR Camp 2 Site. (Top left): View along the centerline of the 400 m grid on March 21 during the ASIRAS overflights. Looking towards the west. (Top Right): View of the ridge running across the 400m grid near its eastern edge. (Bottom Left): View of the snow surface near the grid. (Bottom Right): Looking along the grid centerline towards the eastern edge of the 400 m grid.

On March 19, the center line of the survey grid was sampled for snow depth and snow surface elevation at 5 m spacing with drill hole measurements every 50 m. Additionally, scans of the first 100 m of the East end of the measurement grid were surveyed using a ground based laser scanner (LiDAR). A seasonal ice mass balance buoy from CRREL (CRREL IMB 2014C) was also deployed near the camp (Figure 6).

On March 20, with the end of the campaign approaching, the ground team had no choice but to begin measurements of snow depth within the main survey grid even though the DTU Twin Otter carrying ASIRAS and the DC-3 carrying the AEM sensor had not yet flown over the site. Snow depth was measured every 5 m over the entire 400 m by 60 m grid; additionally a 40 m by 40 m grid was established around each corner reflector and the snow depth was measured at one meter spacing (Figure 8).

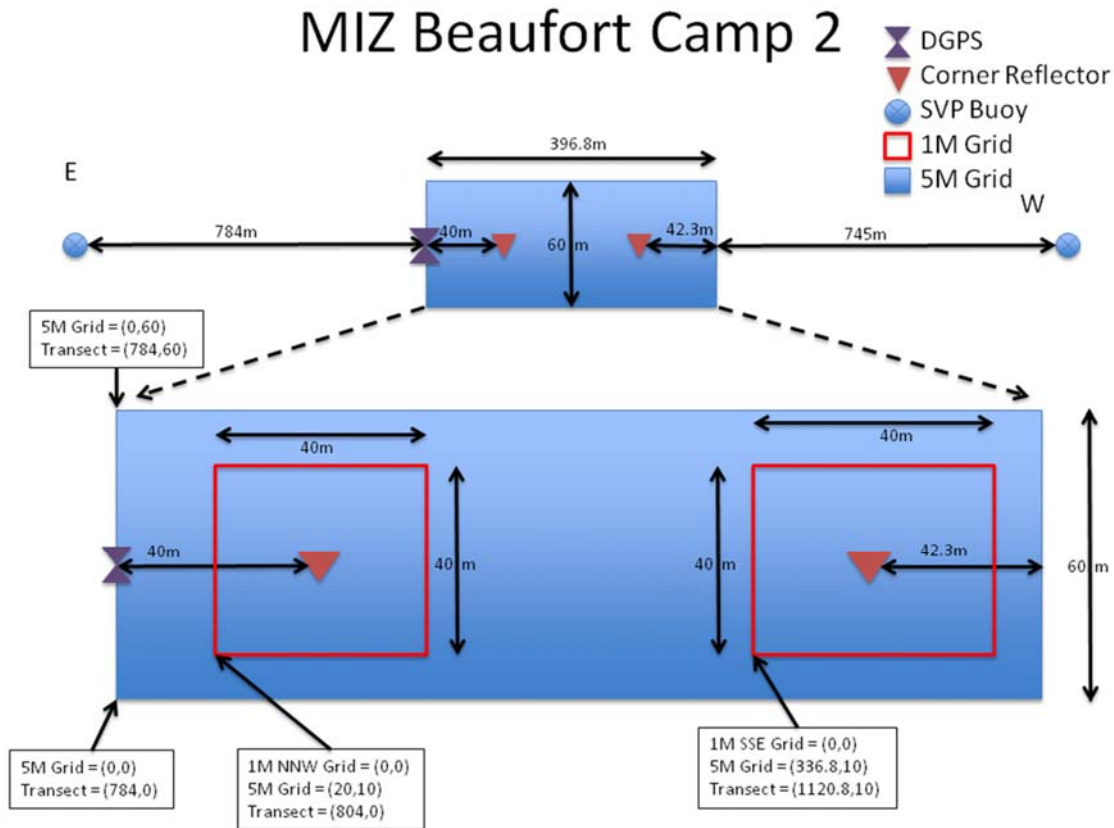


Figure 8: Diagram of Beaufort Sea MIZ/ONR Camp 2 measurement grid and transect

On March 21, 2014, the York University DC-3 AEM system and the ESA/DTU Twin Otter carrying ASIRAS overflow the camp. The DC3 carried out several passes along the transect and to each side of the survey grid. The ESA/DTU Twin Otter conducted several passes over the survey grid. However, during the over flights, visibility was poor with blowing snow, strong winds, and strong ice drift. Conditions worsened between the over flights by the AEM sensor and those of the ESA/DTU Twin Otter. Snow pits to measure snow layer properties were also performed on March 21, 2014 during the DC-3 and ASIRAS over flights.

On March 22 the team moved back to Sachs Harbor for demobilization and preparation for movement to the second camp north of Greenland. Because of the poor visibility over the MIZ/ONR Camp 2 survey grid, the ESA/DTU Twin Otter flew over Camp 2 again on March 23 and the transect and grid centerline were successfully surveyed.

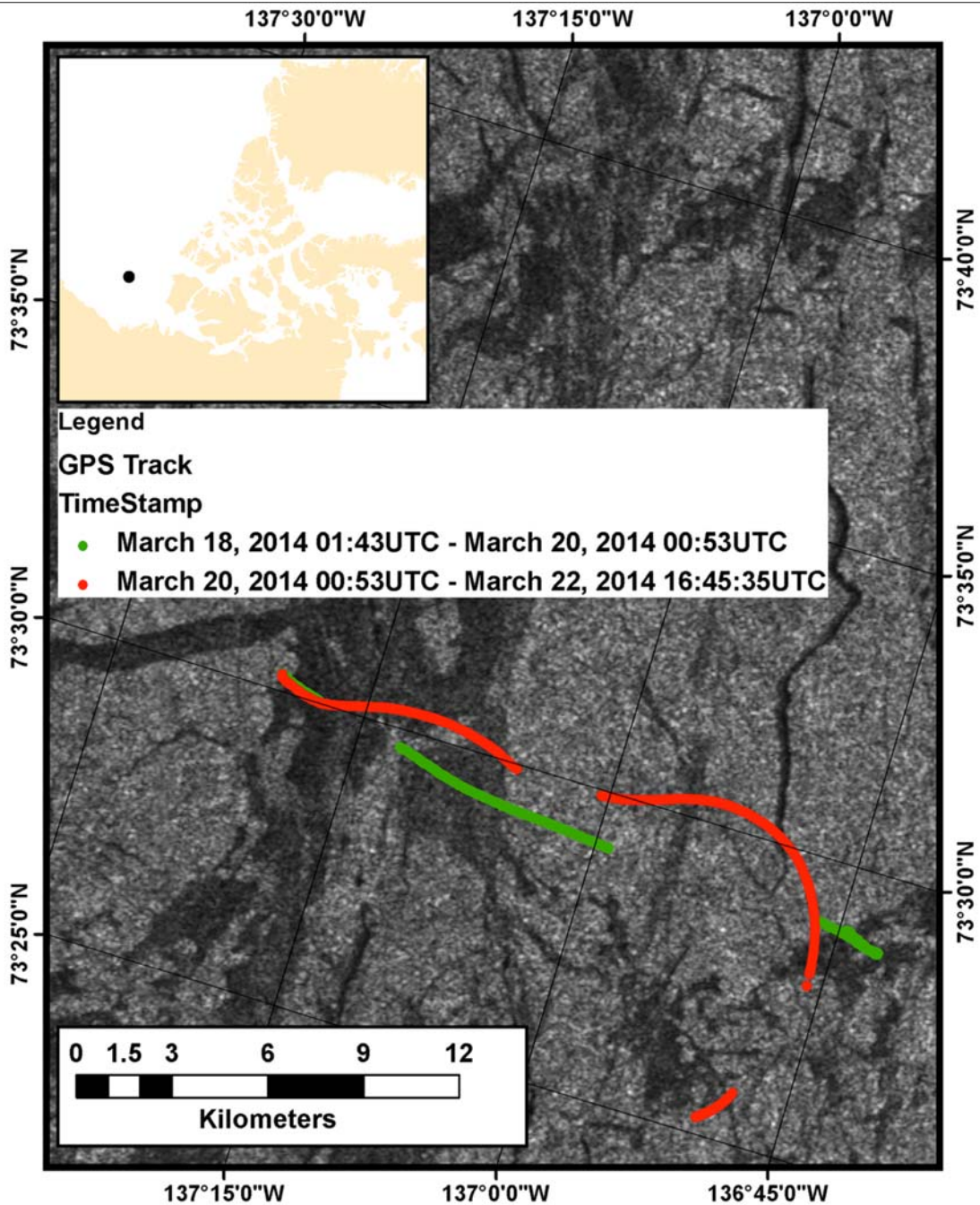


Figure 9: Map of MIZ/ONR Camp 2 drift from the Garmin handheld GPS unit kept in camp. Background image is an uncalibrated RADARSAT-2 HH polarized SAR imaged. RADARSAT-2 Data and Products © MacDONALD, DETTWILER AND ASSOCIATES LTD. (2014) – All Rights Reserved. RADARSAT is an official mark of the Canadian Space Agency.

Transect Data

Basic summary plots of the data collected along the MIZ/ONR Camp 2 survey transect are shown below in Figures Figure 10 and Figure 11; descriptive statistics are provided in Table 1. Figure 10 illustrates the snow and ice freeboard and ice draft profile and presents box plots of ice thickness, snow depth and ice freeboard. Mean snow freeboard determined using the construction laser was 0.43 m and its standard deviation was 0.11 m. Mean bulk snow density along the transect was 0.30 g cm^{-3} but showed a bimodal distribution with peaks at 0.28 to 0.30 g cm^{-3} and 0.36 to 0.38 g cm^{-3} (Figure 11). The agreement between the statistical measures of the drill-hole snow depth, and the drill and laser ice and snow freeboards in Table 1 suggests

that the drill hole data is representative of conditions along the entire transect and that it accurately samples the variability observed over the floe.

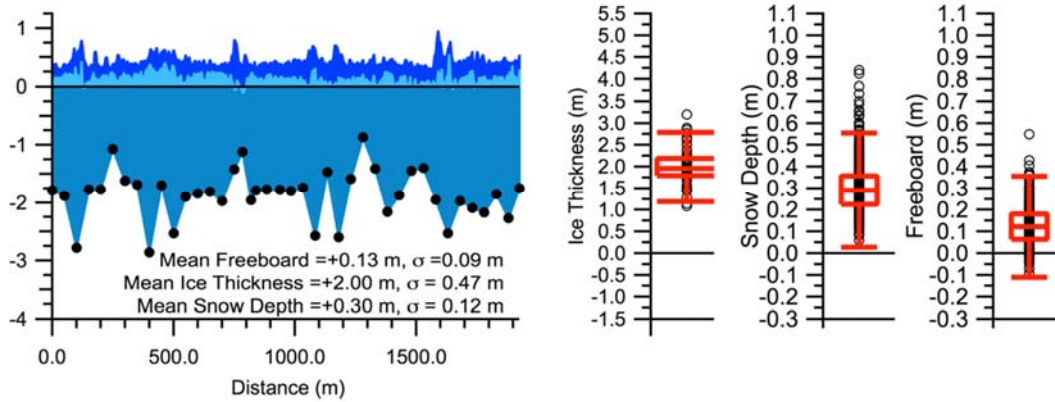


Figure 10: Snow surface elevation (dark blue), ice draft (med blue) and ice freeboard (light blue) profile along the 2km transect conducted at MIZ/ONR Camp 2. Snow surface elevation (snow freeboard) and ice freeboard determined using the MagnaProbe and Leica Rugby 100 construction laser and was measured every 5 m. Ice draft is from manual drill-hole measurements is was measured every 50 m (black circles). Box plots of ice thickness, snow depth, and ice freeboard are also presented showing the median, quartiles and outer fences. Note that the measurements are not continuous but are connected by straight lines (i.e. black circles denoting drill-hole ice draft measurements).

