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ELECTOMAGNETIC/RADAR ICE AND SNOW SOUNDING PROJECT OVER THE NEWFOUNDLAND SHELF IN 1992

S.J. Prinsenberg, J.S. Holladay, and L.A. Lalumiere

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Physical and Chemical Sciences Branch
Scotia-Fundy Region
Department of Fisheries and Oceans

Bedford Institute of Oceanography
P.O. Box 1006
Dartmouth, Nova Scotia
Canada, B2Y 4A2

* Aerodat Limited
3883 Nasha Drive
Mississauga, Ontario
Canada, L4V 1R3

** Canpolar Inc.
265 Rimrock Road, Unit 4
Toronto, Ontario
Canada, M3J 3C6

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An Electromagnetic (EM) Induction sensor and Impulse (Ground Penetrating) radar mounted in a helicopter-towed bird was used to collect snow and ice thicknesses of the land fast and mobile ice cover off St. Anthony, Newfoundland in March of 1992. A laser mounted in the bird's sensor package measured sensor height above snow level while the EM measured height above ocean water and the radar height above snow/ice interface. From these data snow plus ice thicknesses were computed in real time while separate snow and ice thicknesses will be computed in post survey analysis. This report documents the field program and lists all calibration data collected to verify the air-borne EM and Radar data. Samples presented of the field processed data show that the system performed well.

RÉSUMÉ

Prinsenberg, S.J., J.S. Holladay and L.A. Lalumiere, 1993. Electromagnetic/Radar Ice and Snow Sounding Project over the Newfoundland Shelf in 1992. Can. Tech. Rep. Hydrogr. Ocean. Sci. No. 144: vii + 59 pp.

Un capteur à induction électromagnétique (EM) et un radar à impulsions (ou géoradar) installés une torpille remorquée par hélicoptère ont été utilisés pour recueillir des données sur l'épaisseur de neige et de glace de la banquise et de la banquise côtière au large de St. Anthony (Terre-Neuve) en mars 1992. Un laser monté dans le groupe des capteurs de la torpille a servi à mesurer la hauteur des capteurs au-dessus de la neige; l'appareil EM, à mesurer la hauteur au-dessus de l'océan; et le radar, à mesurer la hauteur au-dessus de l'interface neige/glace. Ces données ont permis de calculer l'épaisseur totale de neige et de glace en temps réel, tandis que les épaisseurs de neige et de glace séparées seront calculées au moment de l'analyse ultérieure. Le présent rapport décrit le programme de terrain et renferme toutes les données d'étalonnage recueillies pour vérifier les données aériennes EM et radar. Les échantillons de données traitées sur le terrain révèlent que le système a bien fonctionné.

TABLE CAPTIONS

FIGURE CAPTIONS

Figure 1. The St. Anthony sea ice survey tracks of March, 1992. Inserts show the orientation of the Pistolet and Hare Bay calibration lines.

Figure 2. March 7 ice conditions off St. Anthony as copied from Ice Centre's daily ice charts. Also shown are the flight paths taken over the offshore pack ice.

Figure 3. Sketch of EM/Radar ice and snow thickness data collection system.

Figure 4. ERS-1 Satellite SAR coverage and 7-day displacements of the inshore ice edge of the pack ice and the three beacons deployed on March 6 and 7. Beacon trajectories are shown as half daily drifts labelled by day of the month of March at 12hr EST.

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Figure 6 EM ice thickness and surface calibration data from Pistolet Bay for PB-L1 on March 6 in top panel and PB-L2 on March 13 in bottom panel. Data shows the altitude of the EM sensor above the snow surface, the surface roughness (High Pass-Filtered Laser data) and snow plus ice thickness data.

Figure 7 EM ice thickness and surface calibration data for two perpendicular flight tracks over a surveyed floe in Belle Isle Strait on March 6, 1992.

Figure 8 Ice thickness observations along the tracks to and from the pack ice on March 7 and 8.

[illegible] Availability of SLAR [illegible]

[illegible] March 4 and 17 [illegible]

[illegible] 4, 7, 10 and 17

1.0 INTRODUCTION

The seasonal ice cover over the Newfoundland shelf poses a threat to safe operation of marine shipping, fishing activity and hydrocarbon exploration. Sea ice programs of the Department of Fisheries and Oceans (DFO), funded primarily by the Federal Panel of Energy and Resource Development, are investigating, through field programs and numerical modeling, the seasonal variability of pack ice properties such as southern ice extent, ice drift, ice concentration and ice thickness. One of these programs explores the use of the Electromagnetic (EM) Induction technique for measuring the thickness of pack ice. This report documents the field program conducted off the Newfoundland coast in March of 1992, lists all the on-ice collected calibration data and presents preliminary results from field processed data.

The development of practical techniques to remotely measure ice characteristics such as ice and snow thicknesses and ridge depth profiles has been the goal of the Transportation Development Centre (TDC) of Transport Canada and of Cold Regions Research and Engineering Laboratory of US Army Corps of Engineers. The airborne Electromagnetic Induction technique has provided the most promising results to date. Two variations of this technology have been developed to date by Aerodat Ltd. of Mississagua, Ontario; one each for the U.S. and Canadian Governments. The Canadian version was designed and manufactured under contract to TDC for deployment from helicopters based on ice breakers as an aid to autonomous route selections. Under loan to DFO, the TDC's ice sounding equipment was field tested.

The DFO field project off St. Anthony (Fig. 1) used the Canadian EM system which combines the Electromagnetic Induction sensor with a ground-penetrating Impulse Radar. The basic EM method has been demonstrated in the Arctic (Kovacs and Holladay, 1989; Kovacs and Holladay, 1990), and off the Canadian East coast (Maclaren Plansearch, 1988; Holladay et al., 1990; Rossiter et al., 1990). The combined EM/Radar system was tested over the pack ice in the Beaufort Sea off Tuktoyaktuk (NWT) (Rossiter et al., 1991: Prinsenberg et al., 1992). It was found that the radar did not interfere with the EM operation and that the combined system was indeed capable of providing separate snow depths and ice thicknesses in post survey data processing.

2.0 STUDY AREA AND FIELD WORK

2.1 STUDY AREA

The 1992 EM/Radar ice sounding project concentrated on the land fast and mobile ice cover off the northern tip of Newfoundland (Fig. 1). The predominant westerly winds continually moved the mobile ice offshore. Thin ice or open water conditions occurred near the shore. Ice thicknesses and ice concentrations increased with increasing distance from shore until the main pack ice was encountered at about 50km offshore (Fig. 2). These ice conditions provided a good cross-section of ice conditions for the EM/Radar system, but at times one would have felt more comfortable in the helicopters if thicker ice conditions had occurred. The main pack ice consisted of very rough consolidated large floes which were made up smaller floes over 1m thick. The large smooth floes used for calibration in the pack ice were newer and thinner and had a very homogeneous ice thickness. The snow layer on the sampled floes was thin and wet (salty).

Along the northern coast in Belle Isle Strait, permanent flat land fast ice only forms in protected bays, while very rough land fast ice forms in narrow bands along the unprotected coasts (Fig. 1). The land fast ice cover of two bays, Pistolet Bay, northeast of the airport, and Hare Bay, east of the airport, were used as calibration sites since ice thickness of these bays was very homogeneous and a thick snow cover was present for radar work. The salinity of the sea water beneath these calibration sites was not diluted and provided a good conductive reflector for the EM signal. A small fresh water lake near the airport, accessible by road, was used as an additional calibration site for radar work. The lake itself had a thin snow cover, but snow drifts of 2m occurred along its shore.

In Pistolet Bay, a total of three lines marked by black plastic garbage bags filled with snow were set out (Fig. 1). The two main lines run in a NE-to-SW direction and had 20 marker bags spaced at 12.5m intervals. At these locations ice thickness measurements were collected through augered ice holes. Snow depths were taken at 3.1m intervals, i.e. at the bags and three extra samples between each set of marker bags. A third line, perpendicular to the main lines, was set out with 10 marker bags at 50m spacing. The EM data showed consistently that rougher and thicker ice existed seawards of the two main lines. This area was sampled for ice thicknesses at the end of the survey. Ice thicknesses were very consistent over the smooth area ranging from 59cm to 67cm with a mean of 63cm. Snow depths varied more; ranging from 20cm to 45cm with a mean of 29cm. At most places the weight of the snow pushed the snow/ice interface below the water level. Along the southern main line a negative ice freeboard of 5cm was observed. To prevent flooding of the ice near the ice holes, ice thickness measurements along the other two lines were taken only at the end of the survey.

The second calibration site in eastern Hare Bay was chosen because the flooding problem through augered ice holes did not occur here and the site was on the way to the pack ice and could be used to check out the system before starting a long trip to the pack ice. Two lines perpendicular to each other were set out (Fig. 1). Ice thickness measurements were taken at 25m intervals (marked by bags) and snow samples were collected at 5m intervals. Ice thicknesses ranged from 66cm to 75cm with a mean of 68.5cm. Snow depths decreased during the period when fog and rain was present on March 11 and 12. Before the rain, the depths ranged from 15 to 47cm with a mean of 25cm; while after the rain, they ranged from 2 to 24cm with a mean of 12cm: the rain had melted and compacted the snow. A similar reduction of 12cm in snow depth occurred in Pistolet Bay.

At the fresh water lake site, two lines marked with bags were set out. The marker bags were at 30m separation along which snow depth measurements were taken at 1.0m interval on March 7. Two radar profiles with antennas on the surface of the snow were taken on March 7 to obtain accurate measurements of the radar velocity in snow.

EM/Radar ice and snow data of the main pack ice was obtained during three trips. The flight paths and the locations of the floes sampled in the pack ice are shown in Fig. 2. The total over-ice distance covered by each ice sounding trip was 210km for March 7, 160km for March 8 and 250km for March 13 with extra sounding being done around the pack ice calibration floes.

2.2 FIELD WORK

The survey started on March 4 with unpacking and installation of the EM equipment. Two helicopters chartered from Universal Helicopters Ltd. were stored at the new St. Anthony airport. Space for one helicopter and the bird were made available in the hanger of the International Grenfell Association. This excellent facility provided heated space for work on the electronics of the EM/Radar components of the towed bird and helicopter.

On March 4, 5 and 6 calibration lines in Pistolet Bay were set out and the EM equipment was readied and tested over the calibration lines and Belle Isle pack ice. Ice thickness data from the offshore pack ice was obtained by the EM sensor during two long trips on March 7 and 8. During the offshore trips to the pack ice, three satellite-tracked ice beacons were deployed on the pack ice to monitor the position of the surveyed areas in order to evaluate ERS-1 SAR data against EM ice thickness and concentration data.

The radar was installed in the bird and tested during March 9 and 10 over the Hare Bay site which was set at the same time. Warmer weather prevented offshore work on March 11 and 12 as the above-zero air temperatures brought in fog and rain. On March 13, a long offshore EM/Radar line was done. Bad weather (snow) prevented the helicopters from landing on the pack ice to collect surface calibration data. The equipment was packed up in the afternoon of March 13 and the helicopters returned to their base camp in Goose Bay. The day-by-day work is listed below in more detail.

March 2 -Monday, -20 $^{\circ}$C, winds 270 at 20knots
-Readied gear for helicopter transport
-Trip delayed due to coastal blizzard
-Aerodat personnel stranded in Halifax

March 3 -Tuesday, -16 $^{\circ}$C, winds 270 at 35knots
-St. Anthony airport being opened
-Aerodat personnel arrived in St. Anthony

March 4 -Wednesday, -10 °C, winds 280 at 35knots
-Unpack EM equipment
-2hr flight Goose Bay to St. Anthony
-On-board computer installed in helicopter (C-GQNS)
-EM bird test flight
-Reconnaissance of Hare Bay (C-GLSH)
-Line 1 Pistolet Bay (10 holes)

March 5 -Thursday, -8 °C, winds 240 at 15knots
-EM bird test flights
-Line 1 Pistolet Bay (10 extra holes)
-CCRS personnel arrived
-Pistolet snow data line 1
-EM bird tested over Pistolet Bay
-Sampled ice floes and land fast ice in Belle Isle Strait
-L. Lalumiere (Canpolar) arrived

March 6 -Friday, -15 °C, winds 320 at 15knots
-Radar test flights
-Snow data Pistolet Bay along line 1
-Line 2 (20 bags) and line 3 (10 bags) Pistolet Bay marked only
-Land-fast ice stn. 4, Belle Isle Strait
-Pack-ice via Belle Isle, 2 beacons deployed
-Ice floe Belle Isle Strait sampled
-EM sounding of Pistolet Bay (7 passes)
-EM sounding of Belle Isle ice floe and land fast ice

March 7 -Saturday, -5 °C, winds 300 at 45knots
-EM pack ice sounding #1 (PI-L1)
-Pack ice thickness and ice chip samples collected
-Strong head winds on way home, low on fuel
-Ice survey helicopter ferried fuel to EM bird helicopter
-Ground Radar data from airport lake site

March 8 -Sunday, -10 °C, winds 330 at 10knots
-EM bird sounded Pistolet Bay and land fast ice of Belle Isle Str.
-Em sounding on way out to pack ice
-EM pack ice sounding #2 (PI-L2)
-Floe drilled, bags 12.5m apart
-Floe snow and ice samples
-CCRS collected wind-blown snow texture data
-Small ridge drilled and other areas sampled
-Ice beacon #4759 deployed
-EM sounding on way in from pack ice

March 9 -Monday, -10 ^{O}C, winds 100 at 10knots
-Hare Bay E-W line #1, 10 bags
-Slush and snow layer samples
-Ice samples at bag #5
-Tested refrozen patches in Hare Bay
-Set out N-S line #2 of Hare Bay
-Set out N-S line #3 of Pistolet Bay
-Radar installed and tested in bird over Lake and Hare Bay sites

March 10 -Tuesday, -8 ^{O}C, winds 215 at 10knots in morning
-4 ^{O}C, winds 270 at 25knots in afternoon
-Icing on helicopter blades, freezing rain and snow
-Snow depths and ice thicknesses, Hare Bay lines 1 and 2
-Snow depths Pistolet Bay lines
-EM/Radar sounding data of Hare Bay lines

March 11 -Wednesday, +2 ^{O}C, winds 220 at 5knots
-Poor weather for EM/Radar work
-Ice chip and water samples from Hare Bay
-No flying in afternoon
-CCRS personnel left

March 12 -Thursday, +3 ^{O}C, winds 150 at 10knots
-Fog and rain, no flying

March 13 -Friday, +2 ^{O}C, winds 190 at 5knots
-Packed processing equipment from hotel in truck
-Pack-ice trip #3
-EM/Radar sounding out to pack ice (54W/51N)
-Snowing prevented on ice work
-EM/Radar sounding on way back to Hare Bay
-Radar data collected over airport lake site
-EM/Radar sounding over Pistolet Bay
-Snow and ice thicknesses Hare Bay
-Snow and ice thicknesses Pistolet Bay
-Packed up, helicopters left for Goose Bay (1530 EST)

3.0 INSTRUMENTATION

3.1 SENSORS IN THE BIRD

The EM induction method typically uses frequencies in the 1000 to 50,000Hz range. A sensor package is towed in a bird about 30m beneath the helicopter at between 15 to 30m above the ice surface (Fig. 3). Low frequency EM signals are transmitted by the antenna in the sensor bird and excite eddy currents in nearby conductors, sea water being the main conductor in this case. These currents in turn generate secondary EM fields which are measured by the receiver also mounted in the bird. By measuring the amplitude and phase of the secondary field relative the primary field, the distance of the bird to the water/ice interface can be determined.