SNOW DENSITY

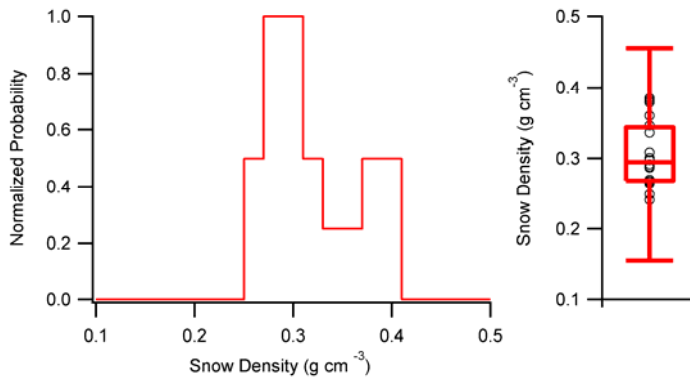


Figure 11: MIZ/ONR Camp 2 distribution of bulk snow density measured using the Federal Snow Sampler. Measurements were taken along the transect.

Table 1: Descriptive statistics of ice and snow properties measured along the 2 km transect at MIZ/ONR Camp 2. Modal values are determined using 0.05 m bins for drill, laser, and MagnaProbe data, except for ice thickness and draft, which used 0.10 m bins; 0.02 gcm⁻³ bins were used for snow density. Snow density values computed from bulk snow density measurements only and besides the mode are reported to nearest 0.01 g cm⁻³.

Parameter	Mean	Std. Dev	Mode	Min	Max	N
Ice Draft (Drill) (m)	1.86	0.44	1.8	0.87	2.86	41
Ice Freeboard (Laser) (m)	0.13	0.09	0.15	-0.09	0.55	387
Ice Freeboard (Drill) (m)	0.14	0.09	0.10	-0.02	0.34	41
Snow Freeboard (Laser) (m)	0.43	0.11	0.4	0.27	0.96	387
Snow Freeboard (Drill) (m)	0.44	0.12	0.45	0.24	0.82	41
Snow Depth (Magna Probe) (m)	0.30	0.12	0.3	0.06	0.84	387
Snow Depth (Drill) (m)	0.30	0.13	0.3	0.16	0.80	41
Ice Thickness (Drill) (m)	2.00	0.47	2.00	1.09	3.2	41
Snow Density (gcm ⁻³)	0.31	0.05	0.29	0.24	0.39	18

Grid Data

A 400 m by 60 m grid was sampled at 5 m spacing and a 40 m by 40 m grid sampled with 1 m spacing was established around each corner reflector. Figures 12 and 13 present the snow depth grid data for MIZ/ONR Camp 2. Figure 12 represents snow depth with a common color scale for all three grids to facilitate comparisons between the different grids. The x and y axis of each grid are proportionally scaled by their length. Figure 13 represents the snow depth using a separate color scale for each individual grid in order to best illustrate the internal variability within a snow grid. In Figures 12 and 13, the plots of the 5 m grid data shows the snow drift of a ridge along the eastern edge and a drift extending eastwards from the western edge. In Figure 13 we can also see that the two corner reflectors were situated in different snow depth conditions with the western reflector being surrounded by generally deeper snow.

Figure 14 presents histograms of snow depth for the 2 km transect, the 5 m grid and the two 1 m grids. Good agreement is observed between the transect and 5 m grid suggesting that the grid was representative of conditions found along the transect. The two 1 m grids show different distributions reflecting the different conditions at each corner reflector with the westwards reflector being influenced by the snow drift extending eastwards from the western edge of the 5 m grid.

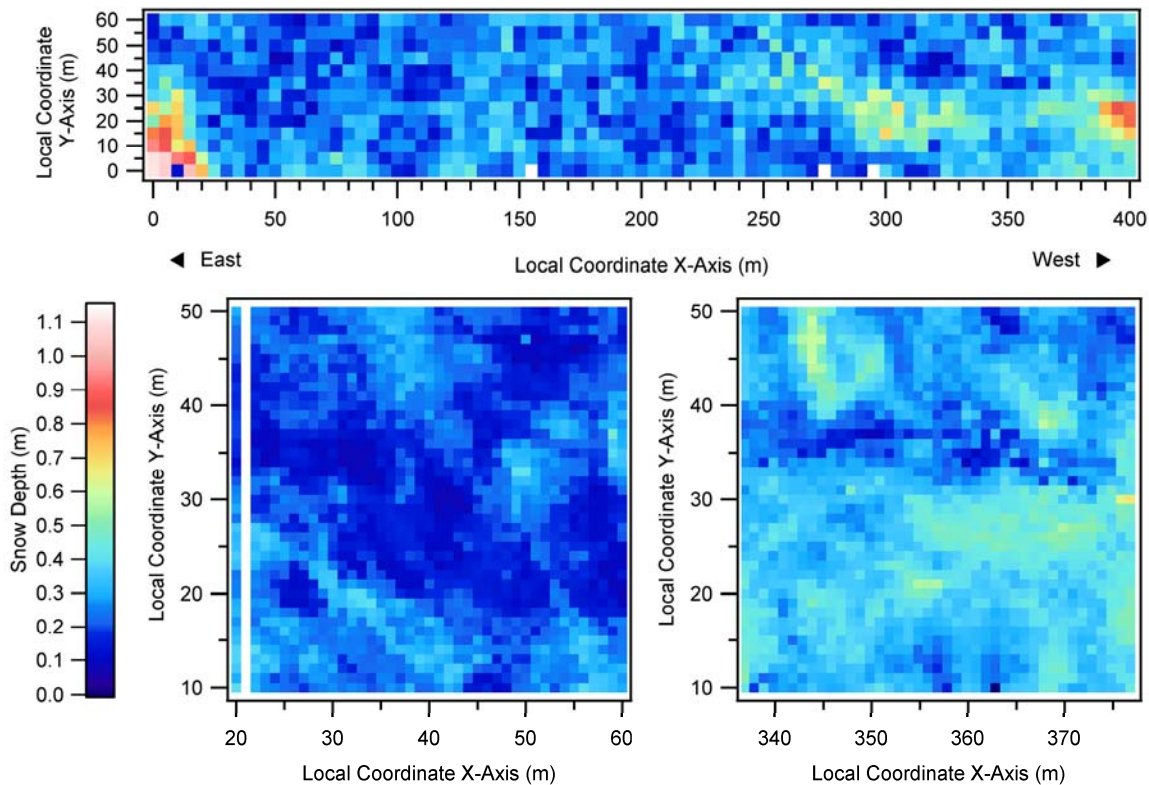


Figure 12:(Top): Snow depths for the 5 m spaced 400 m by 60 m measurement grid. (Bottom left): Snow depths for the 1 m spaced grid centered on the east radar corner reflector. The line of white pixels at X=21 in the East 1 m grid indicates missing data. (Bottom Right): Snow depths for the 1 m spaced grid centered on the west corner reflector. Note all grids are represented by the same color scale (from 0 m to 1.15 m) in order to better visualize the inter-grid variability.

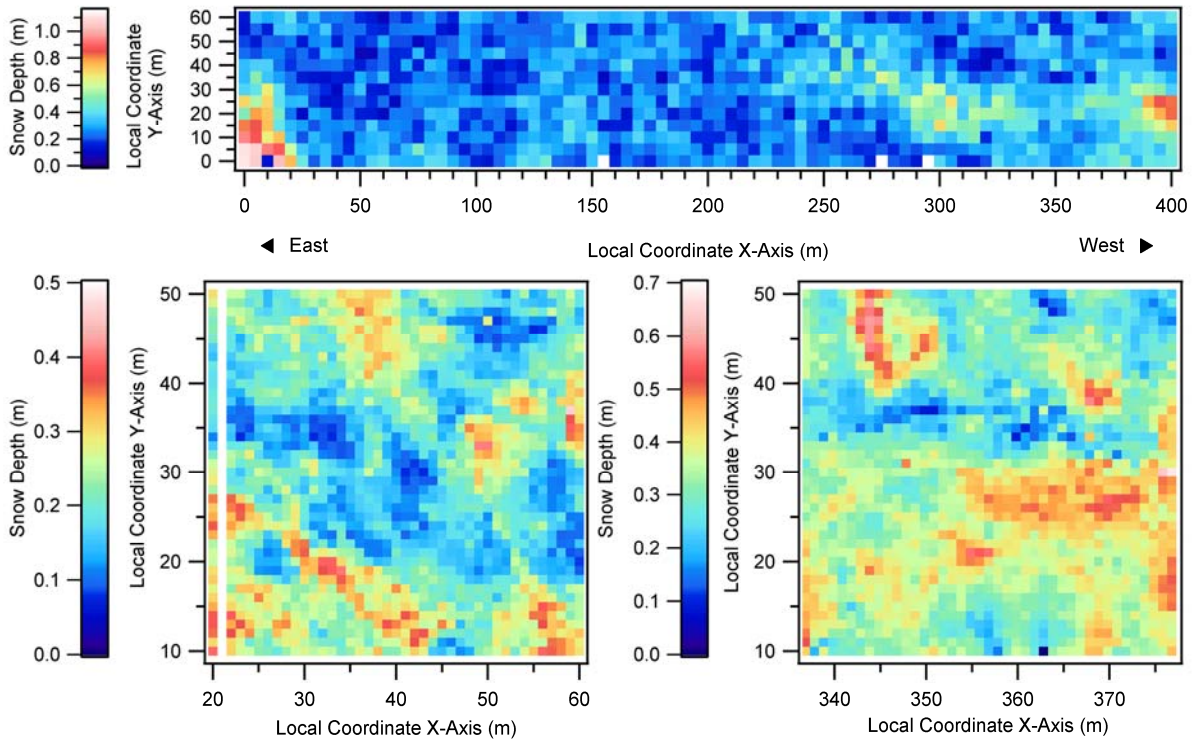


Figure 13: (Top): Snow depths for the 5 m spaced 400 m by 60 m measurement grid. (Bottom left): Snow depths for the 1 m spaced grid centered on the east radar corner reflector. The line of white pixels at X=21 in the East 1 m grid indicates missing data. (Bottom Right): Snow depths for the 1 m spaced grid centered on the west corner reflector. Note all grids are represented by an individual color scale in order to better visualize the intra-grid variability.

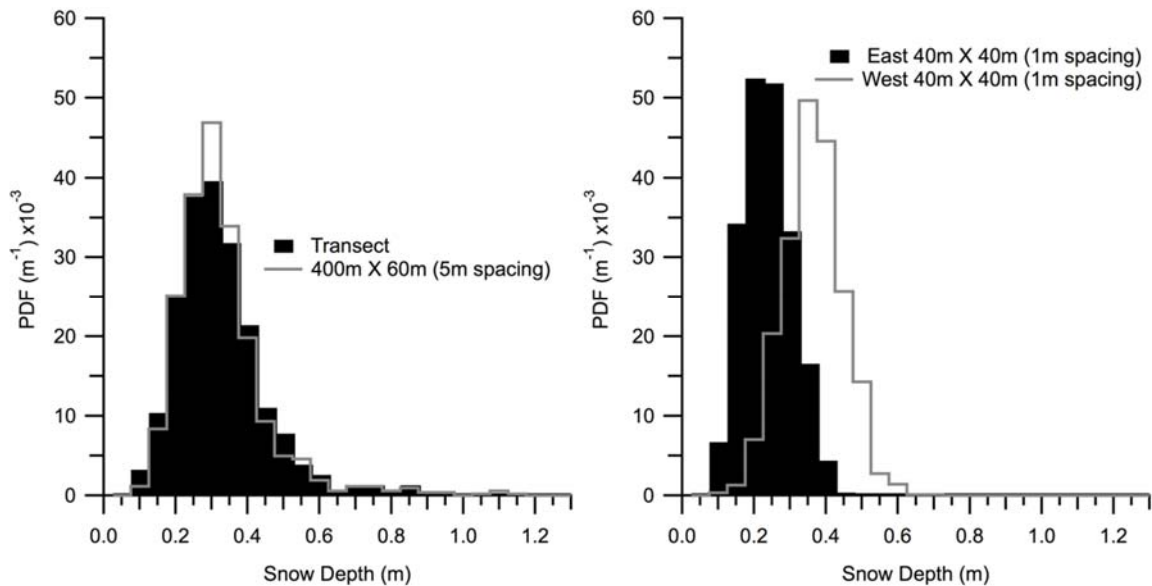


Figure 14: (Left): Distributions of snow depth for the 2 km transect conducted at MIZ/ONR Camp 2 and the 400 m by 60 m grid (5 m spacing). (Right): Distributions of snow depth for the 1 m spaced grids centered around each corner reflector on the right.