The frequencies and antenna configurations used in the TDC system are 2.5 kHz in the coaxial mode and 100kHz in the coplanar mode. The transmitter and receiver antennas are separated by 3.0m. The overall length of the bird is just under 4m, while its weight is about 125kg. The bird is slung from the helicopter's cargo hook on a 30-meter tow cable which carries power and digital control signals down to the bird and digital data up to the helicopter. The frequencies and coil separations were chosen to optimize the capabilities of the system for ice thickness, conductivity and keel geometry estimation while controlling the bird size and weight. The EM responses at the lower frequency contributes to the accurate estimation of ice thickness, while the phase of the 100kHz response is also sensitive to the bulk electrical conductivity of the sea ice, which is in turn related to the strength of sea ice (Kovacs et al., 1978). This system was modified since the 1991 Beaufort Sea survey to reduce noise and drift.

An Optech G150 laser profilometer in the sensor bird is used to measure the distance from the bird to the snow/air interface. Its footprint has a radius of less than .05m when flying the sensor at an attitude of 15 to 20m. In contrast, the radius of the EM sensor's footprint is much larger, being comparable to the height of the sensor above the ice surface. A radar altimeter operating at about 2GHz was mounted in the helicopter to assist the pilot in maintaining survey attitude.

A 500MHz impulse radar was used to obtain the distance from the bird to the snow/ice interface. The radar hardware consisted of a GSSI Model 3102DP 500MHz transducer modified to contain the timing control electronics, a calibration unit and high power supply. The radar was ground tested at the airport lake site where a large variety of snow depths existed. This lake site was marked with bags and became an additional calibration site for the airborne radar sensor. The radar transducer was mounted forward of the EM transmitter, near the nose of the bird, with two coax cables and a power cable added to the bird's tow cable. The radar data was stored on the hi-fi audio channels of a VCR and was not available for real time processing.

3.2 HELICOPTER INSTRUMENTATION

The system console is mounted on a rack in the back seat area of the helicopter in such a way that an operator can use the master computer/data logger and see the power distribution unit while viewing the annotated data from the video flight path monitoring camera on the CRT. A Panasonic AG-7400 S-VHS video recorder makes an analog recording of this imagery for later use in assessing ice conditions below the helicopter. The camera is mounted in front of the forward passenger's seat, pointing downwards to observe not only the ice conditions but also bird flight behavior.

The master computer controls the entire system. It collates and reduces EM and other incoming data and logs the data on magnetic media. It controls the auxiliary processor which inverts the data to ice thicknesses and other parameters, plots the data on the graphic recorder, and generates a text overlay on the video flight path imagery including time, position and ice parameters.

The helicopter was equipped with a Trimble T2000 GPS navigation unit. Data from this instrument was also logged on the EM computer and displayed on the CRT.

3.3 OTHER INSTRUMENTATION

Calibration and remotely sensed data were collected during the project to assess whether the EM/Radar sensors would be a good sampling technique to ground-truth data collected either by fixed-wing aircraft (SLAR) or by satellite (SAR). To compare the different data sets from different times, the ice motion of the region is required to realign the areas covered by the various observation techniques. Three ice beacons tracked by ARGOS satellite were deployed to monitor the pack ice motion. The locations of the beacons are monitored every 3 hours by the satellite when it passes overhead. The beacons were designed and built by MetOcean Ltd. of Dartmouth, N.S. and were deployed early in the project. Due to the uncertainty in ARGOS location fix of 0.2km, comparison of data sets will be limited to large scale ice features.

SAR and SLAR data from the region were collected by Can. Ice Centre's surveillance aircraft and by the ERS-1 satellite. The SLAR data was collected by a Dash-7 equipped with a real aperture, side-looking airborne X-Band radar made by CAL Corporation. It collects data on both sides of the airplane covering a 100km wide strip when data is acquired on a 1:1 million scale. More detail can be obtained by going to half or one-quarter of this scale but then the area covered reduces respectively to 50 and 25km wide strips. The SLAR or SAR have the ability to map the surface in all weather conditions, and can identify ice types, ice edges locations and ice concentrations. Alongside the SLAR, the airborne imaging micro-wave radiometer (AIMR) measures the brightness temperature of the ice surface, which varies as a function of the ice type, snow cover and surface wetness. It complements the SLAR data by being able to discriminate most ice types and deduce ice edge locations and ice concentrations.

The Earth Resources Satellite (ERS-1) uses a 5.3 GHz frequency C-band SAR to collect ice data from a polar orbit with a 3-day repeat cycle. In the image mode, the SAR obtains strips of high-resolution imagery, 100m wide to the right of the satellite track. Imagery is built up from the time delay and strength of the returning radar beam which depends on roughness and dielectric properties of the reflecting surface. The resolution (Pixel size) is 12.5m.

4.0 DATA COLLECTION AND ANALYSIS

4.1 AIRBORNE DATA COLLECTION

Wind conditions during March 1992 were somewhat unusual. Strong southwesterly winds caused large stretches of open water and thin ice in the near shore area which had to be traversed in order to reach the pack ice. Despite this fact, three long-range data collection missions were undertaken to the pack ice during which large quantities of air-borne and surface ice thickness data were collected (Table 1). During the first two trips only EM data was collected while on the last trip both EM and radar data was collected. A total of 269km of EM and EM/Radar data was collected, 35km over pack ice in the area of the surveyed floe and 234km during the trips to and from the pack ice (Table 1).

Table 1. EM and EM/Radar data sets of the pack ice trips.

Date	Type	Location	Km of data	Comments
March 7	EM	Trip Out	21	lots of open water
March 7	EM	Pack Ice	3	3 passes over floe
March 7	EM	Trip In	28	patchy, strong winds
March 8	EM	Trip Out	103	thin to heavy ice
March 8	EM	Pack Ice	32	13 passes/ 2 lines
March 8	EM	Trip In	48	variety of ice types
March 13	EM/Radar	Trip Out	26	patchy ice to pack ice
March 13	EM/Radar	Trip In	8	pack ice to patchy ice
		Total	269km of data over offshore pack ice	

In addition, a series of shorter validation flights were performed over the two land fast calibration sites and the mobile ice in Belle Isle Strait. The data sets collected from Pistolet Bay are listed in Table 2 and that from

Hare Bay in Table 3. Data sets are identified by their station's name which contains information on its location through the first two letters, its data type (third letter) and station number. The location letters are PB for Pistolet Bay, HB for Hare Bay, BI for Belle Isle Strait, PI for the offshore pack ice and AL for the airport lake site. The third letter distinguishes line data sets "L" from isolated station data "S".

The Pistolet Bay site was profiled on 19 occasions, 11 with just the EM sensor and 8 with both EM and Radar sensors (Table 2). An additional 22 data sets were collected in the Pistolet/Belle Isle area. The Hare Bay site was profiled on 8 occasions, 6 by the EM sensor alone and 2 by the EM and Radar combined sensor unit (Table 3). Another 11 data sets in the Hare Bay area were collected while flying to and from the pack ice and from the calibration site. The other EM data is from Belle Isle Strait where an additional 4 data sets were collected over and around a small calibration line BI-L1.

Table 2. EM and EM/Radar data sets of Pistolet Bay along the ice and snow calibration lines PB-L1 to PB-L6.

Date	Type	Amount of Data
March 6	EM	7 line and 2 areal passes
March 7	EM	1 line and 10 areal passes
March 8	EM	3 line and 9 areal passes
March 13	EM/Radar	4 E-W, 4 N-S line and 1 areal passes
	Total	19 passes over calibration lines and 22 areal passes over Pistolet Bay and Belle Isle Strait

Table 3. EM and EM/Radar data sets for Hare Bay along the ice and snow calibration lines HB-L1 to HB-L4.

Date	Type	Amount of Data
March 9	EM	2 areal passes
March 10	EM/Radar	3 E-W, 3 N-S line and 3 areal passes
March 13	EM/Radar	1 E-W, 1 N-S line and 6 areal passes
	Total	8 passes over calibration lines and 11 areal passes over Hare Bay

Radar data was collected over the airport lake site as part of the EM/Radar towed package and as calibration data by putting the radar antenna directly on the snow surface. The airport lake site was surveyed several times with the radar alone and as part of the bird sensor package. In the towed mode, radar data alone could be collected by turning the EM transmitter off. A total of 14 data sets of radar data was collected.

Table 4 Radar data sets of the airport lake site along the snow depths calibration lines AL-L1 and AL-L2.

Date	Type	Amount of Data	Comments
March 7	Radar	2 lines (60m)	Ground Cal. Data
March 9	Radar	4 test passes	Test flight
March 10	EM/Radar	4 passes	EM switched on/off
March 13	EM/Radar	4 passes	EM switched on/off
	Total	14 data sets over calibration lines	

4.2 SURFACE DATA

The second helicopter was used to collect the surface calibration data, to mark the surveyed points with snow-filled garbage bags and to deploy satellite-tracked ice beacons. Ice thickness data was collected through hand-augered ice holes and snow depths with a metric snow staff. At selected locations ice chip samples from various depths of the ice sheet were collected to determine salinity content of the ice to verify the bulk ice salinity estimates obtained by the EM sensor and used in calculations of the speed of the electromagnetic signal in ice. Snow samples were also collected for salinity determinations after it was discovered that the thin snow layer on some pack ice floes had high salinity contents. This was thought to interfere with the radar and EM return signals even though the real time processing did not encounter any problems. The ice and snow calibration and salinity data are listed in the Appendix A for the five regions: Pistolet Bay, Hare Bay, Belle Isle Strait, offshore pack ice and the airport lake site. Tables 5 and 6 below summarizes the surface ice and snow data.

Table 5. Number of ice thickness, snow depth and freeboard measurements taken along calibration lines. (Observation numbers are listed first followed by slanted bar and their mean values)

Line#	Date	Ice thickness	Snow Depth	Freeboard	Location
PB-L1	Mar5	20/63	20/29	20/-5	Pistolet Bay
BI-L1	Mar6	8/40	8/5	8/2	Belle Isle Str
AL-L1	Mar7	---	36/--	---	Airport Lake
AL-L2	Mar7	---	47/--	---	Airport Lake
PI-L1	Mar7	9/49	9/2	9/2	Pack Ice
PI-L2	Mar8	14/36	13/2	13/2	Pack Ice
PI-L3	Mar8	8/44	6/2	---	Pack Ice
HB-L1	Mar9	10/68	10/13	10/1	Hare Bay
HB-L2	Mar10	10/69	10/20	10/-2	Hare Bay
HB-L3	Mar10	---	46/17	---	Hare Bay
HB-L3	Mar13	---	46/6	---	Hare Bay
HB-L4	Mar10	---	46/24	---	Hare Bay
HB-L4	Mar13	---	46/12	---	Hare Bay
PB-L4	Mar6	---	77/31	---	Pistolet Bay
PB-L4	Mar10	---	77/37	---	Pistolet Bay
PB-L4	Mar13	---	77/24	---	Pistolet Bay
PB-L5	Mar6	---	77/31	---	Pistolet Bay
PB-L5	Mar10	---	77/32	---	Pistolet Bay
PB-L5	Mar13	---	77/19	---	Pistolet Bay
PB-L6	Mar9	---	10/26	---	Pistolet Bay
PB-L6	Mar10	---	46/28	---	Pistolet Bay
PB-L6	Mar13	---	46/16	---	Pistolet Bay
PB-L2	Mar13	24/67	24/21	24/-6	Pistolet Bay
PB-L3	Mar13	10/70	10/17	10/-2	Pistolet Bay
	Total	113	935	104	

The ice and snow line data summary in Table 5 shows that a total of 113 ice thickness samples and a total of 935 snow depth samples were collected along the calibration lines.

Table 6. Number of measurements taken at separate ice stations.

Station	Date	Location Line #	Salinity Ice	Salinity Snow	Salinity Water	Thickness Ice	Thickness Snow
PB-S1	Mar5	PB-L1.11	3	1	1	1	1
BI-S1	Mar5	Pack Ice	--	--	--	1	1
BI-S2	Mar5	Pack Ice	--	--	--	3	3
BI-S3	Mar5	Land-fast	--	--	--	3	3
BI-S4	Mar6	Land-fast	--	--	--	1	1
BI-S5	Mar6	Pack Ice	--	--	--	1	1
PI-S1	Mar6	Pack Ice	--	--	--	2	2
PI-S2	Mar6	Pack Ice	--	--	--	3	3
PI-S3	Mar7	PI-L1.01	3	3	--	--	--
PI-S4	Mar8	PI-L2.05	2	2	--	--	--
PI-S5	Mar8	Pack Ice	--	--	--	5	5
HB-S1	Mar9	HB-L1.05	4	3	--	--	--
HB-S2	Mar9	Inner Bay	--	--	--	1	1
HB-S3	Mar10	HB-S2	--	2	--	--	--
HB-S4	Mar10	HB-S2	--	2	--	--	--
HB-S5	Mar11	HB-L1.05	4	--	--	--	--
HB-S6	Mar11	HB-L1.05	4	--	--	--	--
HB-S7	Mar11	HB-L1.05	4	--	1	--	--
		Total	24	13	2	21	21

Figure 4 shows the trajectories of the three beacons deployed on March 6 and 7 during the time of the project. The beacons moved 40km southwards in 3days under the northwesterly winds before turning eastwards 40km in 4 days under southwesterly winds. The beacon tracks did not show measurable convergence or divergence in the pack ice but did show that the near shore pack ice moved faster southwards than the pack ice over the offshore banks, causing an 30 degree counterclockwise rotation of the ice in the area of the beacons.

4.3 REMOTELY-SENSED DATA

The SAR data of the ERS-1 covering the area of interest was collected during the northward pass of the satellite at 22.00 EST. During the period of the EM project, data was collected on the evenings of March 4, 7, 10, 13 and 16 and covered the approximate area shown in Fig. 5 which shows the available SLAR data collected by Ice Centre during the same 12 day period. There is some overlap of the data sets which can be geometrically realigned to the same observation time by the ice drift data. SAR and SLAR data from 5 days will thus be used for analysis and compared to the offshore EM and on-ice data collected on March 7, 8 and 13.

4.4 DATA ANALYSIS

Determining the distance of the bird to the water/ice interface is a complex inverse calculation. The amplitude and phase of the secondary signal depends not only on the bird's altitude above the ice surface, but also on the operating frequency, the ice conductivity and the sea water conductivity. The response can be numerically estimated in a precise and efficient manner for horizontally-layered ice and water layers of known thicknesses and conductivity (1D models), while approximations to the complex ice features (ridges) are more difficult and time-consuming to model. Using such models, the measured EM signals can be inverted to yield estimates of distances from the bird to the sea water surface on a point-by-point basis (1D model) or as a profile or grid data (2D and 3D models). The 1D inversion technique was used for the real-time data display during the 1992 St. Anthony survey and provided excellent accuracy over the relatively smooth ice conditions found at the calibration test sites. The full-scale inverse 2D or 3D modeling is not yet practical for the real-time data collection mode required by Transport Canada. Presently, 2D ice structures are being interpreted using look-up tables similar to those constructed by Liu and Becker (1990) and successfully used on the 1991 Beaufort Sea data (Prinsenberg et al., 1992). It should be noted that this process has been automated to a large extent, but is not yet ready for real-time 2D inversions.

5.0 DATA SAMPLES

5.1 LAND FAST ICE

The EM/Radar system was extensively tested over the calibration lines in Pistolet and Hare Bays. One example of this data from Pistolet Bay shows the conditions before and after the rain of March 12 (Fig. 6). The calibration surface data was collected along an 237.5m line at 12.5m intervals for ice and at 3.1m intervals for snow (All listed in Appendix A). The calibration line was just shore ward of a thicker rafted ice zone located to the northeast of the area. This thicker ice can be seen on both figures to the left of the calibration lines and was sampled on the last day for verification. The figures also show the altitude of the bird being in the range of 15 to 20m, and the filtered high frequency laser data (HPF-Laser). The HPF Laser data represents surface roughness as it plots the surface heights at 1.5m intervals when the flying speed is 100kmph. The surface roughness was very small over Pistolet Bay (Fig. 6) in comparison to the roughness observed over the rubble of the mobile pack ice (shown later).

Snow plus ice thickness surface data from the EM system compares well with surface calibration data for the PB-L1 line on March 6 and for the PB-L2 line on March 13. The data do show the reduction in the overall thickness from March 6 to March 13 due to the loss of snow. In general the thickness estimated by the EM sensor were lower than those obtained by direct observation by about 5cm (Fig. 6). This difference is being investigated by another analysis contract, but is suspected to arise from side ward motion of the bird. The laser, due to pointing then slightly off the vertical, will measure a larger distance to the surface; whereas the EM sensor, due to its larger footprint, will still measure the shorter distance straight downward. Their difference will thus underestimate the snow plus ice thickness. Engineering data collected by an accelerometer and role and tilt meters inside the bird will be used to further investigate this discrepancy.

In Fig. 6, the rafted ice northeast of the lines were sampled and found to be on average 113cm thick (3 places) but reaching a thickness of 156cm at one place. Very little, if any, snow was present in this area on March 13.

5.2 PACK ICE

During the test flights over Pistolet Bay on March 6, ice thickness data was collected from the pack ice in Belle Isle Strait. One floe was sampled for ice thicknesses and snow depths to verify the offshore EM data (Fig. 7). The 40cm ice cover was covered with a wet 5cm layer of snow. Eight ice thickness samples at 12.5m spacing were taken over the small ice floe (130x150m). The ice thickness varied from 38 to 45cm and had a mean of 40cm (Line BI-L1 in Appendix A).

The EM data reproduced the observed ice thicknesses well and showed that beyond the ice floe the pack, ice rafted to 1.2m and 1.8m average depths. In the HPF-Laser data, the smooth surface of the ice floe can clearly be distinguished from the rough surface topography of the pack ice. Crossing the floe perpendicular to the calibration line show the same ice characteristics (lower panel of Fig. 7). The homogeneous 45cm thick ice floe is bordered by rafted ice having variable ice thicknesses of up to 1.5m thick and a high degree of surface roughness (HPF-Laser data).

Ice thickness data collected along the flight tracks to and from the pack ice on March 7 and 8 are shown in Fig. 8. The area covered by the figure is 30x40km and represents the transition zone from thin inshore ice on the left (west) side and thick offshore pack ice on the right (east) side. The two top lines are from March 7 while the bottom two tracks are from March 8. During mid-day of March 7, the ice drifted rapidly (1kmph) to the south east (Fig. 4) under strong westerly to northwesterly winds. Rafted ice with an average ice thicknesses of 1.0 to 1.5m were observed in the pack ice area while thinner ice, 10 to 30cm thick, was observed west of the pack ice.

A triangular flight pattern was flown around the calibration floe on March 7 (Fig. 9). The small tracks covered 2 to 3km with several shorter flight tracks over the 130 by 150m floe itself shown in the left/centre of the figure. In the right hand corner of the survey area, an 5m thick multi-year ice floe was surveyed twice. The displacement between the location (75m) in 3 minutes is mainly caused by the 1kmph ice drift which can cause a displacement of 50m in the 3 minute period between overflights (Fig. 4).

Ice thicknesses along three tracks from the area are shown in Fig. 10. The multi-year ice floe can be seen in the short track in the top panel. The multi-year floe was over 5m thick with 50 to 75cm thick ice around it. It also floats higher in the water than the surrounding ice; this is clearly visible in the surface roughness data. The edges of the multi-year floe have high roughness values. The middle panel shows the data for a track crossing the calibration floe. Ice thicknesses are very constant around the 40 to 50cm value with thicker ice (up to 1m) away from the surveyed floe. Measurements indicated that the floe was on the average 49cm thick and covered with a thin 2cm layer of snow (Appendix A). The EM data from a longer track across the surveyed floe in the bottom panel of the figure indicates that some open water occurred to the west of the floe. Histograms of ice thickness or surface roughness can be made from the data (Fig. 11). Ice thickness histograms are plotted for the tracks around the surveyed floe of March 7 whose line numbers were identified in Figs. 9 and 10. The histogram of the short track (Line 10050) across the multi-year floe shows that the ice thickness of the floe was between 4.0 and 5.5m thick. For the longer track (Line 10040), the multi-year still shows up but contributes less to the total number of samples of the histogram. The histograms from the tracks crossing the surveyed floe (10020 and 10030) indicate that ice thicknesses ranged between 0.4 to 1.0m with a mean of 60cm. The surveyed floe was the largest floe in the area but had an average thickness of only 49cm and was covered by a 2cm layer of snow. It appears to be the youngest ice in the area and least reworked into rubble by winds. The ice chart (Fig. 2) indicated thicker ice for the area but since it refers to a much larger area, direct comparison to this small areal sample is not justified.

5.3 ICE SALINITY

Ice salinities were obtained from ice chips collected from various depths in the ice sheet. All salinity values are listed in the Appendix A. Ice salinities from the land fast ice stations in Pistolet and Hare Bays were very uniform throughout the ice sheet and throughout the area. The values in Pistolet Bay were higher (mean of 11ppt) than those in Hare Bay (mean of 8ppt). Three sites were drilled in Hare Bay, 1m apart, to check on the horizontal salinity variation. No differences between the sites were noticed suggesting that within the accuracy of the instrument (.2ppt), one profile per calibration site appears to be sufficient.

Ice salinities of the thin floes sampled in the pack ice varied widely. At pack ice station #3 (PI-S3), sea ice salinity had a mean value of 28ppt, whereas at station #4 (PI-S4) only 8ppt was observed. Ice thicknesses were respectively 49cm and 38cm, indicating that the floes were made up of very young, locally grown 5-6 week old ice. What was peculiar about the pack ice was the high salinity content of its snow layer. The 2cm snow layers had salinity values of 40 and 45ppt, even though samples from deeper snow in ridges of the floes were fresh (zero ppt). The thin snow layer may obtain its salinity content from spray in the air, which after being deposited on the pack ice continually evaporates from the snow cover leaving the salt behind. Alternately, these ordinary high salinity values may arise from the ice sheet itself when during the day the temperature gradient in the surface of the ice reverses permitting an upwards salt flux. This high snow salinity condition has never been noticed by one of the authors (Prinsenberg) during several trips to the pack ice off the Labrador coast.

6.0 CONCLUSION

The St. Anthony ice thickness survey successfully demonstrated that the present Aerodat's EM/Radar sensor package can obtain in real-time ice plus snow thicknesses. The survey also showed that:

- the drift problems in the EM system encountered during the 1991 Beaufort Sea project were solved,

- the installation of the Radar does not interfere with the EM sensor,

- ice thickness data collected agreed with surface calibration data,

- and the large amount of EM thickness data from the pack ice can verify remotely sensed data collected by ERS-1 and Ice Centre's reconnaissance plane.

Future surveys planned for the system include a field test in the Gulf during the winter of 1993 by the Coast Guard using one of their helicopters based on an ice breaker. During the winter of 1994 the system will again be used by DFO off the mid-Labrador coast in conjunction with an ice pressure experiment. The contractor is also considering a fixed-wing version of the system using a winch and cradle to bring the bird into a safe position for take-off and landing. The fixed-wing version would greatly extend the potential survey area over the helicopter version which was aimed to aid Canadian Coast Guard ice breakers in their route selection, and would be suitable for routine ice thickness reconnaissance flights. The helicopter version is optimal for Coast Guard needs, but the fixed-wing version would increase maximum traverse lengths from their present 200-300km (round trip with no refueling) to about 3000-4000km, depending on the aircraft used. With refueling at Arctic supply bases such as the one at Alert, the entire Arctic basin could be traversed over the course of one day. G. Fowler and M. Ikeda are thanked for their comments on the original draft.

ACKNOWLEDGEMENT

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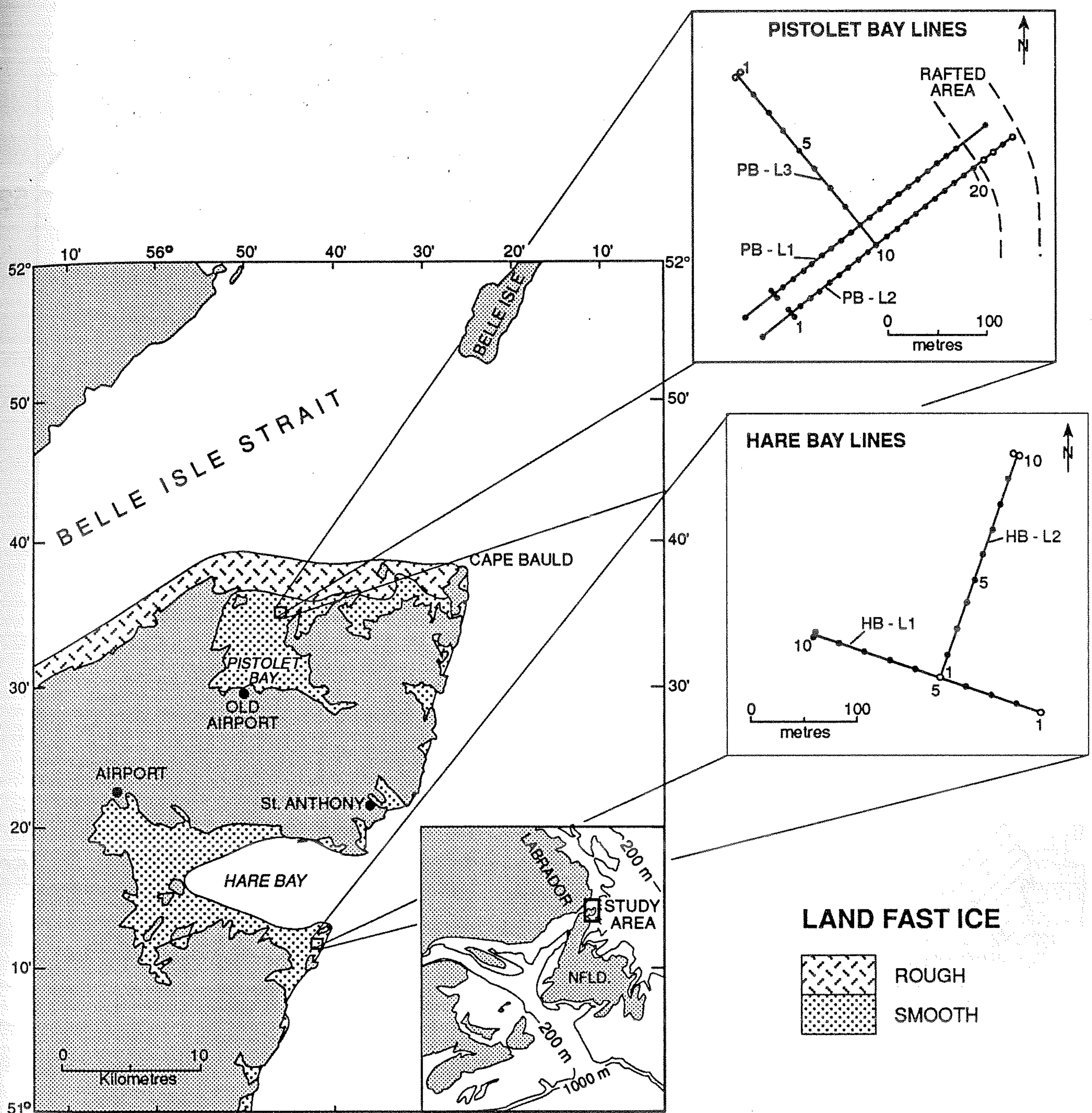


Figure 1. The St. Anthony sea ice survey tracks of March, 1992. Inserts show the orientation of the Pistolet and Hare Bay calibration lines.