Auxiliary Site: MIZ/ONR Camp 3

Site and Measurement Description and Timeline

On March 16, the CryoVEx team deployed to the ONR/MIZ Camp 3. Measurements of snow depth, laser snow surface elevation, ice thickness/freeboard/draft and snow density were performed along two transects. Measurements of snow depth and snow surface elevation were performed at 1 m spacing with the MagnaProbe and Leica laser. The first transect was 480 m long and extended out from the end of the camp runway over very smooth first year ice with a thin snow cover. Drill-hole measurements of ice thickness, freeboard, draft and snow freeboard were taken at 120 m intervals. The second transect was nearly perpendicular to the first, but located on the far side of the camp, and included both multiyear ice and first year ice. Transect 2 was 500 m in length, and crossed several large ridges. Measurements of snow depth and snow surface elevation were performed at 1 m spacing with the MagnaProbe and Leica laser. Drill-hole measurements of ice thickness, freeboard, draft and snow freeboard were taken at 100 m intervals. Bulk snow density was also measured along Transect 2 at approximately 100m intervals (some measurements were offset to sample undisturbed snow). Observations of snow layer properties were made in a snow pit at X = 100 m.

No EM-31 measurements of ice thickness were performed along either transects as both EM31 devices were inoperable. The measurements of bulk snow density and snow pits were performed in the morning of March 17, 2014 (local time). The CryoVEx ground team departed MIZ Camp 3 around noon (local time) on March 17, 2014.

MIZ Beaufort Camp 3

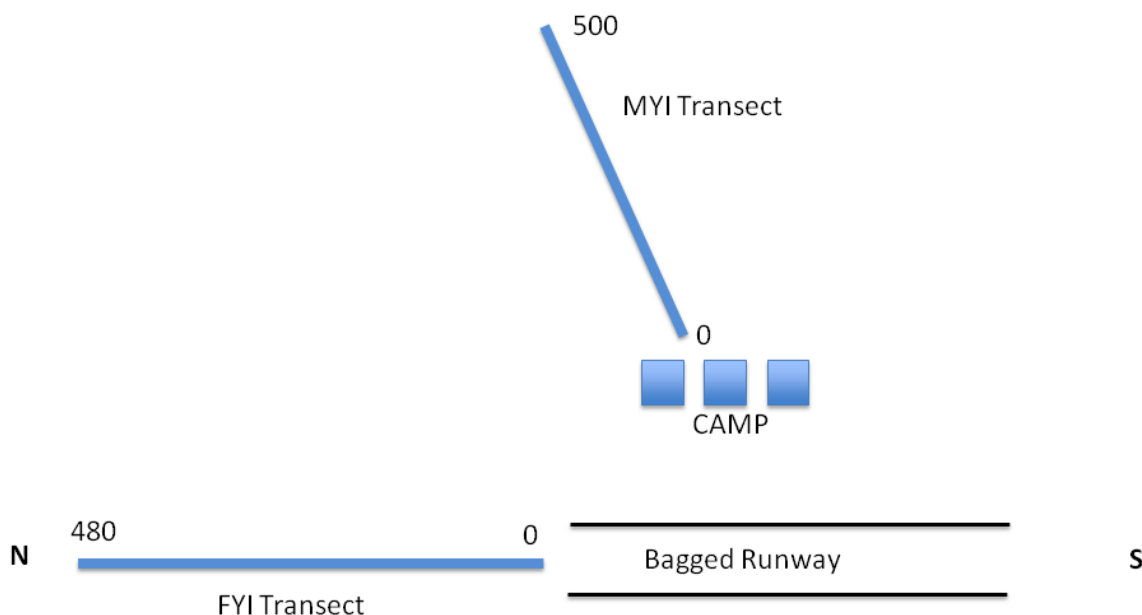


Figure 15: Overview schematic of the MIZ/ONR Camp 3 auxiliary site.

Transect Data

Basic summary plots of the measurements performed along Transect 1 (FYI) and Transect 2 (MYI) at MIZ/ONR Camp 3 are provided in Figures 16, 17, and 18. Descriptive statistics for Transects 1 and 2 can be found in Table 2 and Table 3, respectively. Figure 16 presents the profile plot of snow and ice freeboard and ice draft along Transect 1 along with box plots of the ice thickness, freeboard, and snow depth. Transect 1 was entirely over very smooth FYI. Figure 17 presents the same profile and boxplot data for Transect 2. Transect 2 was mainly over MYI but appeared to move onto FYI towards the end. Transect 2 also includes several large ridges. Note that the ice draft in the profile plots is simply connected from drill hole to drill hole and does not actually denote a smooth transition, i.e. one can generally expect much deeper drafts near ridges. The roughness of the ice bottom is under-sampled by the coarse point spacing.

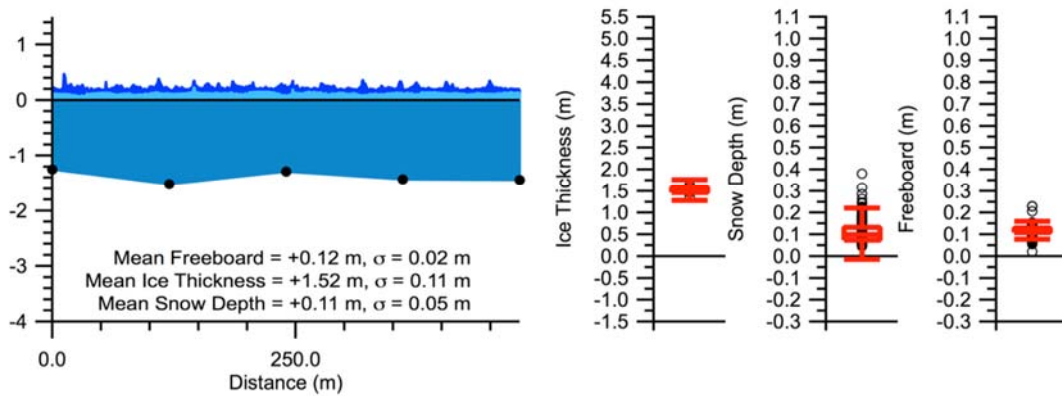


Figure 16: Profile plot of snow and ice freeboard and ice draft along MIZ/ONR Camp 3 Auxiliary Site Transect 1 (FYI). Snow surface elevation (snow freeboard; dark blue) and ice freeboard (light blue) determined using the MagnaProbe and Leica Rugby 100 construction laser. Ice draft (medium blue fill and black circles) is from manual drill-hole measurements. Box plots of ice thickness, snow depth, and ice freeboard are also presented.

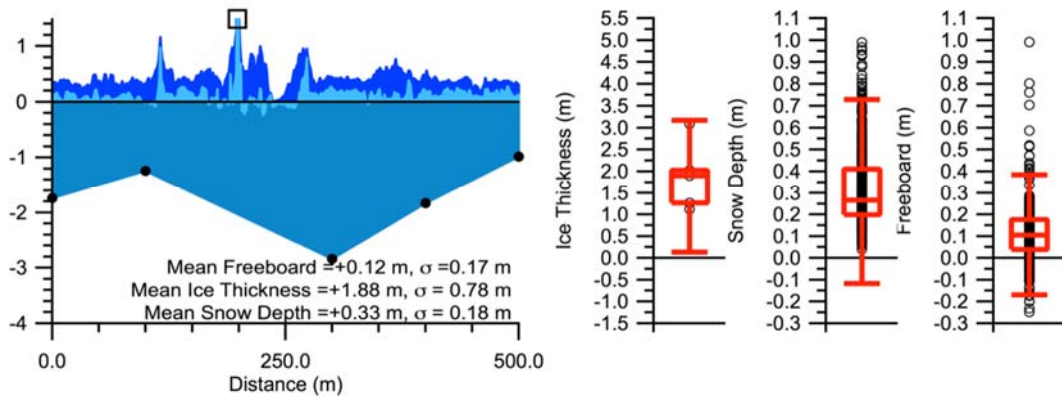


Figure 17: Profile plot of snow and ice freeboard and ice draft along MIZ/ONR Camp 3 Auxiliary Site Transect 2 (MYI). Snow surface elevation (snow freeboard; dark blue) and ice freeboard (light blue) determined using the MagnaProbe and Leica Rugby 100 construction laser. Ice draft (medium blue fill and black circles) is from manual drill-hole measurements. Boxplots of ice thickness, snow depth, and ice freeboard are also presented. The ridge peak marked with a square box at Distance = ~200.0 m has a snow freeboard of 2.26 m and an ice freeboard of 2.05 m.

SNOW DEPTH

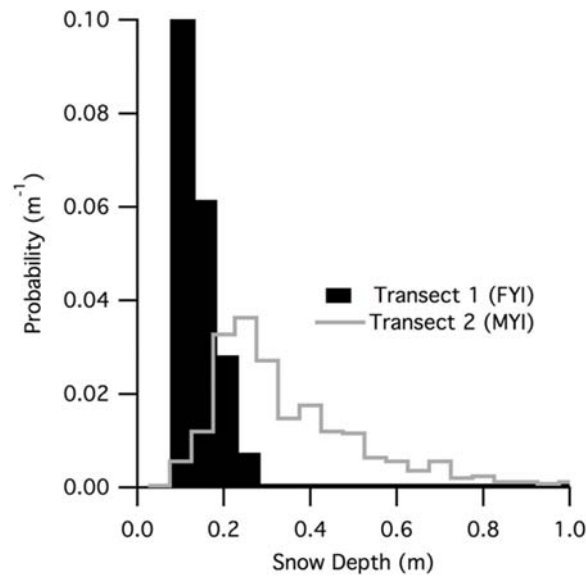


Figure 18: Snow depth distributions for the two transects performed at MIZ/ONR Camp 3 over Transect 1 (FYI) and Transect 2 (MYI).

Table 2: Descriptive statistics of snow and ice properties measured at MIZ/ONR Camp 3 Transect 1 (FYI). Modal values of drill holes measurements were not calculated because only N=5 drill hole measurements were acquired along Transect 1. Modal values are determined using 0.05 m bins for drill, laser, and MagnaProbe data. Snow Density was not measured.

Parameter	Mean	Std. Dev.	Mode	Min	Max	N
Ice Draft (Drill) (m)	1.39	0.11	N/A	1.25	1.52	5
Ice Freeboard (Laser) (m)	0.12	0.02	0.15	0.02	0.22	481
Ice Freeboard (Drill) (m)	0.13	0.02	N/A	0.11	0.17	5
Snow Freeboard (Laser) (m)	0.22	0.04	0.25	0.14	0.49	481
Snow Freeboard (Drill) (m)	0.23	0.06	N/A	0.18	0.33	5
Snow Depth (Magna Probe) (m)	0.11	0.05	0.10	0.05	0.38	481
Snow Depth (Drill) (m)	0.10	0.05	N/A	0.05	0.16	5
Ice Thickness (Drill) (m)	1.52	0.11	N/A	1.36	1.64	5
Snow Density (gcm ⁻³)	N/A	N/A	N/A	N/A	N/A	N/A

Table 3: Descriptive statistics of snow and ice properties measured at MIZ/ONR Camp 3 Transect 2 (MYI). Modal values of drill holes measurements were not calculated because only N=5 drill hole measurements were acquired along Transect 1. Snow density values are calculated from bulk snow density measurements only and reported to nearest 0.01 g cm⁻³. Modal values are determined using 0.05 m bins for drill, laser, and MagnaProbe data, and 0.02 gcm⁻³ bins for snow density.

Parameter	Mean	Std. Dev.	Mode	Min	Max	N
Ice Draft (Drill) (m)	1.72	0.71	N/A	0.98	2.84	5
Ice Freeboard (Laser) (m)	0.12	0.17	0.10, 0.20	-0.25	2.05	501
Ice Freeboard (Drill) (m)	0.16	0.08	N/A	0.03	0.25	5
Snow Freeboard (Laser) (m)	0.44	0.21	0.4	0	2.26	501
Snow Freeboard (Drill) (m)	0.37	0.06	N/A	0.31	0.45	5
Snow Depth (Magna Probe) (m)	0.33	0.18	0.25	0.04	0.99	501
Snow Depth (Drill) (m)	0.21	0.06	N/A	0.16	0.32	5
Ice Thickness (Drill) (m)	1.88	0.78	N/A	1.12	3.09	5
Snow Density (gcm ⁻³)	0.27	0.02	N/A	0.24	0.30	6

Nord

Nord Camp

Site Description and Timeline

The second CryoVEx 2014 camp was located in the Arctic Ocean, north of Cape Morris Jessup, Greenland at approximately 84N, 40W. The CryoVEx team from the MIZ camp met up with the two camp managers, Marc Cornelissen and Petter Nyquist, the DTU Twin Otter team led by Rene Forsberg, and ESA's CryoSat manager Mark Drinkwater on March 23 in Resolute Bay for final planning and logistics coordination. On March 24 the AEM and CryoVEx ground team transferred to Qaanaaq in the DC-3, Greenland to pick up three team members from the University College London. Weather delays departing Resolute Bay on the morning of March 24 resulted in an unexpected overnight stay in Qaanaaq. On March 25, the CryoVEx team departed for Station Nord, Greenland. Upon landing the ground team and equipment unloaded and the AEM team departed with the DC-3 for CFS Alert, NU, Canada. It was originally planned that the CryoVEx ground team KBAL Twin Otter would arrive in Station Nord on March 24 but it was delayed by repairs and weather and only arrived on March 27.

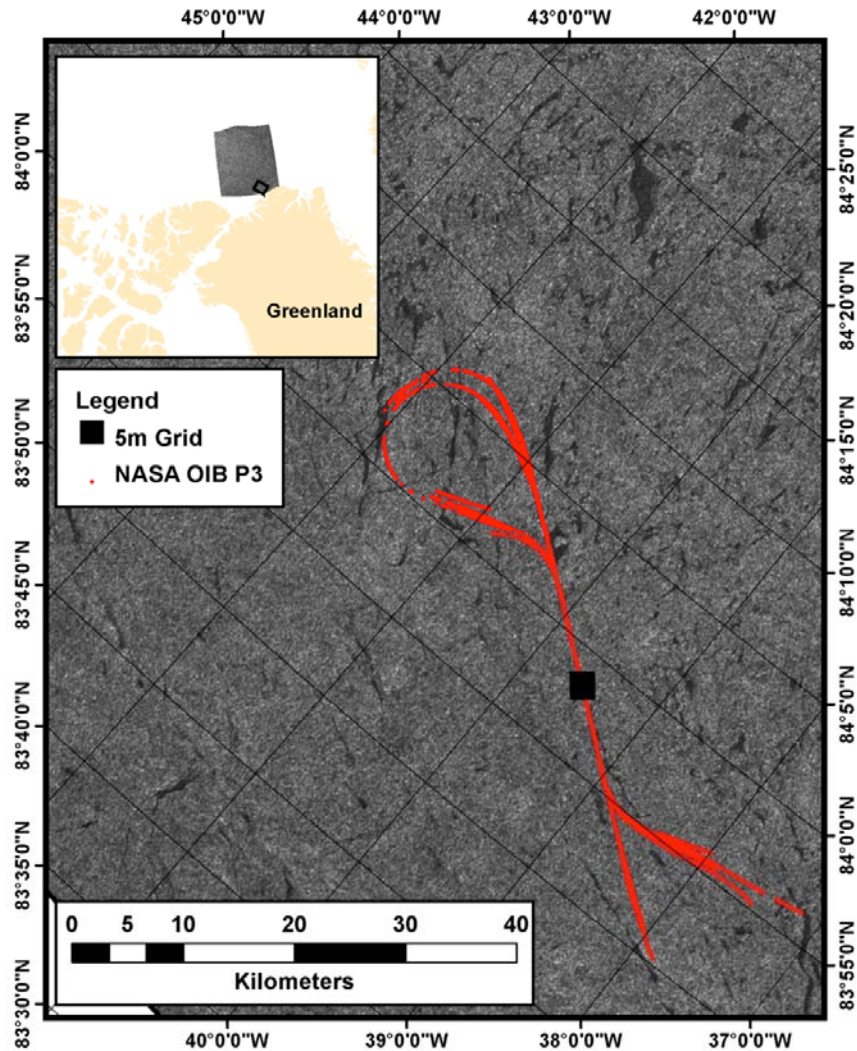


Figure 19: Location of the NORD Camp north of Greenland showing the NASA OIB flight passes and the location of the camp. Background image is a un-calibrated RadarSat-2 HH polarizaed SAR image. RADARSAT-2 Data and Products © MacDONALD, DETTWILER AND ASSOCIATES LTD. (2014) – All Rights Reserved. RADARSAT is an official mark of the Canadian Space Agency.

On March 28, the two camp managers and two members of the CryoVEx ground team were able to deploy the main camp late in the day. The main camp was erected.



Figure 20: View of the NORD Camp 400 m grid centerline looking from the NNW corner reflector towards the SSE corner reflector.

The remaining team members arrived on site in the late morning (local time) of March 29. The Nord Camp site was located on a large MYI ice floe bounded by large ridges. Surface roughness at the site was greater than at either of the MIZ/ONR camps. Temperatures were cold, well below -20°C (est.) for the duration of the Nord campaign. Ice drift was minimal over the duration of the study (see Figure 21).

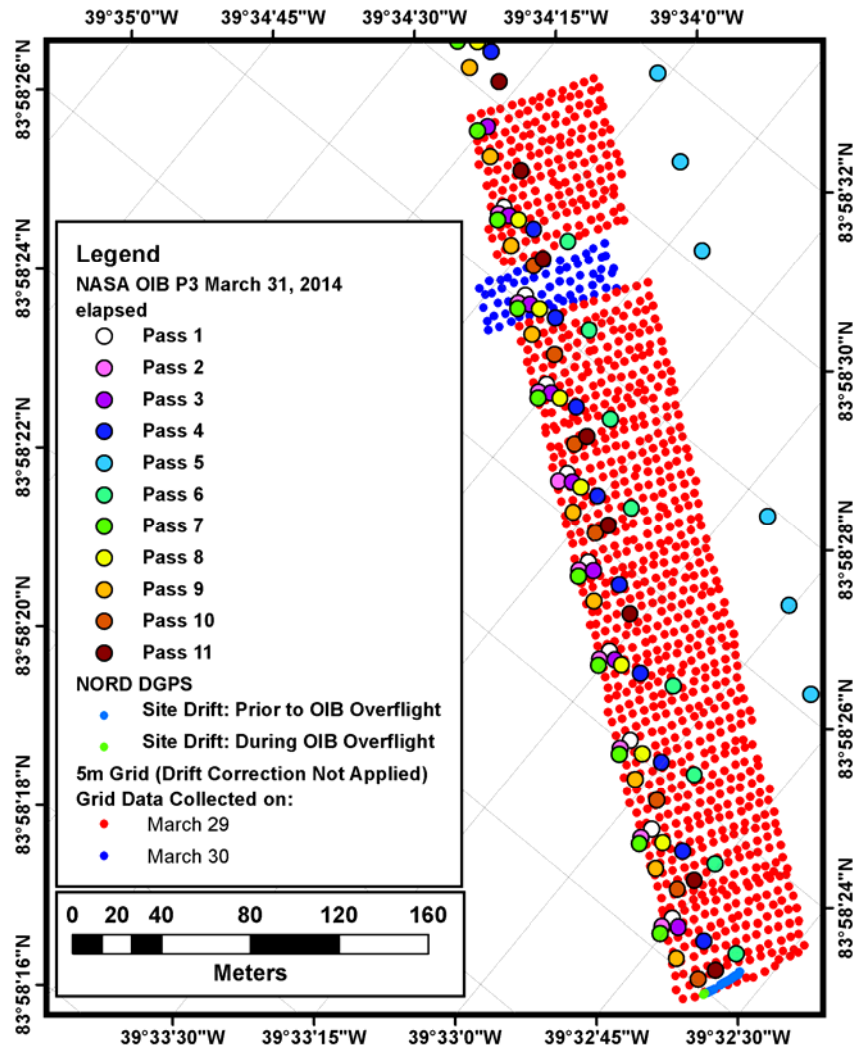


Figure 21: Map showing NASA OIB overpasses, GPS drift from time of site setup to OIB measurements (GPS track near bottom right), and the non-drift correct locations of the snow depths measured in the 5 m grid (red/blue).

The main 400 m by 60 m survey grid and transect were established (see Figures Figure 22 and Figure 23). The majority of the grid was measured on March 29 (see Figure 21). Snow depth was also measured over a 50 m by 60 m grid with 1 m spacing around the SSE corner reflector (from X = 350 to 400 of the 5 m survey grid). The snow depth was then measured along the 5 m spaced grid between X = 95 to X = 350 and X = 0 to X = 45 of the 5 m survey grid. Finally, snow depth was measured over part of the 40 m by 60 m by 1 m snow grid around the NNW corner reflector, from X = 50 to X = 65 of the 5 m survey grid. The DC-3 towing the AEM sensor and the Twin Otter carrying ASIRAS flew over the site in the afternoon of March 29. Measurements of Ku band radar penetration were made using the UCL ground penetrating radar (GPR) unit at various points in the grid. These measurements began on March 29 and concluded on April 1.

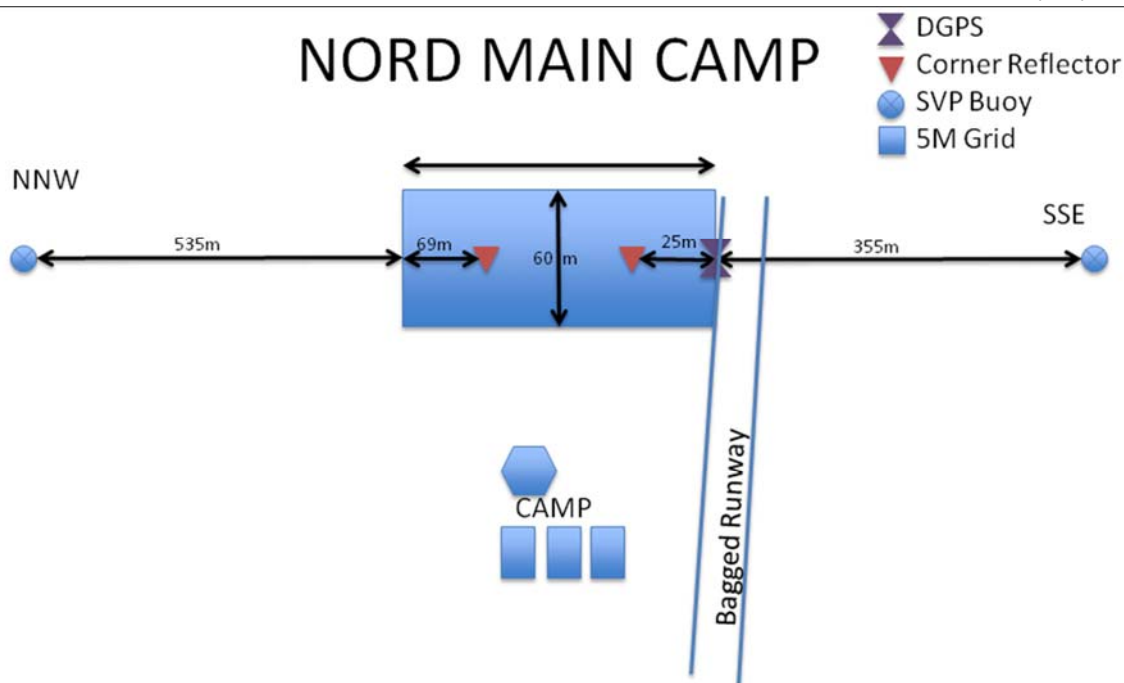


Figure 22: Overview diagram of Nord Camp site.

On March 30, four members of the CryoVEx ground team deployed to the Nord NDaysite, an auxiliary site. Upon returning to the main camp towards the end of the afternoon, the remaining snow depth measurements were collected in the 5m and 1 m snow depth grid around the NNW corner reflector, from X=65 m to X=90 m of the 5 m grid.

On March 31, snow depth, ice thickness, snow density, and snow surface elevation measurements were performed along the 1.3 km long transect. The snow depth, and snow surface elevation measurements were performed at 5 m spacing, ice thickness at 50 m spacing and the snow density at 100 m spacing. The NASA OIB P3 flew 11 passes over the site near the completion of the NNW end transect measurements. A MetOcean/AWI snow depth buoy was installed in the main snow depth grid at approximately X=295, Y=40. Snow pits were performed at the 100 m points of the snow depth grid and near the corner reflectors. Measurements of total ice + snow thickness were also conducted using the EMP-400 operated at 5, 10 and 15 KHz at a sampling rate of 2Hz. EM measurements were interpolated to a consistent spacing to remove variations in walking speed and to match the snow depth and laser measurements.