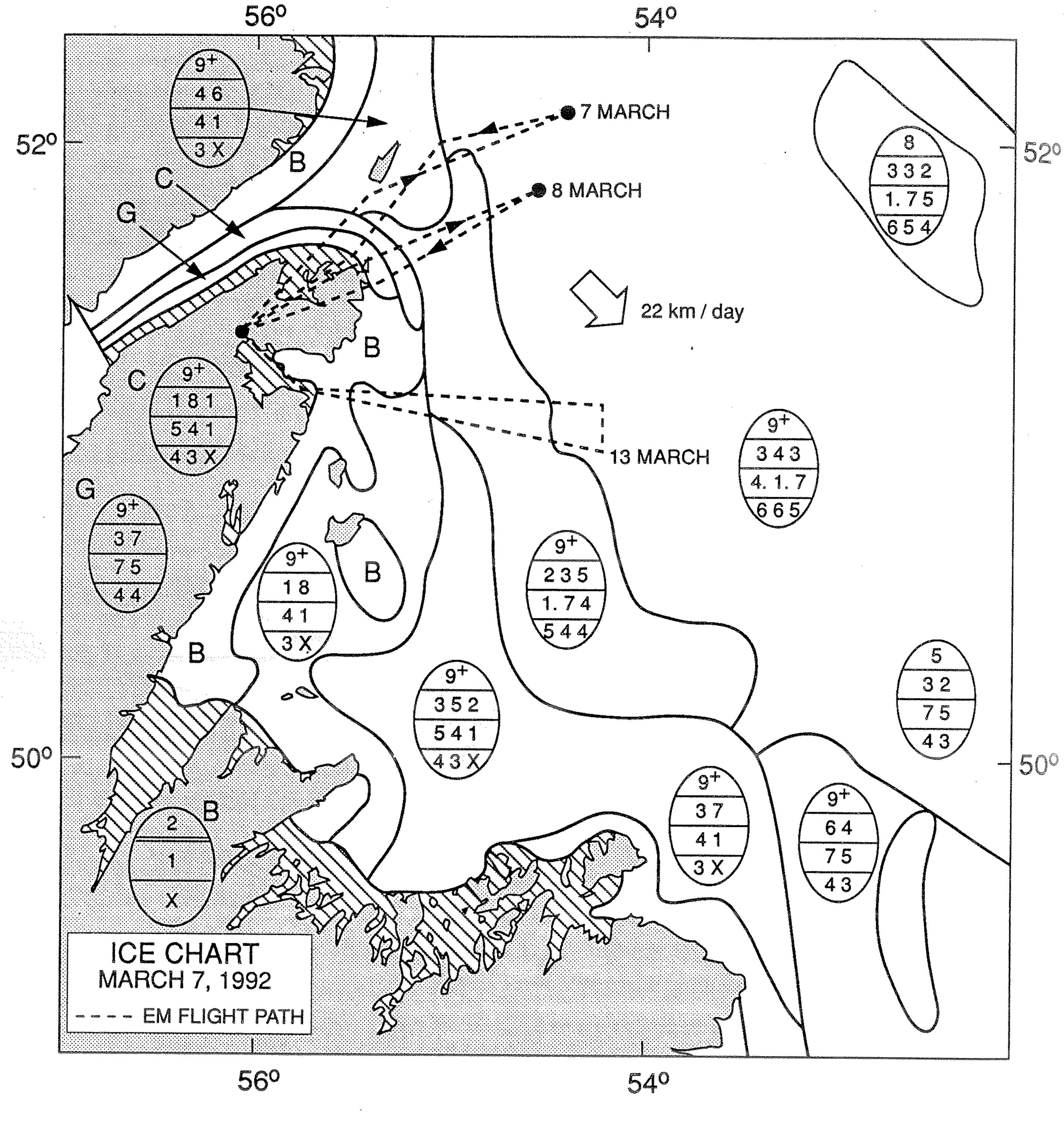


Figure 2. March 7 ice conditions off St. Anthony as copied from Ice Centre's daily ice charts. Also shown are the flight paths taken over the offshore pack ice.

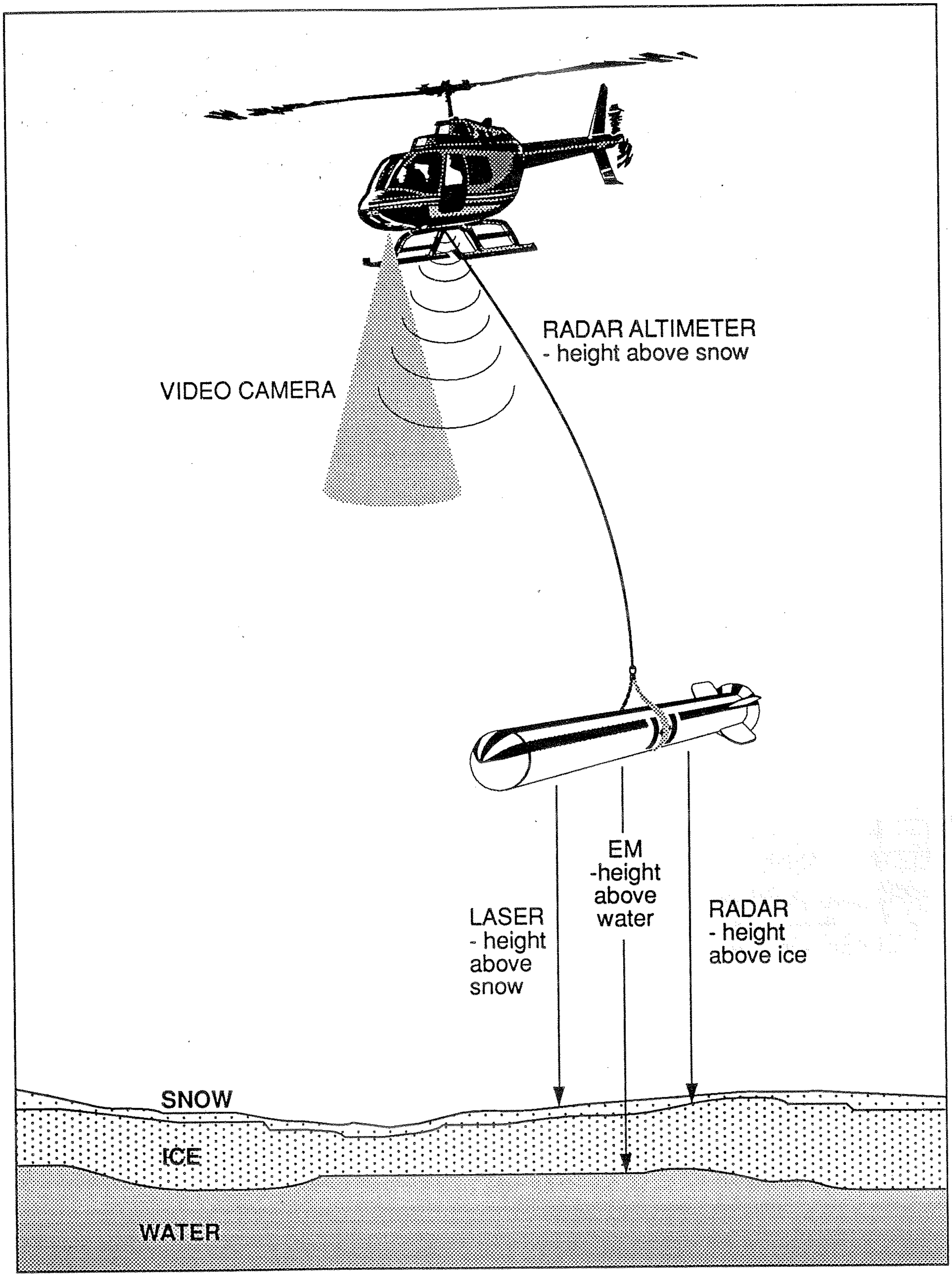


Figure 3. Sketch of EM/Radar ice and snow thickness data collection system.

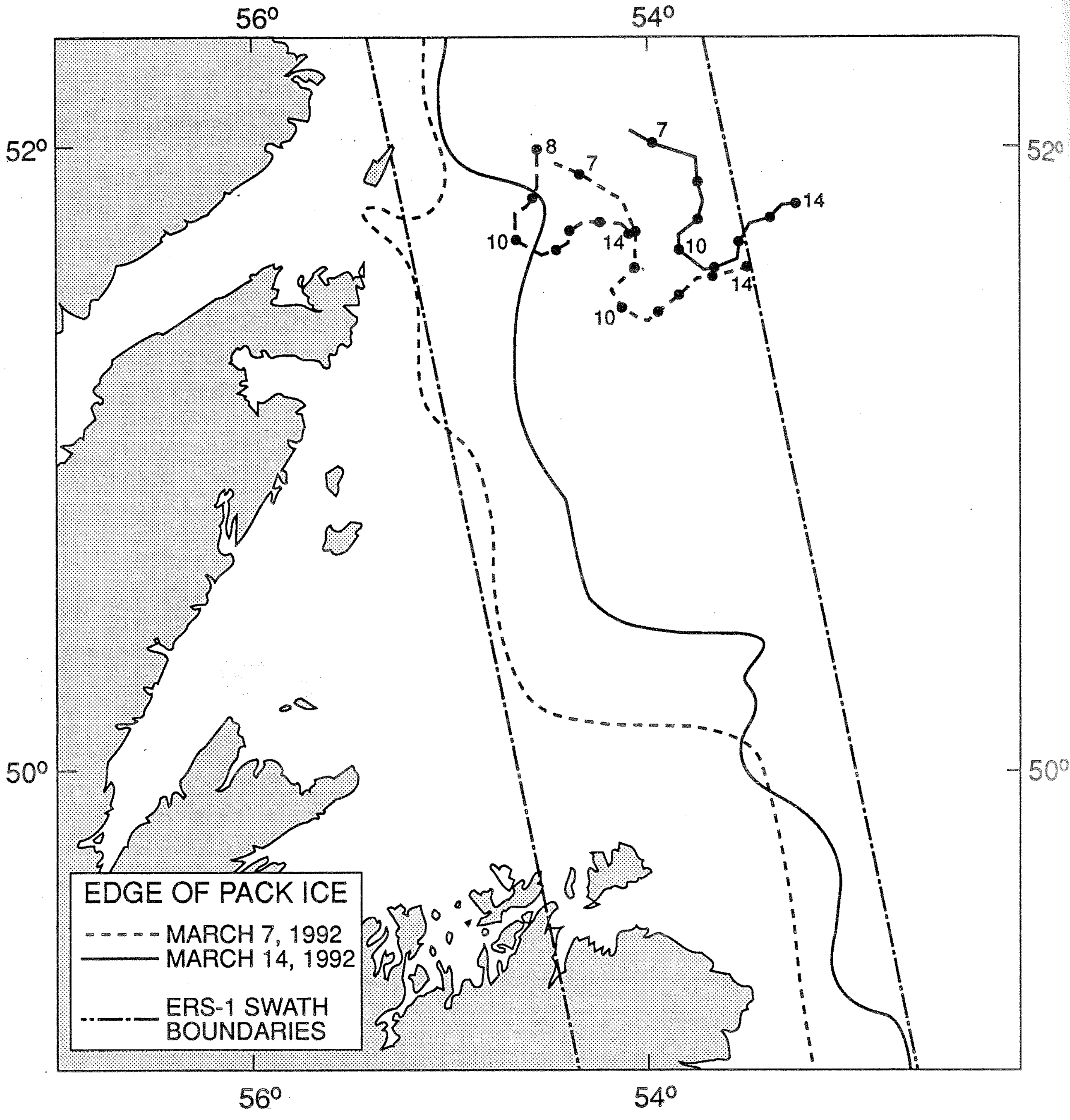


Figure 4. ERS-1 Satellite SAR coverage and 7-day displacements of the inshore ice edge of the pack ice and the three beacons deployed on March 6 and 7. Beacon trajectories are shown as half daily drifts labelled by day of the month of March at 12hr EST.