In addition to the regular grid and transect measurements, measurements of snow and ice characteristics and their influence on radar penetration were performed by the team from UCL using a Ground Penetrating Radar (GPR). The UCL team took GPR measurements nested in both of the snow depth grids around the corner reflectors to investigate the radar scattering surface. GPR measurements were also performed along the centerline between the two 1m snow depth grids. The aim was to choose locations with visually differing surface topography, but where the radar could be rested on a flat surface, so that the GPR was not firing at an angle. For each GPR measurement:

- R1. One GPR shot was taken on the undisturbed surface
- R2. One GPR shot was taken shot with a 60 x 40 cm metal plate placed on the snow surface.
- R3. A pit the size of the metal plate was dug, starting approximately 60 cm from the GPR nadir, and taking care not to disturb the surrounding snow

- R4.** Using the pit for access, the metal plate was pushed laterally into the snow pack, so that it sat at the snow-ice interface at the antenna nadir. Care was taken not to disturb the above snow layer.
- R5.** One GPR shot was taken with the metal plate at the snow-ice interface. Using the metal plate at the snow and ice surface (with snow still on top) allows us to measure two fixed reference points a known distance apart, and therefore the propagation speed of light through the snow pack.
- R6.** We then dug a small pit, around 30 cm square, for snow pit measurements.
- R7.** After the snow pit measurements we dug a larger pit, at least a meter square, ensuring that the ice surface was completely exposed. Then one GPR shot was taken of the exposed ice surface.
- R8.** A final GPR shot was taken with the metal plate on the ice surface

Snow pits were performed at the locations of GPR measurements within the grids but not along the transect. Measurements of snow depth, density, temperature, grain size, and layering.

Table 4: Location of GPR shots within the 400m by 60m snow grid at the Nord main camp.

Name	X (400m by 60m grid)	Y (400m by 60m grid)
CR1	75	25
CR2	75	51
CR3	71	30
CR4	358	3
CR5	386	390
CR6	396	30
CR7	374	30
CR8	374	30
T1	210	30
T2	220	30
T3	230	30
T4	240	30
T5	250	30
T6	260	30
T7	270	30
T8	280	30
T9	290	30

On April 1, site demobilization began and a CRREL IMB was deployed in the survey grid. The survey grid and transect markers were removed and much of camp was packed for transport. Four members of the ground team departed late in the day after the weather finally cleared. Four team members were left in the camp for the final night. On April 2, the remaining four team members arrived back at Station Nord and were given roughly one hour before hopping onto the DC-3 for the flight back to Resolute Bay, NU.

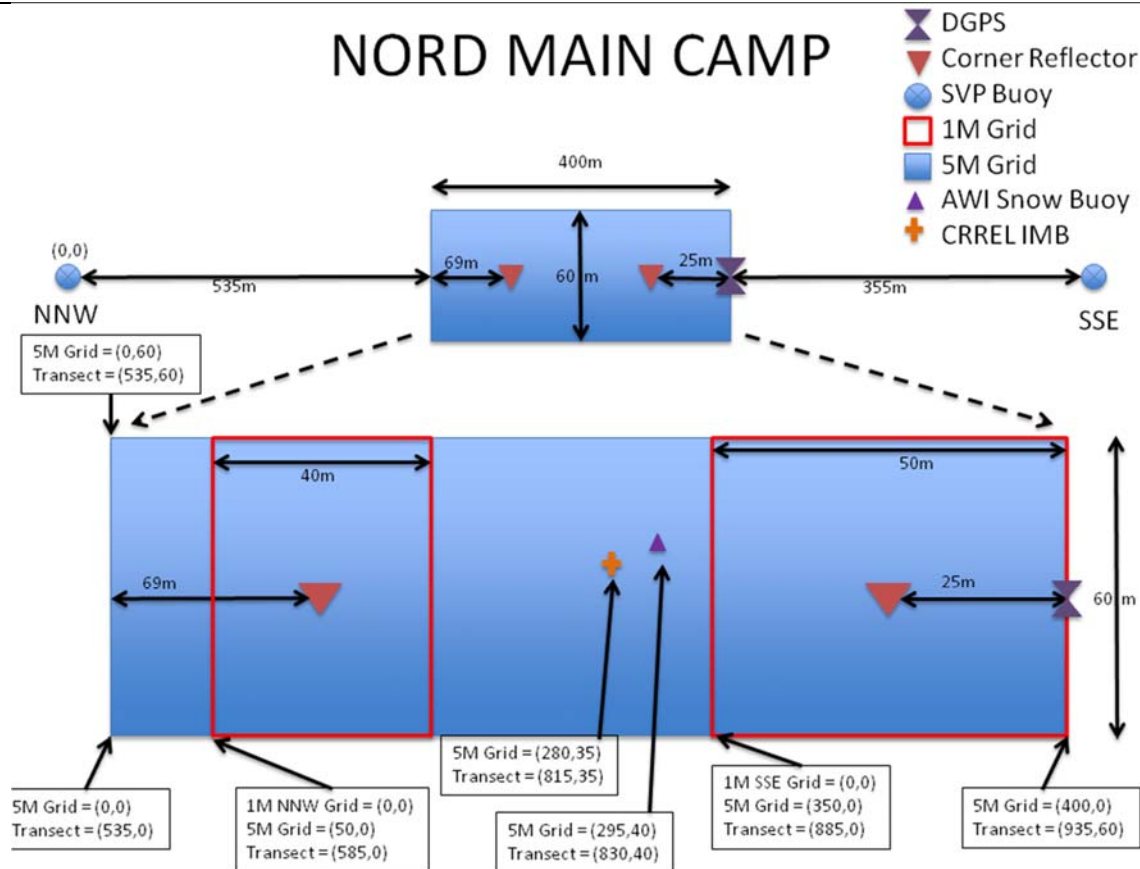


Figure 23: Detailed diagram of Nord Camp measurement transect and grid.

Transect Data

Basic summary plots of the data collected along the Nord Camp transect are presented in FiguresFigure 24 andFigure 25. Descriptive statistics of the snow and ice properties are provided in Table 5.

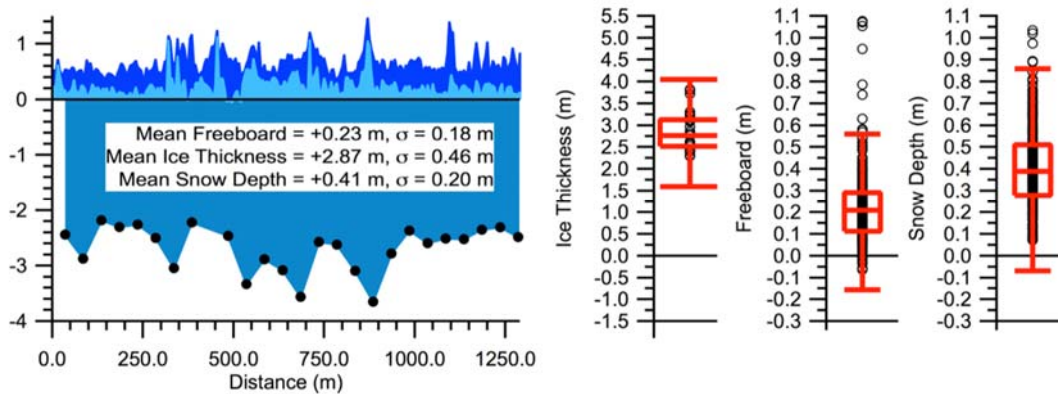


Figure 24: Snow surface elevation, ice draft and ice freeboard profile along the 1.3 km transect conducted at Nord Camp. Snow surface elevation (snow freeboard; dark blue) and ice freeboard (light blue) determined using the MagnaProbe and Leica Rugby 100 construction laser and was measured every 5 m. Ice draft (medium blue and black circles) is from manual drill-hole measurements is was measured every 50 m. Box plots of ice thickness, snow depth, and ice freeboard are also presented showing the median, quartiles and outer fences. Note that the measurements are not continuous but are connected by straight lines.

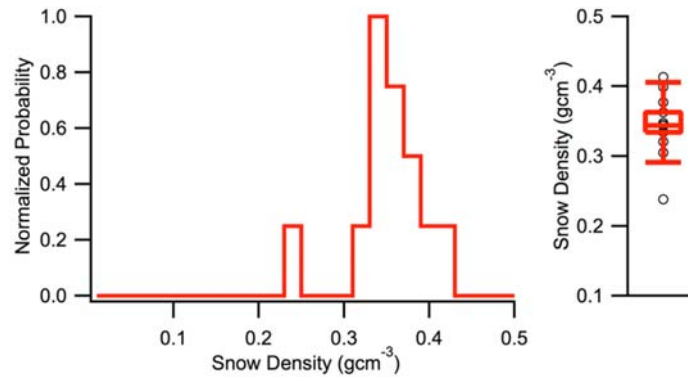


Figure 25: Distribution of bulk snow density measured using the Federal Snow Sampler along the transect at the Nord Camp site.

Table 5: Descriptive statistics of snow and properties measured along the transect at Nord Camp. Modal values are determined using 0.05 m bins for drill, laser, and MagnaProbe data, and 0.10 m bins for ice thickness and draft. The modal value of EM ice thickness was also determined used 0.10 m bins, and 0.02 gcm⁻³ bins were used for snow density. Snow density values are taken from the bulk snow density measurements made along the transect.

Parameter	Mean	Std. Dev.	Mode	Min	Max	N
Ice Draft (Drill) (m)	2.68	0.41	2.60	2.18	3.65	25
Ice Freeboard (Laser) (m)	0.23	0.18	0.25	-0.06	1.14	259
Ice Freeboard (Drill) (m)	0.19	0.12	0.25	-0.04	0.49	25
Snow Freeboard (Laser) (m)	0.65	0.20	0.55	0.35	1.47	259
Snow Freeboard (Drill) (m)	0.60	0.15	0.55	0.39	1.07	25
Snow Depth (Magna Probe) (m)	0.41	0.20	0.40	0.07	1.22	259
Snow Depth (Drill) (m)	0.41	0.19	0.35	0.07	0.98	25
Ice Thickness (Drill) (m)	2.87	0.46	2.60	2.30	3.82	25
Ice Thickness (EM) (m)	3.06	0.55	2.80	1.92	4.82	161
Snow Density (gcm ⁻³)	0.34	0.04	0.34	0.24	0.41	13

Grid Data

A 400 m by 60 m grid was sampled at 5 m spacing. A 40 m by 60 m grid was established around the NNW corner reflector and a 50 m by 60 m grid established around the SSE corner reflector. As the individual grids had very similar ranges in snow depth, Figure 26 shows the three grids using the same color scale. Figure 26 allows for comparison of the conditions between the different grids and the internal variability observed in each grid. The grid appears to contain several hummocks and melt ponds with deeper snow (yellows, reds and white colors) indicating filled-in melt ponds and shallow snow depths (blues, greens) representing hummocks. Figure 27 presents histograms of the snow depths measured along the transect and in the grids and highlights the similarity in the distributions of the grid and transect indicating the grid is representative of the broader conditions observed along the transect. The two 1 m grids show different distributions with the SSE grid showing a broader distribution and greater mean and modal snow depth.