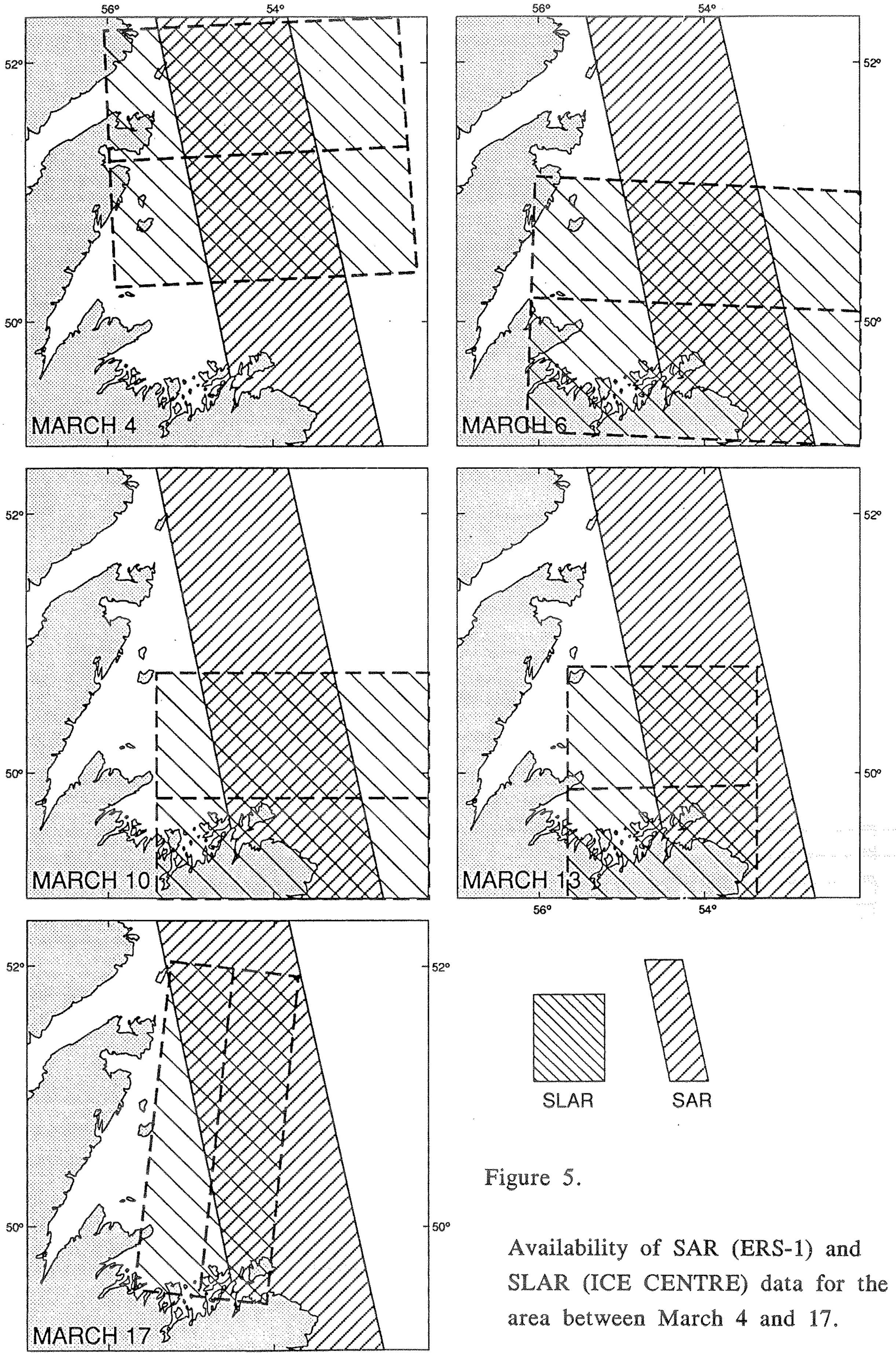


Figure 5.

Availability of SAR (ERS-1) and SLAR (ICE CENTRE) data for the area between March 4 and 17.

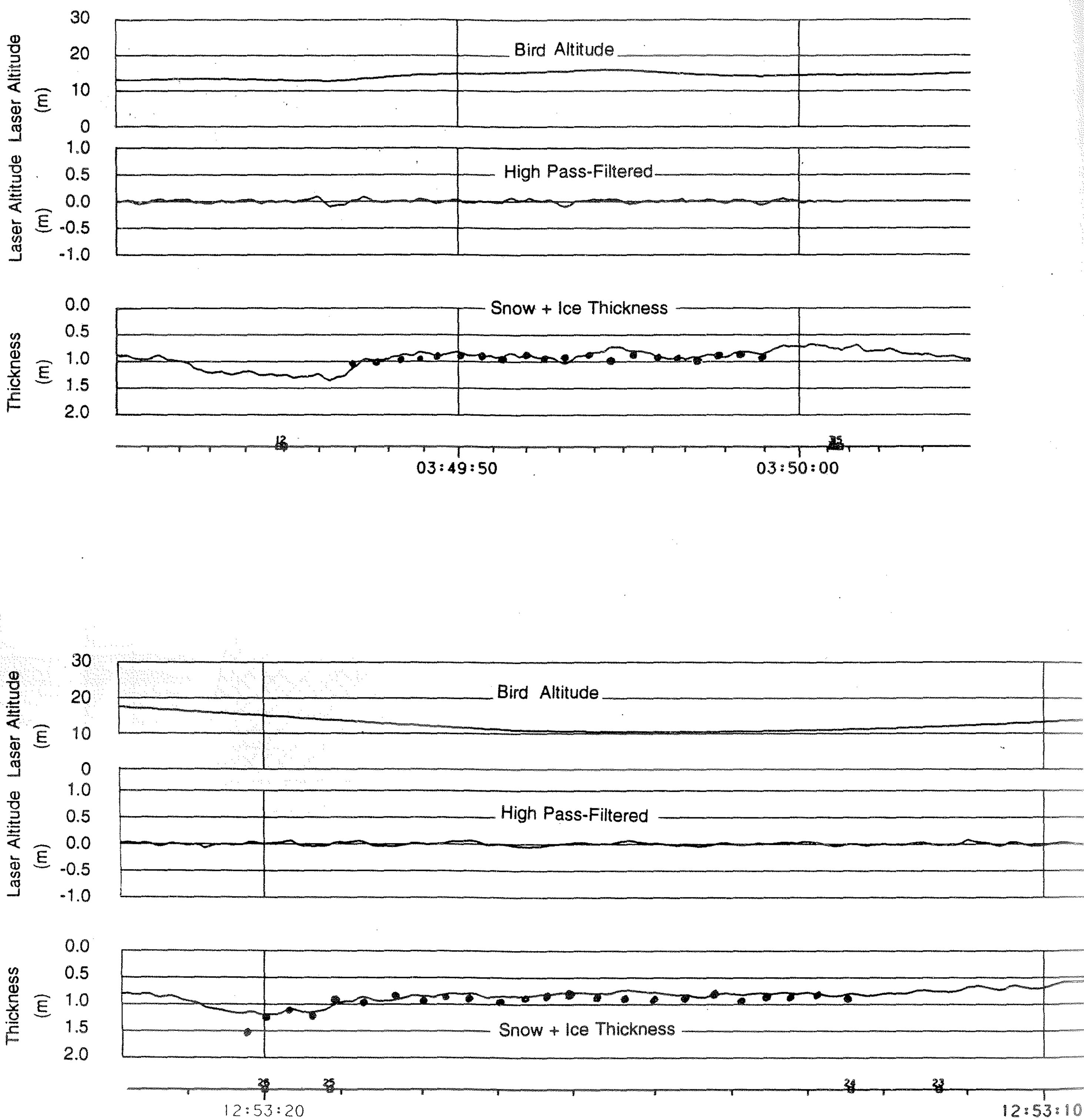


Figure 6 EM ice thickness and surface calibration data from Pistolet Bay for PB-L1 on March 6 in top panel and PB-L2 on March 13 in bottom panel. Data shows the altitude of the EM sensor above the snow surface, the surface roughness (High Pass-Filtered Laser data) and snow plus ice thickness data.

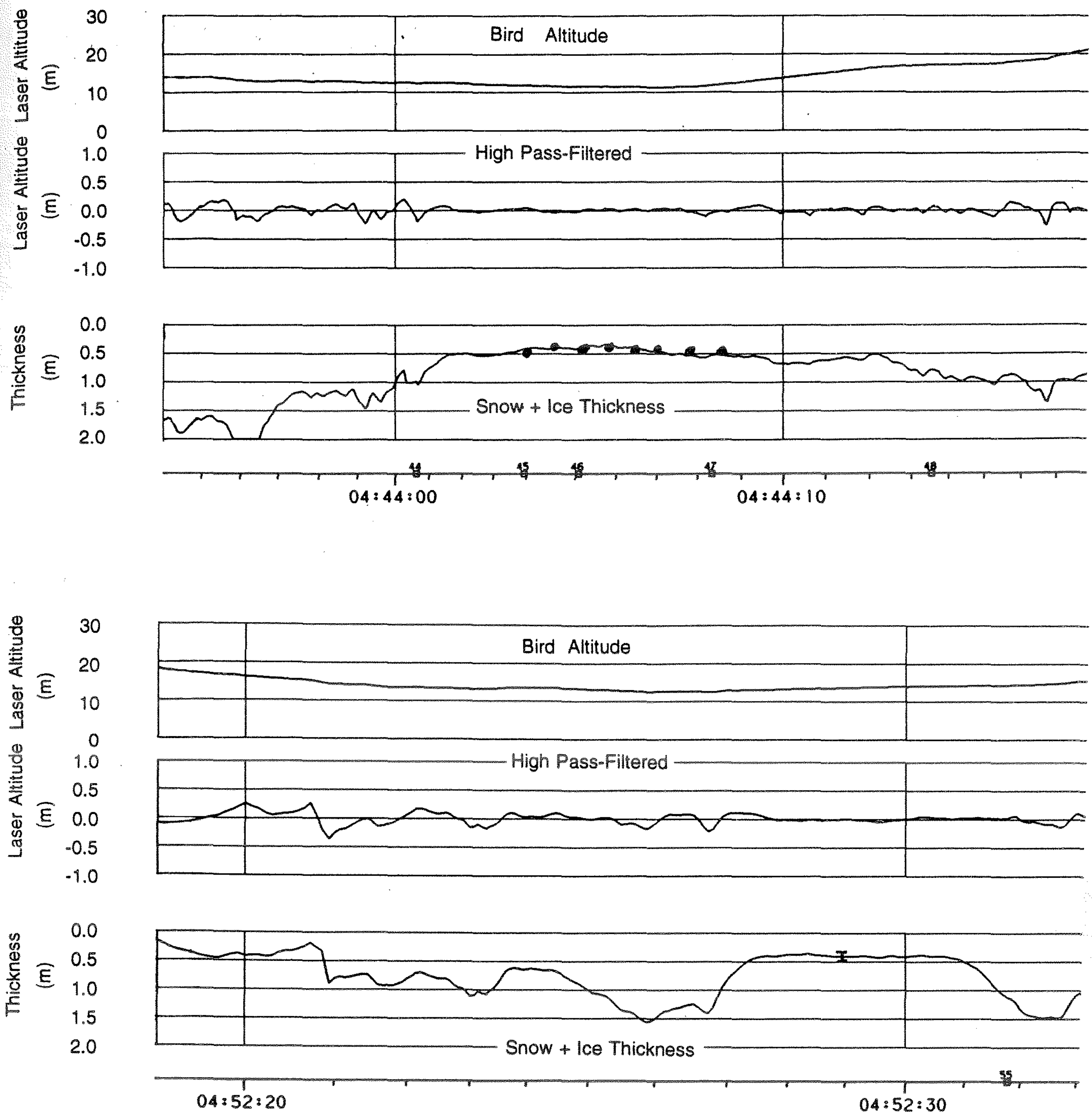


Figure 7 EM ice thickness and surface calibration data for two perpendicular flight tracks over a surveyed floe in Belle Isle Strait on March 6, 1992.

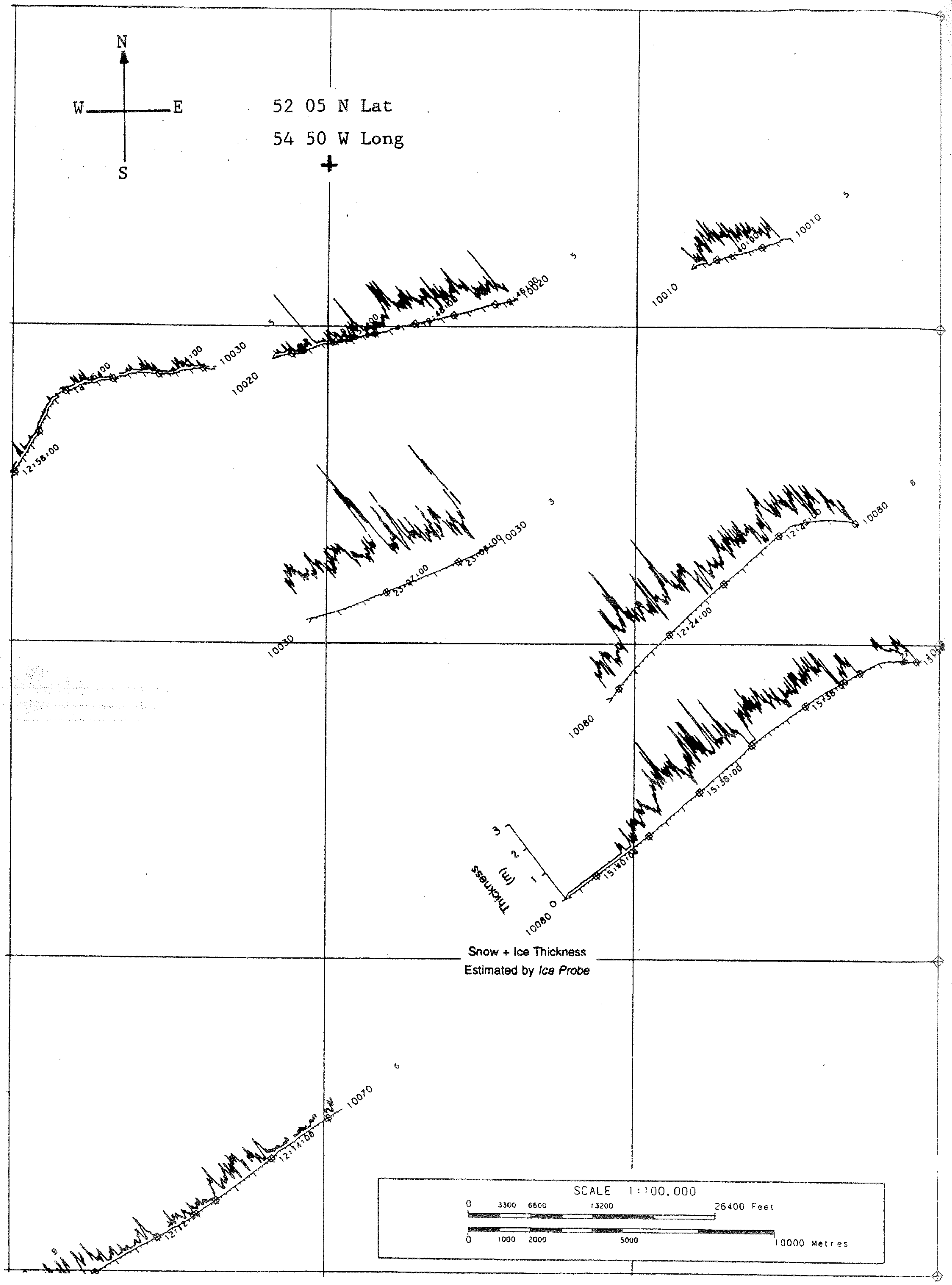


Figure 8 Ice thickness observations along the tracks to and from the pack ice on March 7 and 8.

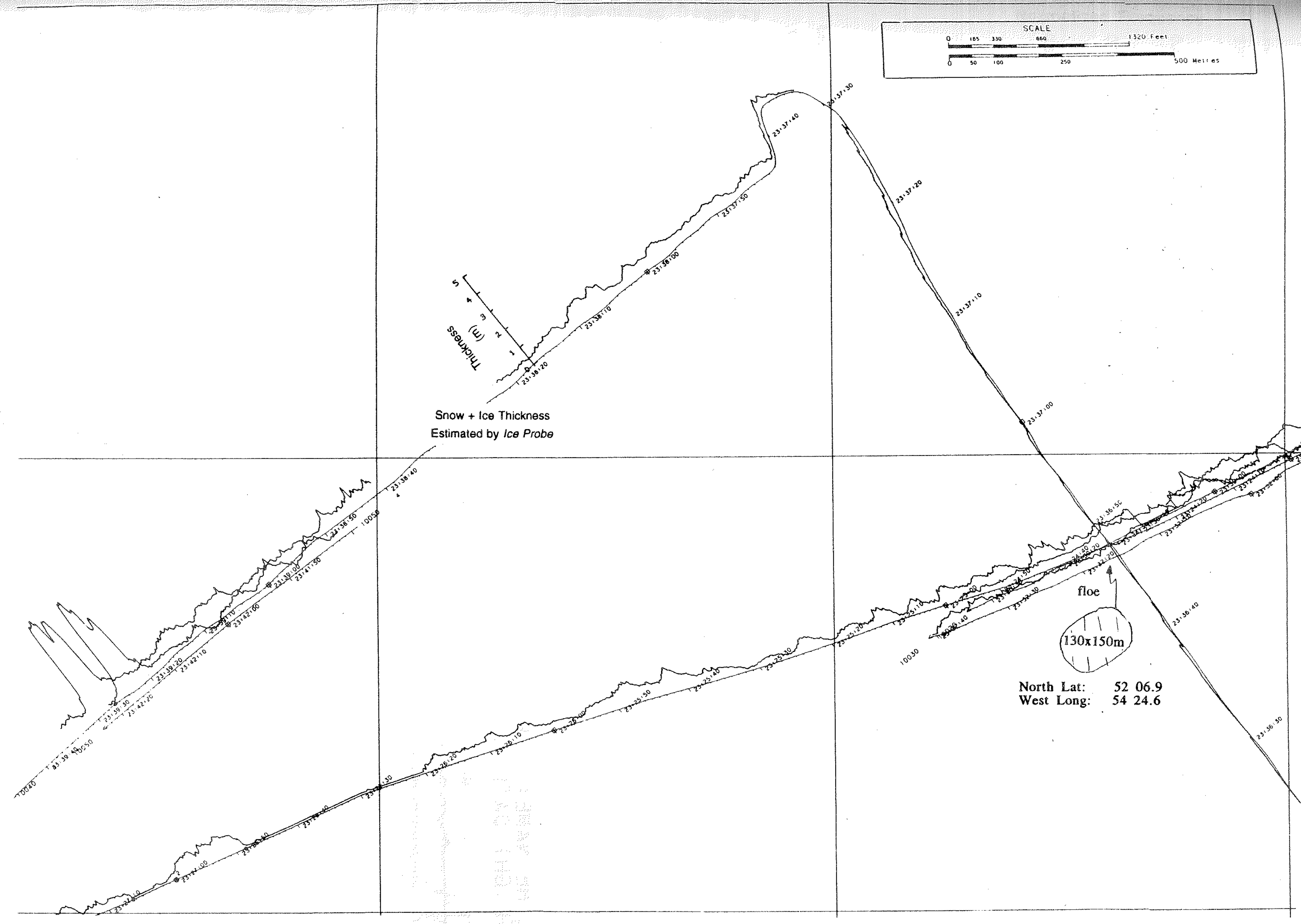


Figure 9 Triangular track distribution of EM flights around the surveyed pack ice floe on March 7.

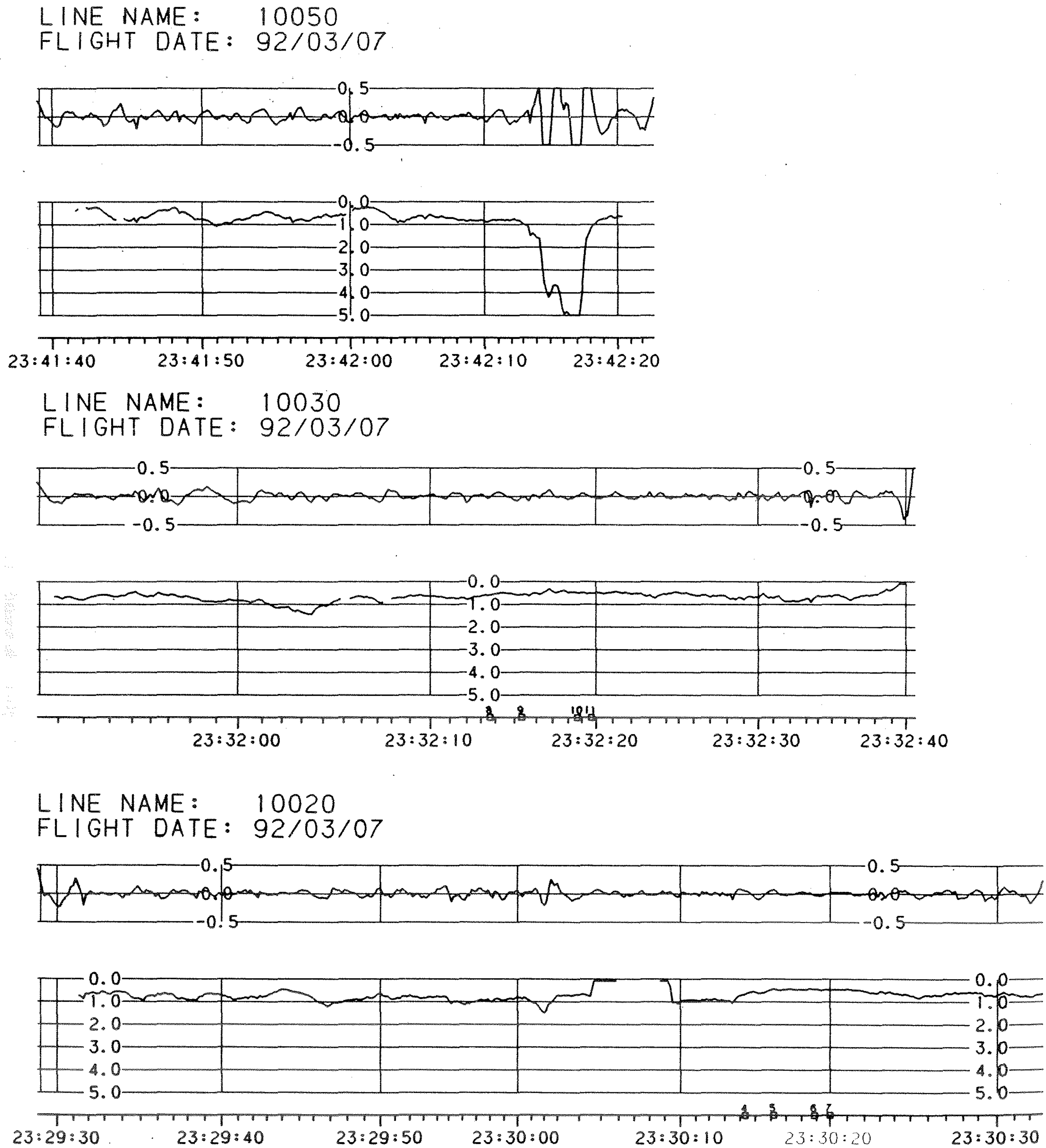
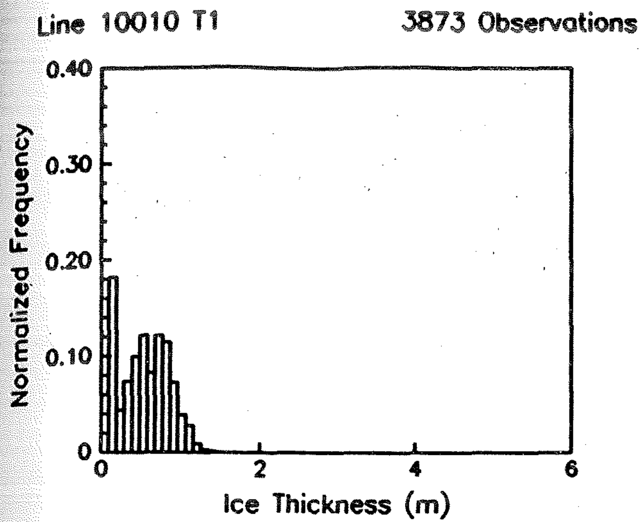
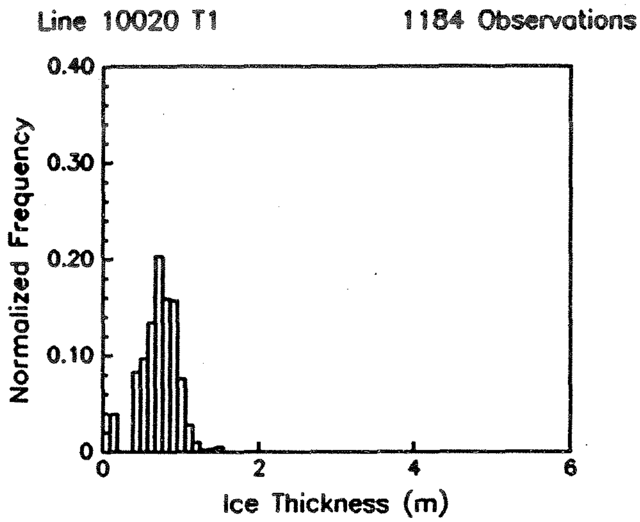
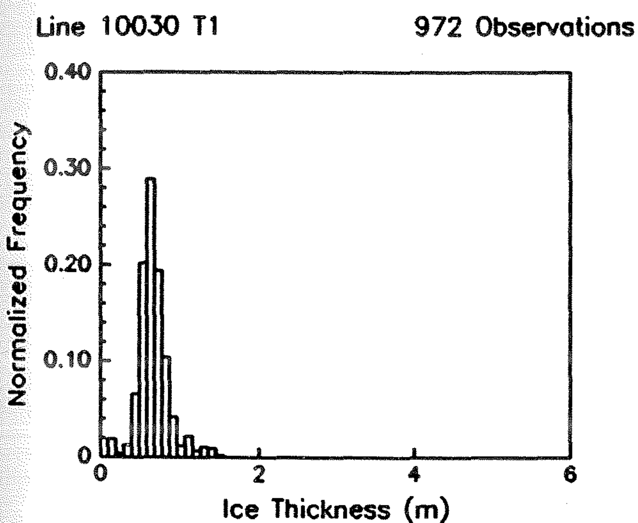
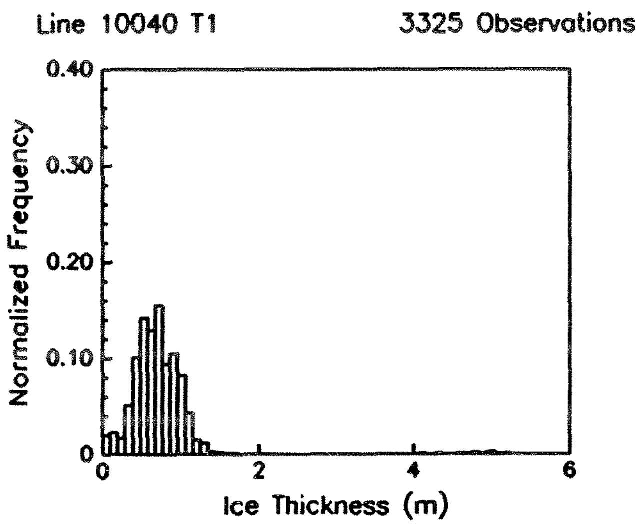


Figure 10 Horizontal distribution plots of surface roughness and ice plus snow thickness for three tracks near and over the surveyed floe on March 7 (Track locations are shown on Fig. 9).