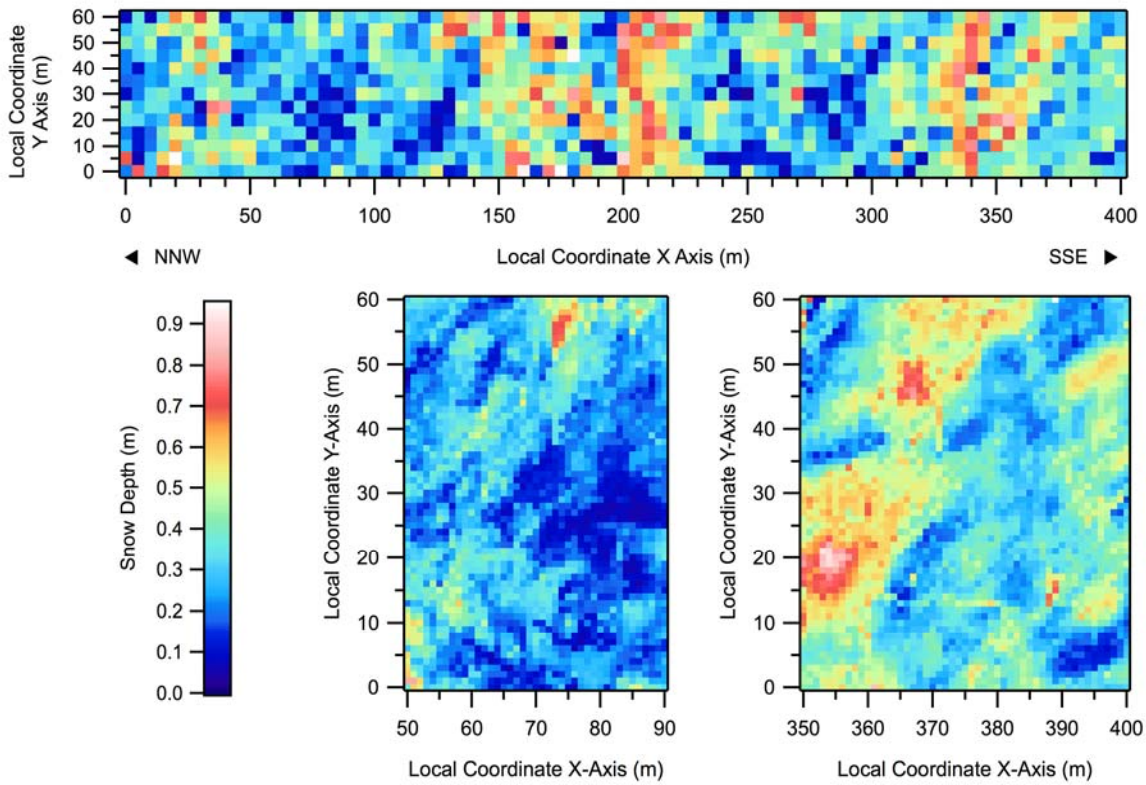


Figure 26: Snow depth survey measurements performed at the Station Nord Main camp along the 400 m by 60 m grid with 5 m spacing (top), and a 40 m by 60 m grid with 1 m spacing centered around the NNW corner reflector (bottom left), and a 50 m by 60 m grid with 1 m spacing centered around the SSE corner reflector (bottom right). All grids are represented using the same color scale.

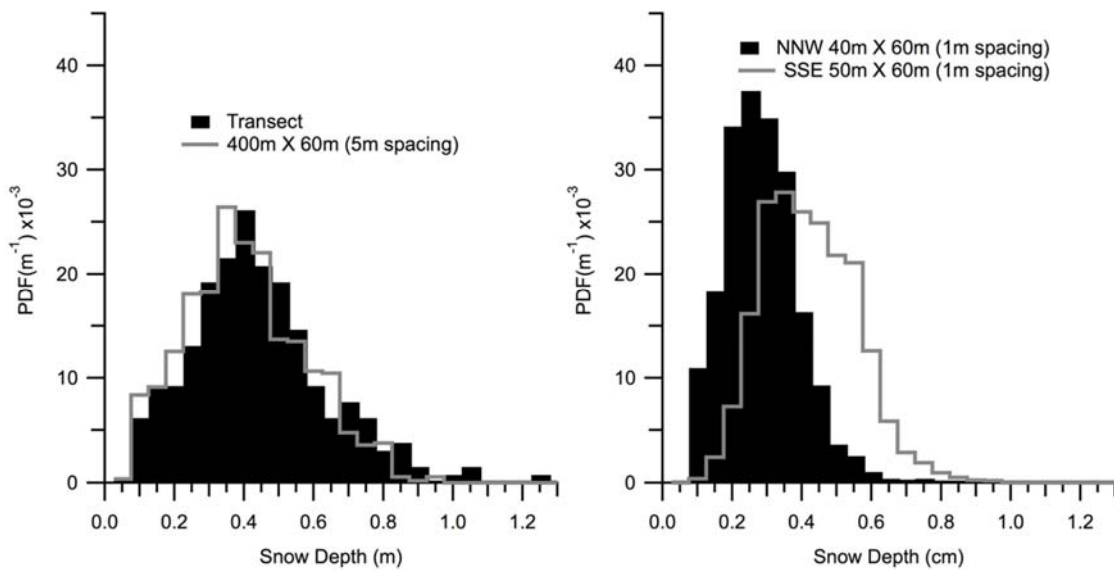


Figure 27: Distributions of snow depth for the 1.3 km transect conducted at the Nord Main Camp and the 400 m by 60 m grid (5 m spacing) on the left, and the two 1 m spaced grids centered around each corner reflector on the right.

Auxiliary Site: Nord NDaysite

Site Description and Timeline

On March 30, four members of the CryoVEx ground team conducted snow depth and ice thickness measurements at a more northerly auxiliary site (Nord NDaysite) at 86N, 35W. Snow depth was measured approximately every 5 m and ice thickness approximately every 50 meters over a 500 m long transect passing mainly over second- or multiyear ice; a small ridge and refrozen lead were present in the final 25 m of the transect. Distances were estimated using paces marked by Chris Hiemstra. Additionally, a ground based electromagnetic induction sensor, the EMP-400, was used to measure thickness along the entire transect at 5, 10, and 15kHz at a temporal sampling of 2 Hz. Shortly after completion of the ground measurements, the DC3 and Twin Otter aircraft with the AEM and ASIRAS sensors made several passes over the site while the ground team remained on site. Additionally, a prototype MetOcean / AWI snow depth buoy was deployed at X=175 m along the transect. Two SVP buoys were deployed on the transect at X=0m and X=350m.

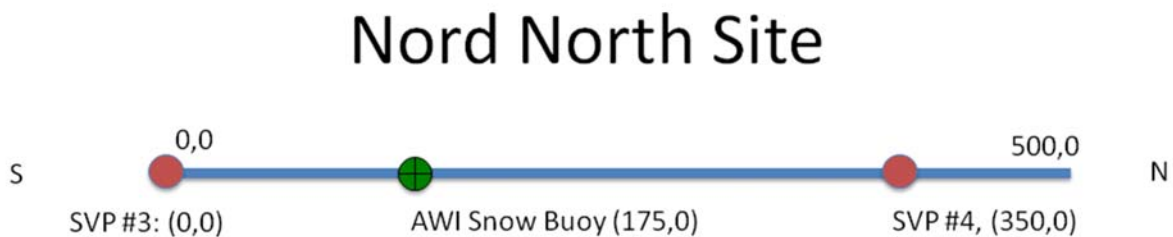


Figure 28: Station Nord North Day Site overview.

Transect Data

Figure 29 presents the ice thickness and ice and snow freeboard profile measured at the Nord NDaysite, showing only the drill hole data. Figure 29 also presents boxplots of the distribution of ice thickness, freeboard and snow depth along the transect using the MagnaProbe snow depth data instead of the drill hole snow depth data. Table 6 presents the descriptive statistics for the snow and ice properties measured along the transect. Figure 30 presents a histogram of the snow depth measured along the transect at the Nord NDaySite along with a profile of the snow depth and the EM and drill hole measured total ice plus snow thickness.

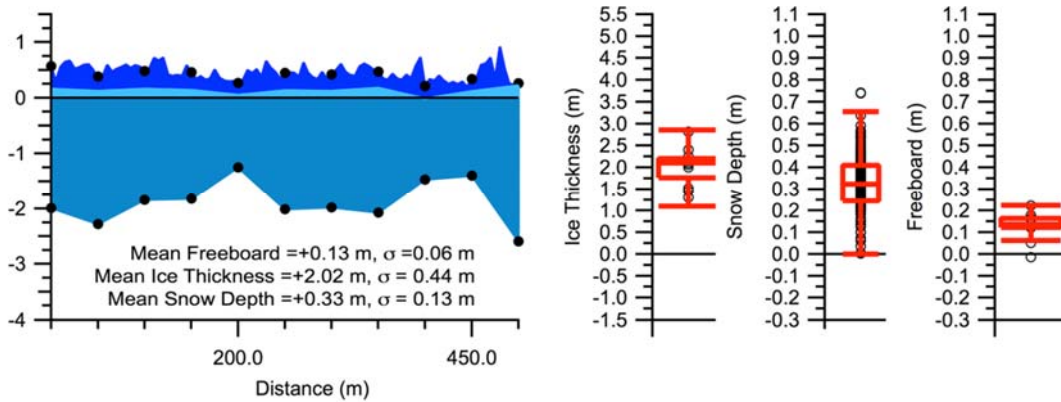


Figure 29: Profile plot of snow (dark blue) and ice freeboard (light blue) and ice draft (medium blue) along Nord Auxiliary Site (NDaysite). Profile data is from the manual drill-hole measurements (black dots) and the MagnaProbe snow depth. Snow freeboard (dark blue) is determined by adding a linear interpolation of the drill-hole freeboard to the MagnaProbe snow depth measurements. Statistics of ice thickness and snow depth presented in the profile plot are calculated using the EMP and MagnaProbe data. Boxplots of ice thickness, snow depth, and ice freeboard are also presented. The boxplot of snow depth is calculated using the MagnaProbe data. The box plot of ice thickness is calculated using the EMP data.

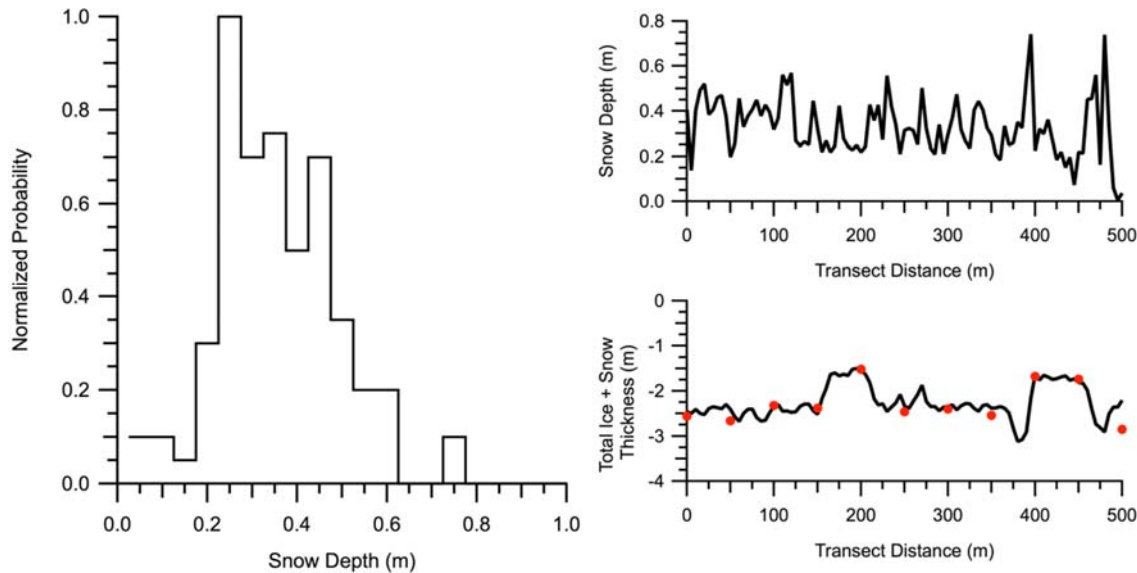


Figure 30: (Left) Distribution of snow depths at the Nord North Day site. (Right) Profile of the snow depth (top) and the EM (black line) and drill hole (red circles) total snow + ice thickness measured along the transect (bottom).

Table 6: Descriptive statistics of the ice and snow properties measured along the transect at the auxiliary Nord NDaysite. Modal value of EM ice thickness was calculated using 0.10 m bins, while the calculation of modal snow depth from the MagnaProbe used 0.05 m bins. Modal values are not computed for drill-hole data as there were only 11 measurements.

Parameter	Mean	Std. Dev.	Mode	Min	Max	N
Ice Draft (Drill) (m)	1.88	0.39	N/A	1.25	2.59	11
Ice Freeboard (Drill) (m)	0.13	0.06	N/A	-0.02	0.22	11
Snow Freeboard (Drill) (m)	0.39	0.11	N/A	0.21	0.57	11
Snow Depth (Magna Probe) (m)	0.33	0.13	0.25	0.01	0.74	101
Snow Depth (Drill) (m)	0.26	0.09	N/A	0.04	0.41	11
Ice Thickness (Drill) (m)	2.02	0.44	N/A	1.30	2.81	11
Ice Thickness (EM) (m)	1.92	0.34	2.10	1.24	2.77	11

Acknowledgements

A large campaign such as this involves high levels of coordination, co-operation, and support from nearly countless people and organizations. So if we miss you, we are sorry, but know that we are thankful.

This campaign involved the coordination of four aircraft, the Ken Borek DC-3 carrying the AEM sensor from York University, the Ken Borek Twin Otter used to carry equipment and personnel, and to deploy the field camps and auxiliary sites, the NASA Operation Ice Bridge P3, the Nordland Air Twin Otter carrying ASIRAS and an ALS operated by ESA/DTU. These aircraft were coordinated by John Alec Casey and Anne Bublitz (U of Alberta / York University), Michael Studinger and John Sonntag (NASA), and Rene Forsberg (DTU).

US Office of Naval Research / Marginal Ice Zone Project allowed the CryoVEx ground team to stay in their excellently setup and well equipped camps in the Beaufort Sea and provided logistical support by providing food and accommodations in Sachs Harbor and transport to/from the camps for the team and gear. Special thanks to Jim Johnson, Mike Carpenter, Adam Huxtable, Craig Lee (U of Washington), Jeremy Wilkinson (BAS), and Martin Jeffries (ONR).

We are very grateful to the personnel at Station Nord, the Polar Continental Shelf Program, and Sachs Harbor for food and accommodation, and other support. Rene Forsberg and Emil Nielsen (DTU) are thanked for their support at Station Nord.

We also thank the various aircraft crew and support teams as without them coordinated, coincident airborne surveys over the ground measurements would not be possible. Jackie Richter-Menge (CRREL) strongly supported coordination across organizations and design of field measurements. Marc Cornelissen and Petter Nyquist are thanked for preparing and managing the Greenland ice camp.

Funding of CryoVEx2014 was provided by ESA, and we are most grateful for planning and coordination efforts by Malcolm Davidson and Tânia Casal.

APPENDIX: CryoVEx 2014: UCL Ground Team Report, by R. Tilling

CryoVEx 2014: UCL Ground Team Report

Rachel Tilling

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The following is a summary of the UCL contribution to CryoVEx 2014, using the UCL Ground Penetrating Radar (GPR). Section 1 summarises the scientific context: what we wanted to achieve, why, and how this will build on previous knowledge. Section 2 describes the measurements that were made in the field.

1. Scientific Objectives

The Earth's sea ice cover significantly influences our global climate. Sea ice reflects a large fraction of incoming solar radiation and provides an insulating layer between the ocean and atmosphere. Changes in sea ice thickness and volume impact the Global heat and freshwater budgets. When using radar altimeter data from CryoSat-2 (CS-2) to estimate Arctic sea ice freeboard and thickness, which can then be used to estimate volume, we make a number of assumptions. These include, but are not limited to, the densities of sea ice, seawater and snow, the speed of light propagation through snow on sea ice, the depth of snow on sea ice, and the behaviour of the radar scattering.

The key aim of the UCL contribution to CryoVEx 2014 was to investigate the validity of what we consider to be our main assumption when using CryoSat-2 data to estimate ice thickness; that the snow-ice interface is the dominant scattering surface of the CS-2 radar. With this assumption in mind, our **Key Experiment Objectives** were:

01. To use the UCL 2-18GHz Ground Penetrating Radar (GPR) GPR to investigate radar return profiles on sea ice with different snow pack characteristics, at locations in the Lincoln Sea.

02. To dig snow pits at each GPR location and record snow depth and snow characteristics, such as layering, grain size and density. This enables us to compare the GPR return echoes to the physical snow characteristics on small scales.

When analyzing the GPR data, we want to be able to accurately estimate the depth-delay return to the dominant radar scattering surface. With that in mind, our **Secondary Experiment Objective** was:

03. To investigate the speed of light propagation through snow on sea ice

2. UCL Ground Team Experiment

2.1. Experiment Overview

Over the period of 29th March – 1st April 2014, the CryoVEx team was based at an ice camp in the Lincoln Sea, and member of the team from UCL were responsible for taking measurements using the UCL GPR. Below is a diagram of the experiment site, from above:

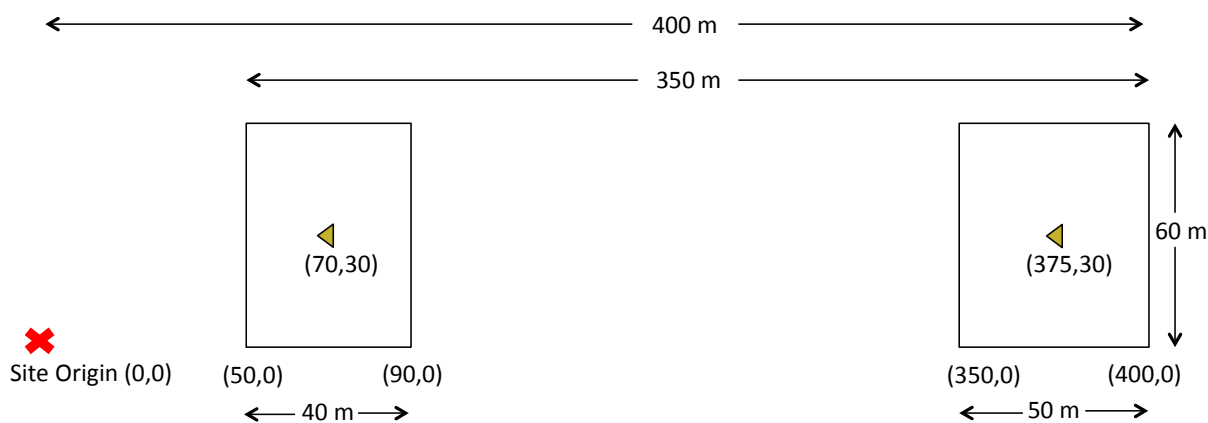


Figure 31: Plan view of the experiment set-up. Site coordinates of the Corner Reflectors and grid corners are shown.

Corner Reflectors (CRs) were erected, to act as height references for ASIRAS and the EM-bird (see Figure 3). Each CR marked the centre of a snow grid, in which snow depth measurements were taken every square metre. The distance between the CRs was 305 m.

The UCL team took GPR measurements nested in both CR grids, to investigate the radar scattering surface. They then dug snow pits at the locations of GPR measurements, and recorded snow characteristics. The aim was to choose locations with visually differing surface topography, but where the radar could be rested on a flat surface, so that the GPR was not firing at an angle.

2.2. GPR measurements

GPR measurements were taken nested in the CR grid, and along a transect between the two CRs. For the grid measurements, we also carried out snow pit measurements (see Section 2.3). We did not carry out snow pit measurements along the transect, as the aim was to get as many GPR measurements as we could in a limited time.

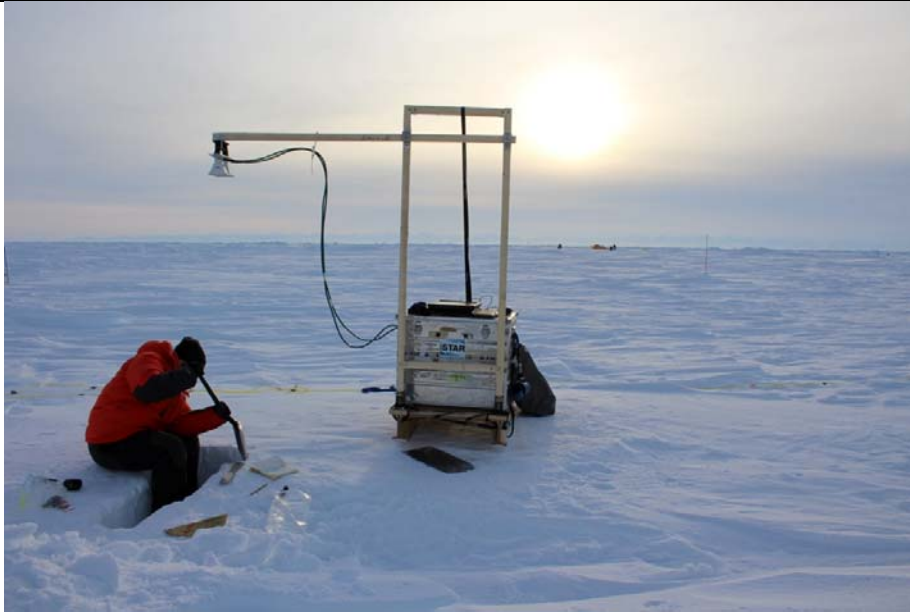


Figure 2: The UCL Ground Penetrating Radar

The site coordinates for each GPR measurement were:

CR Grids

GPR shot 1 = (75, 25)

GPR shot 2 = (75, 51)

GPR shot 3 = (71, 30)

GPR shot 4 = (358, 3)

GPR shot 5 = (386, 9)

GPR shot 6 = (396, 45)

GPR shot 7 = (374, 29)

GPR shot 7 = (374, 33)

Transect

GPR shot 1 = (210, 30)

GPR shot 2 = (220, 30)

GPR shot 3 = (230, 30)

GPR shot 4 = (240, 30)

GPR shot 5 = (250, 30)

GPR shot 6 = (260, 30)

GPR shot 7 = (270, 30)

GPR shot 8 = (280, 30)

GPR shot 9 = (290, 30)

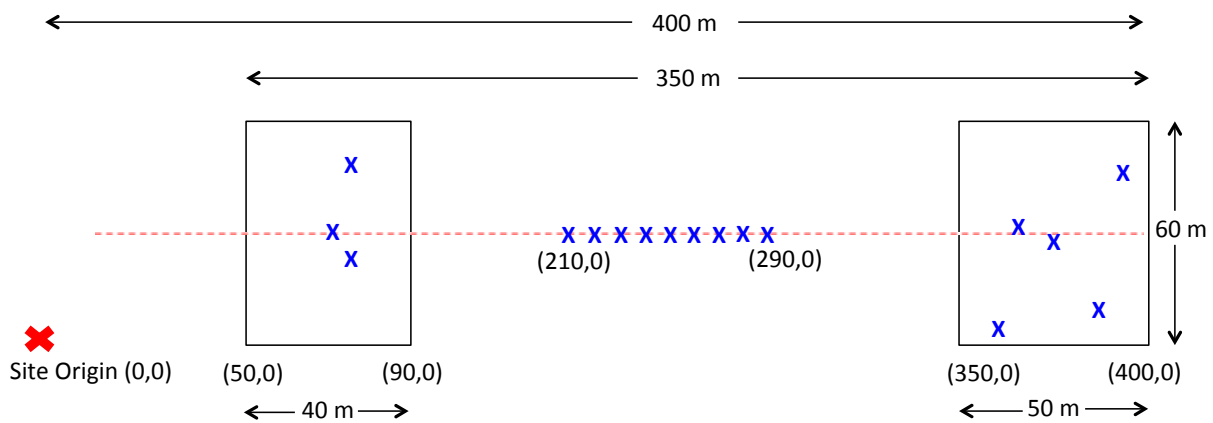


Figure 3: Approximate GPR measurement locations (blue crosses) in the Corner Reflector grids

A breakdown of the GPR measurement technique is given below. The idea was that these measurements would allow us to investigate the dominant scattering surface of the radar, and the speed of light propagation through snow on sea ice.

- R9. One GPR shot was taken on the undisturbed surface
- R10. One GPR shot was taken shot with a 60 x 40 cm metal plate placed on the snow surface.
- R11. A pit the size of the metal plate was dug, starting approximately 60 cm from the GPR nadir, and taking care not to disturb the surrounding snow
- R12. Using the pit for access, the metal plate was pushed laterally into the snow pack, so that it sat at the snow-ice interface at the antenna nadir. Care was taken not to disturb the above snow layer.
- R13. One GPR shot was taken with the metal plate at the snow-ice interface. Using the metal plate at the snow and ice surface (with snow still on top) allows us to measure two fixed reference points a known distance apart, and therefore the propagation speed of light through the snow pack.
- R14. We then dug a small pit, around 30 cm square, for snow pit measurements (see Section 2.3).