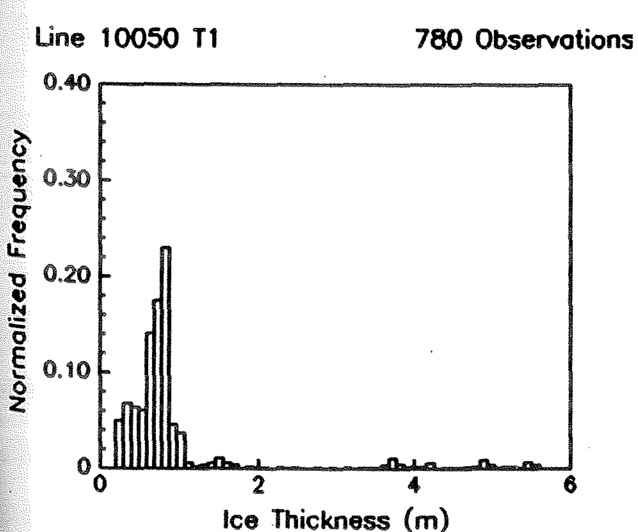


Figure 11 Ice plus snow thickness histograms for the tracks displayed in Figs. 9 and 10.

APPENDIX A: SURFACE CALIBRATION DATA

The surface calibration data is listed sequentially for each of the following five locations:

1. PISTOLET BAY
2. HARE BAY
3. BELLE ISLE STRAIT
4. PACK ICE
5. AIRPORT LAKE SITE

PISTOLET BAY SURFACE CALIBRATION DATA

Station	Pistolet Line #1	Temperature: -10 C
	SW (bag #1) to NE (bag #20)	Winds: 280 at 35knts
PB-L1	Bags 1 to 10 on March 4	North Lat: 51 33.6
	Bags 11 to 20 on March 5	West Long: 55 48.6
	Bags 12.5m apart	

	Snow(cm)	Freeboard(cm)	Ice(cm)
PB-L1.01	28	-6	61
PB-L1.02	28	-4	59
PB-L1.03	21	-4	61
PB-L1.03	21	-4	61
PB-L1.04	45	-8	61
PB-L1.05	27	-4	59
PB-L1.06	25	-2	67
PB-L1.03	23	-3	67
PB-L1.08	35	-6	65
PB-L1.09	23	-4	64
PB-L1.10	35	-5	60
PB-L1.11	33	-4	63
PB-L1.12	24	-4	63
PB-L1.13	30	-4	64
PB-L1.14	22	-3	67
PB-L1.15	25	-3	65
PB-L1.16	20	-3	65
PB-L1.17	32	-5	64
PB-L1.18	23	-5	63
PB-L1.19	41	-6	65
PB-L1.20	47	-8	65
MEAN	29	-5	63

- -

Station	Pistolet Bay Ice Stn.#1	Temperature > -8 °C
	at bag #11 (PB-L1.11)	Winds: 240 ap 15knts
PB-S1	March 5, 1992	North Lat: 51 33.6
		West Long: 55 48.6

	bottle#	Salinity	Location/Depth
PB-S1.01	10834	8.0	slush layer*
PB-S1.02	10835	11.0	10-15 cm
PB-S1.03	10836	9.0	25-30 cm
PB-S1.04	10837	13.0	40-45 cm(w)
PB-S1.05	10833	32.0	surface water

* 2cm refrozen layer on top of ice
(w) means ice chips were wet but were drained

Station	Pistolet Bay Snow Line #4	Temperature: -15 °C
	Snow depths along PB-L2	Winds: 320 at 15knts
PB-L4	March 6, 1992	North Lat: 51 33.6
	Snow depths 3.1m apart	West Long: 55 48.6
	March 10, 1992	Temperature: -4 °C
		Winds: 270 at 20knts
	March 13, 1992	Temperature: +1 °C
		Winds: 130 at 5knts

	Snow(cm)				Snow(cm)		
	Mar6	Mar10	Mar13		Mar6	Mar10	Mar13
PB-L4.010	35	26	28	PB-L4.110	26	31	14
PB-L4.011	30	35	27	PB-L4.111	33	32	22
PB-L4.012	30	40	25	PB-L4.112	30	30	20
PB-L4.013	29	31	18	PB-L4.113	33	36	23
PB-L4.020	31	31	16	PB-L4.120	34	38	17
PB-L4.021	29	31	20	PB-L4.121	27	32	14
PB-L4.022	31	31	19	PB-L4.122	26	36	17
PB-L4.023	29	34	24	PB-L4.123	32	33	21
PB-L4.030	35	35	23	PB-L4.130	30	36	20
PB-L4.031	24	31	23	PB-L4.131	25	32	25
PB-L4.032	27	31	17	PB-L4.132	22	37	30
PB-L4.033	36	35	26	PB-L4.133	30	34	25
PB-L4.040	35	35	24	PB-L4.140	35	39	29
PB-L4.041	37	46	28	PB-L4.141	39	39	30
PB-L4.042	35	46	24	PB-L4.142	42	45	25
PB-L4.043	34	51	30	PB-L4.143	32	36	25
PB-L4.050	41	52	29	PB-L4.150	34	35	22
PB-L4.051	30	43	28	PB-L4.151	31	35	26
PB-L4.052	26	32	18	PB-L4.152	33	30	19
PB-L4.053	27	34	15	PB-L4.153	36	32	19
PB-L4.060	24	28	12	PB-L4.160	27	30	16
PB-L4.061	30	32	24	PB-L4.161	33	28	20
PB-L4.062	26	36	18	PB-L4.162	25	38	22
PB-L4.063	28	41	22	PB-L4.163	31	48	26
PB-L4.070	33	31	19	PB-L4.170	36	40	24
PB-L4.071	31	36	26	PB-L4.171	32	50	29
PB-L4.072	35	40	27	PB-L4.172	31	46	26
PB-L4.073	29	49	31	PB-L4.173	30	40	25
PB-L4.080	32	37	30	PB-L4.180	29	36	17
PB-L4.081	37	39	27	PB-L4.181	27	35	23
PB-L4.082	34	35	24	PB-L4.182	30	33	24
PB-L4.083	37	38	25	PB-L4.183	35	37	28
PB-L4.090	39	38	29	PB-L4.190	35	40	31
PB-L4.091	34	36	27	PB-L4.191	40	48	36
PB-L4.092	27	30	18	PB-L4.192	38	45	32
PB-L4.093	26	31	19	PB-L4.193	35	34	24
PB-L4.100	19	35	22	PB-L4.200	31	36	25
PB-L4.101	17	34	27				
PB-L4.102	25	40	31	MEAN	31	37	24
PB-L4.103	22	30	21				

Station	Pistolet Bay Snow Line #5	Temperature: -15 °C
	Snow depths along PB-L1	Winds: 320 at 15knts
PB-L5	March 6, 1992	North Lat: 51 33.6
	Snow depths 3.1m apart	West Long: 55 48.6
	March 10, 1992	Temperature: -4 °C
		Winds: 270 at 20knts
	March 13, 1992	Temperature: +1 °C
		Winds: 130 at 5knts

	Snow(cm)				Snow(cm)		
	Mar6	Mar10	Mar13		Mar6	Mar10	Mar13
PB-L5.010	27	25	12	PB-L5.110	29	26	12
PB-L5.011	29	29	17	PB-L5.111	32	26	22
PB-L5.012	26	27	19	PB-L5.112	28	35	19
PB-L5.013	28	31	12	PB-L5.113	30	30	20
PB-L5.020	25	30	14	PB-L5.120	23	25	7
PB-L5.021	31	31	19	PB-L5.121	32	32	25
PB-L5.022	29	27	17	PB-L5.122	41	38	30
PB-L5.023	26	27	16	PB-L5.123	32	27	18
PB-L5.030	21	18	13	PB-L5.130	30	27	13
PB-L5.031	26	32	13	PB-L5.131	33	33	21
PB-L5.032	31	36	24	PB-L5.132	28	32	15
PB-L5.033	35	33	27	PB-L5.133	28	28	15
PB-L5.040	38	35	18	PB-L5.140	23	20	9
PB-L5.041	41	41	35	PB-L5.141	24	27	13
PB-L5.042	41	49	39	PB-L5.142	32	30	14
PB-L5.043	29	35	29	PB-L5.143	27	24	10
PB-L5.050	33	29	16	PB-L5.150	25	24	15
PB-L5.051	32	33	22	PB-L5.151	27	31	14
PB-L5.052	34	33	21	PB-L5.152	32	35	18
PB-L5.053	27	30	17	PB-L5.153	28	29	15
PB-L5.060	24	25	12	PB-L5.160	25	26	11
PB-L5.061	24	24	15	PB-L5.161	28	29	14
PB-L5.062	20	22	6	PB-L5.162	26	37	18
PB-L5.063	20	19	6	PB-L5.163	31	33	21
PB-L5.070	24	28	12	PB-L5.170	32	35	18
PB-L5.071	28	29	20	PB-L5.171	32	35	25
PB-L5.072	32	44	29	PB-L5.172	34	36	28
PB-L5.073	34	46	27	PB-L5.173	29	32	20
PB-L5.080	35	40	28	PB-L5.180	37	25	17
PB-L5.081	45	44	38	PB-L5.181	34	36	24
PB-L5.082	42	42	33	PB-L5.182	35	36	23
PB-L5.083	29	33	22	PB-L5.183	34	40	18
PB-L5.090	24	27	16	PB-L5.190	37	30	17
PB-L5.091	40	37	31	PB-L5.191	34	36	15
PB-L5.092	38	37	20	PB-L5.192	34	33	15
PB-L5.093	28	28	14	PB-L5.193	37	32	15
PB-L5.100	30	35	14	PB-L5.200	40	38	22
PB-L5.101	28	36	23				
PB-L5.102	28	31	20	Mean	31	32	19
PB-L5.103	35	36	23				

Station	Pistolet Bay Snow Line #6	Temperature: -4 °C
	Snow depths along PB-L3	Winds: 270 at 25knts
PB-L6	March 10, 1992	North Lat: 51 33.6
	Snow depths 5cm apart	West Long: 55 48.6
	March 13, 1992	Temperature: +1 °C
		Winds: 130 at 5knts
	March 9, 1992	Temperature: -10 °C
		Winds: 100 at 15knts

	Snow(cm)				Snow(cm)		
	Mar9	Mar10	Mar13		Mar9	Mar10	Mar13
PB-L6.010	27	36	20	PB-L6.060	25	24	17
PB-L6.011	---	21	9	PB-L6.061	---	33	21
PB-L6.012	---	15	7	PB-L6.062	---	30	15
PB-L6.013	---	22	7	PB-L6.063	---	31	23
PB-L6.014	---	32	12	PB-L6.064	---	42	36
PB-L6.020	19	25	10	PB-L6.070	26	36	25
PB-L6.021	---	32	21	PB-L6.071	---	36	24
PB-L6.022	---	28	15	PB-L6.072	---	27	8
PB-L6.023	---	28	16	PB-L6.073	---	23	8
PB-L6.024	---	25	18	PB-L6.074	---	21	7
PB-L6.030	23	33	13	PB-L6.080	26	27	15
PB-L6.031	---	27	16	PB-L6.081	---	21	14
PB-L6.032	---	32	18	PB-L6.082	---	28	16
PB-L6.033	---	29	25	PB-L6.083	---	26	15
PB-L6.034	---	38	24	PB-L6.084	---	36	18
PB-L6.040	25	29	20	PB-L6.090	35	26	11
PB-L6.041	---	27	19	PB-L6.091	---	32	19
PB-L6.042	---	30	17	PB-L6.092	---	31	15
PB-L6.043	---	28	16	PB-L6.093	---	28	11
PB-L6.044	---	35	19	PB-L6.094	---	26	12
PB-L6.050	24	29	16	PB-L6.100	30	31	14
PB-L6.051	---	28	16				
PB-L6.052	---	32	18	MEAN	26	28	16
PB-L6.053	---	27	13				
PB-L6.054	---	35	17				

Station	Pistolet Bay Line #2	Temperature:	+1 °C
	SW (bag #1) to NE (bag #20)	Winds:	130 at 5knts
PB-L2	March 13, 1992	North Lat:	51 33.6
	Bags/Ice holes 12.5m apart	West Long:	55 48.6

	Snow(cm)	Freeboard(cm)	Ice(cm)	
PB-L2.01	28	-6	67	(3bags)
PB-L2.02	16	-6	68	
PB-L2.03	23	-8	67	
PB-L2.04	24	-4	67	
PB-L2.05	29	-6	67	
PB-L2.06	12	-6	68*	
PB-L2.07	19	-3	68	
PB-L2.08	30	-8	67	
PB-L2.09	29	-6	67	
PB-L2.10	22	-6	66	
PB-L2.11	14	-6	65	
PB-L2.12	17	-6	66	
PB-L2.13	20	-3	67	
PB-L2.14	29	-8	68	
PB-L2.15	22	-6	66	
PB-L2.16	16	-6	70*	
PB-L2.17	24	-5	69*	
PB-L2.18	17	-6	66*	
PB-L2.19	31	-8	67	
PB-L2.20	25	-8	67	
MEAN	21	-6	67	
PB-L2.21	8	+2	115**	
PB-L2.22	0	+8	113**	
PB-L2.23	8	+8	113**	(line-up bag)
PB-L2.24	0	+14	156**	

* Flooding was present and 2cm of refrozen snow was at level of freeboard (5-6cm above ice surface).

** Ice thicknesses from flat rafted area NE of calibration lines

Station	Pistolet Bay Line #3	Temperature: +1 °C
	NW (bag #1) to SE (bag #10)	Winds: 130 at 5knts
PB-L3	March 13, 1992	North Lat: 51 33.6
	Bags/Ice holes 25.0m apart	West Long: 55 48.6

	Snow(cm)		Freeboard(cm)	Ice(cm)	
PB-L3.01	20	(27)	-0	70	(2 orange bags)
PB-L3.02	10	(19)	-1	74	Light House
PB-L3.03	13	(23)	-8	72	
PB-L3.04	20	(25)	-1	71	
PB-L3.05	16	(24)	-0	70	
PB-L3.06	17	(25)	-1	71	
PB-L3.07	25	(26)	-7	70	
PB-L3.08	15	(26)	+2	73	
PB-L3.09	11	(35)	-2	67	
PB-L3.10	14	(30)	-6	66	
MEAN	17		-2	70	

Snow value in brackets from March 9, 1992; air temp. was -10 °C, wind 100 at 15 knts.