- R15.** After the snow pit measurements we dug a larger pit, at least a metre square, ensuring that the ice surface was completely exposed. Then one GPR shot was taken of the exposed ice surface.
- R16.** A final GPR shot was taken with the metal plate on the ice surface

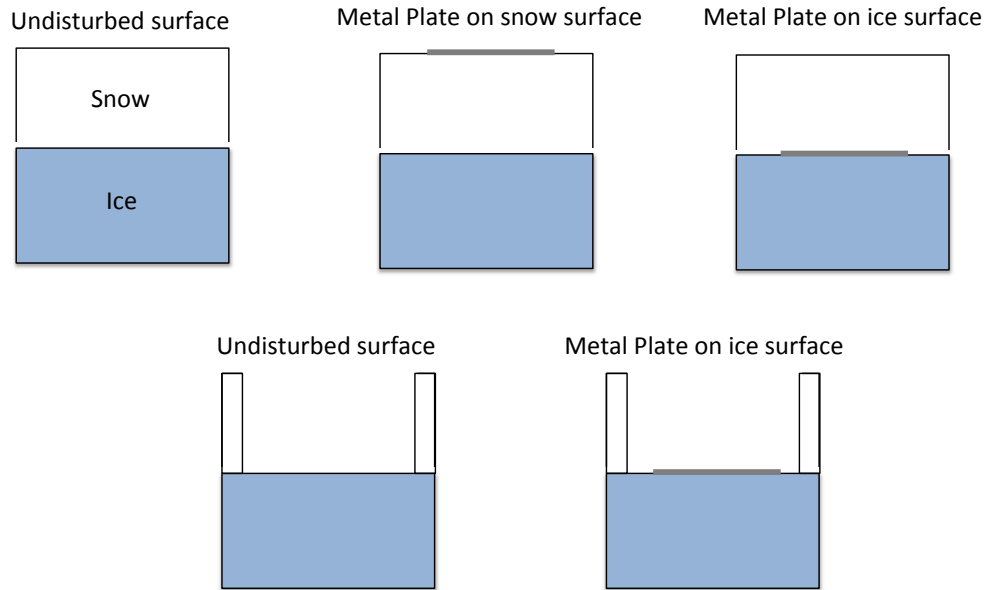


Figure 4: A summary of the Ground Penetrating Radar measurements taken at each location

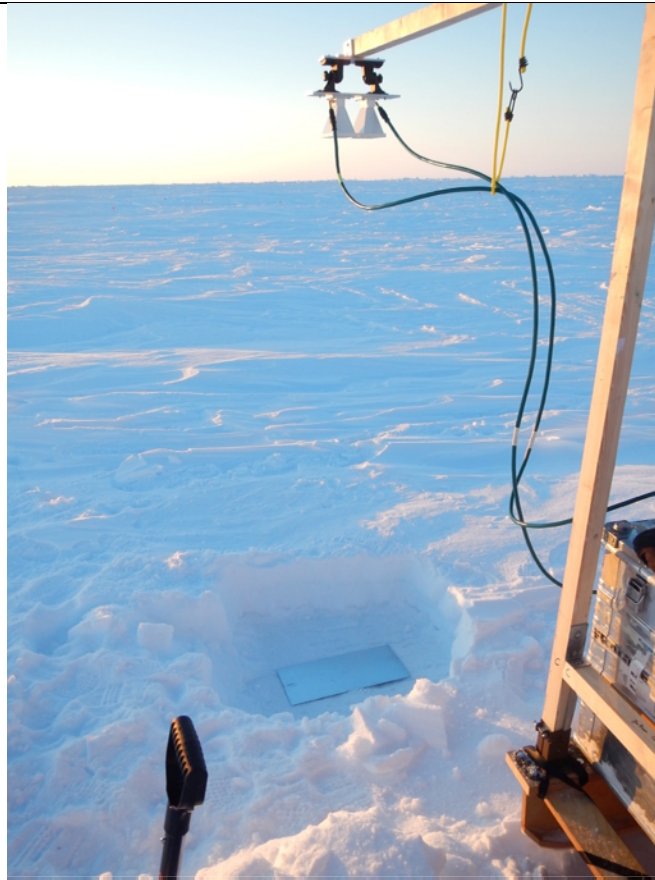


Figure 5: Example of the Ground Penetrating Radar and metal plate setup. Here, a shot is being taken of the metal plate on the sea ice surface. The plate is placed at the radar antenna nadir.

2.3. Snow pit measurements

The aim of the snow pit measurements was to investigate the properties of the snow layer that had just been measured by the GPR, and to attempt to relate returns in the radar signal to features in the snow pack. By estimating the speed of light through the snow pack, we can associate snow features and the snow-ice interface with the depth-delay radar returns, rather than just time-delay. We dug a small hole down to the ice surface, approximately 30 cm square. The idea was that the pit large enough for us to be able to photograph the snow layering and features, but not so wide that measurements were being taken a significant distance from the antenna nadir. We then recorded:

- S1.** Snow depth
- S2.** Snow density
- S3.** Snow temperature
- S4.** Layering and grain size. This was done in an approximate fashion, e.g. looking at dominant length scale with a magnified ruler.
- S5.** Unusual/stand-out features
- S6.** Lots of photos. A ruler was placed in the photos, so the distance to any layers or stand-out features can be seen.



Figure 6: Example of a snow pit dug at a Ground Penetrating Radar measurement site

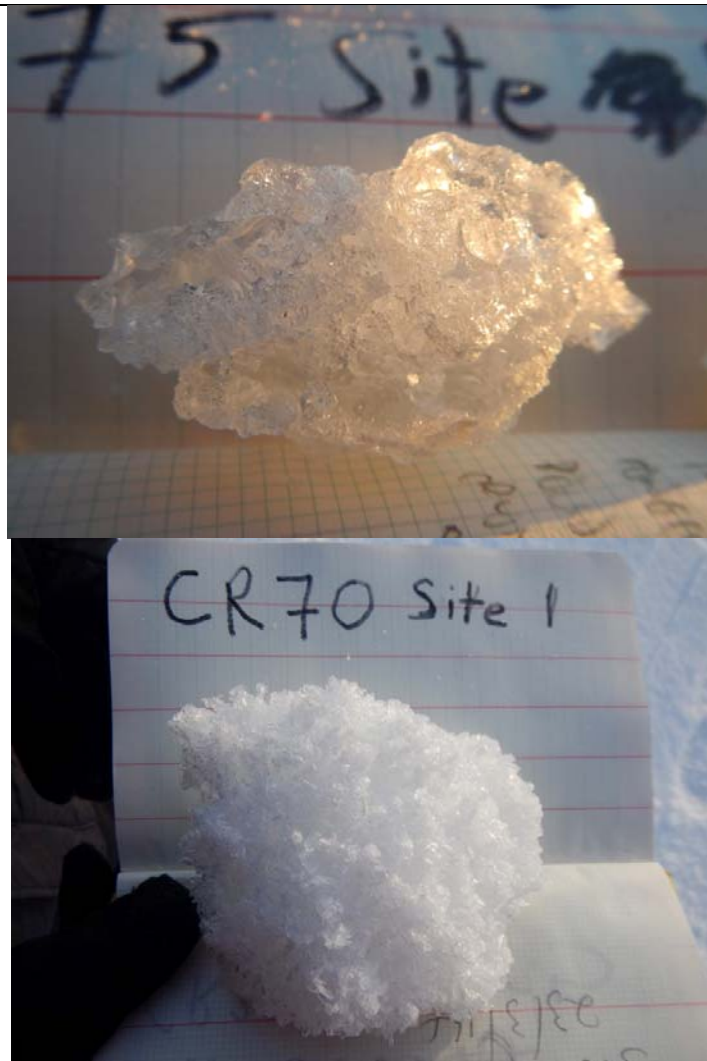


Figure 7: Examples of different crystal types found in the snow pack at a Ground Penetrating Radar measurement site

CryoVEx 2014



Deliverable 2: **CryoVEx 2014 Flight Data**

ESA Contract No. 4000110552/14/MP/vb

Christian Haas
York University
Toronto, Canada



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1 Executive summary

This document contains a short description of the CryoVEx2014 Flight Data obtained by York University submitted to ESA as part of the contractual Deliverable 2. Please see the accompanying Data Acquisition Report (Deliverable 3) for more information.

2 Purpose And Scope

This document summarizes the flight data obtained by York University in the CryoVEx 2014 project. The European Space Agency ESA operates the CryoSat mission which is dedicated to the measurement of sea ice thickness in the Arctic. Numerous CryoSat Validation Experiments (CryoVEx) have been performed over the past several years. York University has lead the CryoVEx 2014 field campaign to obtain ground-truth data from Arctic sea ice to validate the satellite measurements.

CryoVEx2014 has been carried out in March and April 2014, a large, international field campaign in the Arctic to obtain these validation measurements. The campaign involved researchers from Canada, Denmark, the US, the UK, and the Netherlands. It included airborne ice thickness surveys with York University's airborne electromagnetic ice thickness profiler, and in-situ measurements on ice floes visited by aircraft. The campaign was conducted from various locations in Canada (Northwest Territories and Nunavut) and Greenland.

ESA has provided funds for the charter of two aircraft between March 15 and April 5, 2014, a ski-equipped Twin Otter and a Basler BT67. The aircraft were operated by Kenn Borek Air Ltd. from Calgary, AB. Additional funds for small equipment purchases, shipping, travel, and other logistics services required to perform the project were provided as well.

This document is the contractual Deliverable 2: Flight data. It primarily includes the acquired electromagnetic raw data, as well as compiled GPS information for initial plotting of flight tracks. The document is accompanied by Deliverable 3: Data Acquisition Report, which summarizes the measurements made during CryoVEx 2014 and includes plots of the data. Finally processed ice thickness data will be delivered in December 2014 (D4: CryoVEx 2014 Level 1b, 2 ice thickness data in format to be agreed with the Agency).

3 Data files

The Flight Data include all data acquired by the EM bird operated under the Basler aircraft. While only raw EM data files are provided as the data processing is still ongoing, we provide separate files with GPS and laser information.

7 data files were delivered containing all Flight Data of the seven flights performed. These are:

- 20140318_GPSLaser.dat
- 20140319_GPSLaser.dat
- 20140321_GPSLaser.dat
- 20140326_GPSLaser.dat
- 20140329_GPSLaser.dat
- 20140330_GPSLaser.dat
- 20140331_GPSLaser.dat

Figure 1 shows the geographical coverage of each flight. Please refer to the Data Acquisition Report for more information.

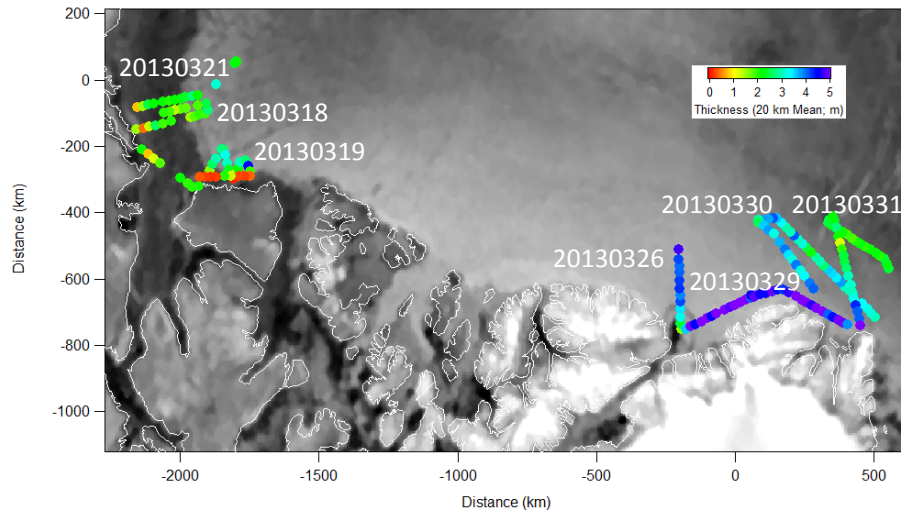


Figure 1: Map of all EM ice thickness flights carried out with the EM bird operated by the Basler aircraft. Ice thickness information is preliminary. Background map is ASCAT radar backscatter information on March 26, 2014, obtained from BYU. See data acquisition report (Deliverable 3) for more information.

3.1 Data format

Files are named according to the date of flight: YYYYMMDD_GPSLaser.dat, with

YYYY: Year of flight (e.g. 2014)

MM: Month of flight (e.g. 03)

DD: Day of flight (e.g. 18)

The file format is ascii, tab delimited, and includes a header line identifying the variables in each column. There are 5 data columns in each file, separated by a tabulator character:

- GPSseconds: Time of measurement in seconds of the day, GPS time.
- Fid: Fiducial number, a measurements index referencing to all other measurements performed by the EM ice thickness sensor
- Lat: Latitude of measurement
- Lon: Longitude of measurement
- Height: Laser-measured height of EM ice thickness sensor above the snow surface