HARE BAY SURFACE CALIBRATION DATA

Station	Hare Bay Line #1	Temperature: -10 °C
	W (bag #1) to E (2bags #10)	Winds: 100 at 10knts
HB-L1	March 9, 1992	North Lat: 51 11.9
	Bags 25m apart	West Long: 55 42.2

	Snow* (cm)	Freeboard (cm)	Ice** (cm)	
HB-L1.01	12	+0	66	(orange bag)
HB-L1.02	6 (15)	+3	68	
HB-L1.03	5 (9)	+3	72	
HB-L1.04	21	+0	68	
HB-L1.05	8	+2	67	(orange bag)
HB-L1.06	7 (20)	+2	69	
HB-L1.07	10	+1	69	
HB-L1.08	9 (12)	+1	66	
HB-L1.09	23 (35)	-2	66	
HB-L1.10	28	-4	68	(2 black bags)
MEAN	13	+1	68	

* Snow ridge values in brackets
** March 13 ice thicknesses at L1.04 and L1.05 were 75cm

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Station	Hare Bay Stn. #1	Temperature: -10 °C
	Stn. at bag #5 (HB-L1.05)	Winds: 100 at 10knts
HB-S1	March 9, 1992	North Lat: 51 11.9
	Bags 25m apart	West Long: 55 42.2

	bottle#	Salinity	Location/Depth
HB-S1.01	10838	1.0	top hard snow layer (12cm)
HB-S1.02	10842	14.0	crusty snow layer (6cm)
HB-S1.03	10845	20.0	frozen slush layer (2cm)
HB-S1.04	10861	7.0	ice 5-10 cm
HB-S1.05	10862	6.0	ice 25-30 cm
HB-S1.06	10863	7.0	ice 40-45 cm
HB-S1.07	10839	10.0	ice 60-65 cm

Station	Hare Bay Stn. #2	Temperature: -10 °C
	Inner bay	Winds: 100 at 10knts
HB-S2	March 9, 1992	North Lat: 51 20.1
	Refrozen pactches (5mx5m)	West Long: 56 02.0

HB-S2.01	30cm of dry hard snow
HB-S2.02	10cm of wet snow
HB-S2.03	40cm of soft ice

Station	Hare Bay Line #2	Temperature: -8 °C
	S (bag #1) to N (2bags #10)	Winds: 215 at 10knts
HB-L2	March 10, 1992	North Lat: 51 11.9
	Bags 25m apart	West Long: 55 42.2

	Snow(cm)	Freeboard(cm)	Ice(cm)	
HB-L2.01	8	+2	67	(HB-L1.05)
HB-L2.02	32	-4	69	South
HB-L2.03	25	-3	68	
HB-L2.04	26	-3	66	
HB-L2.05	15	+0	68	
HB-L2.06	10	-1	75	
HB-L2.07	26	-2	74	
HB-L2.08	19	-3	67	
HB-L2.09	25	-3	68	North
HB-L2.10	18	-2	68	(2 orange bags)
MEAN	20	-2	69	

Station	Hare Bay Snow Line #3	Temperature: -4 °C
	Snow depths along HB-L1	Winds: 270 at 20knts
HB-L3	March 10, 1992	North Lat: 51 11.9
	Snow depths 5m apart	West Long: 55 42.2
	March 13, 1992	Temperature: +1 °C
		Winds: 130 at 5knts

	Snow(cm)			Snow(cm)	
	Mar10	Mar13		Mar10	Mar13
HB-L3.010	13	4	HB-L3.060	9	1
HB-L3.011	11	0	HB-L3.061	16	2
HB-L3.012	8	0	HB-L3.062	21	15
HB-L3.013	18	6	HB-L3.063	23	4
HB-L3.014	21	6	HB-L3.064	30	8
HB-L3.020	6	6	HB-L3.070	10	10
HB-L3.021	17	5	HB-L3.071	17	4
HB-L3.022	7	0	HB-L3.072	8	5
HB-L3.023	8	6	HB-L3.073	20	3
HB-L3.024	10	0	HB-L3.074	8	1
HB-L3.030	13	8	HB-L3.080	6	3
HB-L3.031	25	7	HB-L3.081	22	1
HB-L3.032	24	15	HB-L3.082	13	3
HB-L3.033	20	12	HB-L3.083	17	8
HB-L3.034	30	4	HB-L3.084	22	17
HB-L3.040	17	5	HB-L3.090	43	14
HB-L3.041	14	5	HB-L3.091	27	8
HB-L3.042	15	0	HB-L3.092	22	11
HB-L3.043	16	0	HB-L3.093	31	18
HB-L3.044	18	8	HB-L3.094	28	22
HB-L3.050	18	3	HB-L3.100	32	18
HB-L3.051	17	2			
HB-L3.052	16	1	MEAN	17	6
HB-L3.053	10	2			
HB-L3.054	7	0			

Station	Hare Bay Snow Line #4	Temperature: -4 °C
	Snow depths along HB-L2	Winds: 270 at 20knts
HB-L4	March 10, 1992	North Lat: 51 11.9
	Snow depths 5m apart	West Long: 55 42.2
	March 13, 1992	Temperature: +1 °C
		Winds: 130 at 5knts

	Snow(cm) Mar10	Snow(cm) Mar13		Snow(cm) Mar10	Snow(cm) Mar13
HB-L4.010	15	2	HB-L4.060	10	4
HB-L4.011	22	15	HB-L4.061	15	9
HB-L4.012	25	4	HB-L4.062	27	17
HB-L4.013	26	3	HB-L4.063	18	3
HB-L4.014	33	17	HB-L4.064	20	5
HB-L4.020	32	21	HB-L4.070	26	17
HB-L4.021	24	21	HB-L4.071	39	14
HB-L4.022	24	10	HB-L4.072	28	14
HB-L4.023	24	15	HB-L4.073	15	14
HB-L4.024	21	9	HB-L4.074	14	14
HB-L4.030	25	11	HB-L4.080	19	2
HB-L4.031	24	15	HB-L4.081	35	14
HB-L4.032	42	27	HB-L4.082	38	18
HB-L4.033	28	23	HB-L4.083	26	19
HB-L4.034	47	24	HB-L4.084	26	16
HB-L4.040	26	6	HB-L4.090	25	12
HB-L4.041	24	15	HB-L4.091	17	16
HB-L4.042	28	11	HB-L4.092	29	5
HB-L4.043	18	10	HB-L4.093	28	17
HB-L4.044	20	12	HB-L4.094	22	7
HB-L4.050	15	16	HB-L4.100	18	8
HB-L4.051	21	9			
HB-L4.052	18	7	MEAN	24	12
HB-L4.053	17	7			
HB-L4.054	17	12			

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Station	Hare Bay West Stn. #3	Temperature: -4 °C
	Slush snow patch (at HB-S2)	Winds: 240 at 18knts
HB-S3	March 10, 1992	North Lat: 51 20.1
		West Long: 56 02.0

	bottle#	Salinity	Location/Depth
HB-S3.01	10849	0.0	top dry snow layer (10cm)
HB-S3.02	10852	29.0	bottom slush snow layer (10cm)

* 9cm of freshly fallen snow

Station	Hare Bay West Stn. #4	Temperature: -4 °C
	Frozen slush patch (at HB-S2)	Winds: 240 at 18knts
HB-S4	March 10, 1992	North Lat: 51 20.1
		West Long: 56 02.0

	bottle#	Salinity	Location/Depth
HB-S4.01	10851	14.0	5-10 cm (refrozen snow)
HB-S4.02	10853	8.0	15-20 cm (refrozen snow)

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Station	Hare Bay East Stn. #5	Temperature: +2 °C
	Ice chips Stn. (at HB-L1.05)	Winds: 220 at 5knts
HB-S5	March 11, 1992	North Lat: 51 11.9
		West Long: 55 42.2

	bottle#	Salinity	Location/Depth
HB-S5.01	10875	9.0	5-10 cm (ice)
HB-S5.02	10874	8.0	20-25 cm (ice)
HB-S5.03	10872	10.0	30-35 cn (ice)
HB-S5.04	10876	9.0	40-45 cm (ice)

* 67cm of ice, +1cm of freeboard and 15cm of snow

Station	Hare Bay East Stn. #6	Temperature: +2 °C
	Ice chips Stn. (at HB-L1.05)	Winds: 220 at 5knts
HB-S6	March 11, 1992	North Lat: 51 11.9
		West Long: 55 42.2

	bottle#	Salinity	Location/Depth
HB-S6.01	10850	9.0	10-15 cm (ice)
HB-S6.02	10867	6.0	20-25 cm (ice)
HB-S6.03	10869	8.0	30-35 cm (ice)
HB-S6.04	10847	8.0	40-45 cm (ice)

* 68cm of ice, +1cm of freeboard and 13cm of snow

Station	Hare Bay East Stn. #7	Temperature: +2 °C
	Ice chips Stn. (at HB-L1.05)	Winds: 220 at 5knts
HB-S7	March 11, 1992	North Lat: 51 11.9
		West Long: 55 42.2

	bottle#	Salinity	Location/Depth
HB-S7.01	10846	8.0	5-10 cm (ice)
HB-S7.02	10868	8.0	20-25 cm (ice)
HB-S7.03	10866	6.0	30-35 cm (ice)
HB-S7.04	10870	9.0	40-45 cm (ice)
HB-S7.05	10865	33.0	Surface water

* 70cm of ice, +1cm of freeboard and 11cm of snow

BELLE ISLE STRAIT SURFACE CALIBRATION DATA

Station	Belle Isle Str. Ice Stn. #1	Temperature: -8 °C
	Ice floe	Winds: 240 at 15knts
BI-S1	March 5, 1992	Drifting ice at 3knts

BI-S1.01	Ice thickness 10cm	Refrozen pancake ice

Station	Belle Isle Str. Ice Stn.#2	Temperature: -8 °C
	Ice floe	Winds: 240 at 15knts
BI-S2	March 5, 1992	Drifting ice at 3knts

	Snow(cm)	Freeboard(cm)	Ice (cm)
BI-S2.01	5	1	42
BI-S2.02	5	1	45
BI-S2.03	5	1	49

Station	Belle Isle Strait	Temperature: -8 °C
	Land-fast ice	Winds: 240 at 15knts
BI-S3	March 5, 1992	North Lat: 51 37.5
		West Long: 55 35.6

	Snow(cm)	Freeboard(cm)	Ice(cm)
BI-S3.01	28	-6	54
BI-S3.02	35	-4	75
BI-S3.03	31	-4	102 (rafted)

Rafted ice blocks 52cm thick

Station	Belle Isle Strait	Temperature: -15 °C
	Land-fast ice	Winds: 320 at 15knts
BI-S4	March 6, 1992	North Lat: 51 37.8
		West Long: 55 42.4

	Snow(cm)	Freeboard(cm)	Ice(cm)
BI-S4.01	5	+3	56

Rafted ice blocks 17 and 33cm thick

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Station	Belle Isle Strait	Temperature: -10 °C
	Ice floe	Winds: 240 at 10knts
BI-S5	March 6, 1992	Drifting ice

BI-S5.01 38cm of ice and 5cm of wet snow

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Station	Belle Isle Str. line#1	Temperature: -10 °C
	Ice holes 12.5m apart	Winds: 340 at 35knts
BI-L1	1800 GMT, March 6, 1992	Drifting ice floe
		Floe size 130x150m

	Snow(cm)	Freeboard(cm)	Ice(cm)	
BI-L1.01	5(w)	+2	45	(blue bag)
BI-L1.02	5(w)	+2	38	
BI-L1.03	5(w)	+2	40	(yellow bag)
BI-L1.04	6(w)	+2	38	
BI-L1.05	5(w)	+2	40	
BI-L1.06	5(w)	+2	38	
BI-L1.07	4(w)	+2	42	
BI-L1.08	5(w)	+2	42	(black box)
MEAN	5	2	40	

PACK ICE SURFACE CALIBRATION DATA

Station PI-S1	Pack Ice Stn#1 Ice beacon #4758 March 6, 1992 1630 GMT	Temperature: -10 °C Winds: 340 at 35knts North Lat: 52 07.8 West Long: 54 29.0

	Snow(cm)	Freeboard(cm)	Ice(cm)
PI-S1.01	4(w)	+4	96
PI-S1.02	5(w)	+4	95

Large floe made up of 50x50m floes

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Station PI-S2	Pack Ice Stn#2 Ice beacon #4760 March 6, 1992 1700 GMT	Temperature: -10 °C Winds: 340 at 35knts North Lat: 52 13.8 West Long: 54 07.1

	Snow(cm)	Freeboard(cm)	Ice(cm)
PI-S2.01	5(w)	+4	96
PI-S2.02	5(w)	+4	95
PI-S2.03	5(w)	+4	250+ (rafted ice)

Large floe made up of 50x50m floes

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Station PI-S3	Pack Ice Stn.#3 at bag #1 (PI-L1.01) March 7, 1992	Temperature: -5 °C Winds: 300 at 45knts North Lat: 52 06.9 West Long: 54 24.6

	bottle#	Salinity	Location/Depth
PI-S3.01	10840	45.0	2cm slush layer*
PI-S3.02	10841	25.0	10-15 cm
PI-S3.03	10844	17.0	20-25 cm
PI-S3.04	10843	12.0	30-35 cm

* 2cm layer of snow was wet (slush)
(w) means ice chips were wet but were drained

Station	Pack Ice line#1	Temperature: -5 °C
	Drifting pack ice	Winds: 300 at 45knts
PI-L1	1800 GMT, March 7, 1992	North Lat: 52 06.9
	Bags/holes 12.5m apart	West Long: 54 24.6

	Snow(cm)	Freeboard(cm)	Ice(cm)	
PI-L1.01	2(w)	+2	51	(orange bag)
PI-L1.02	2(w)	+2	50	
PI-L1.03	2(w)	+2	48	
PI-L1.04	2(w)	+2	48	
PI-L1.05	2(w)	+2	50	
PI-L1.06	2(w)	+2	55	
PI-L1.07	2(w)	+2	48	
PI-L1.08	2(w)	+2	46	
PI-L1.09	2(w)	+2	50	
MEAN	2	+2	49	

Ice holes 12.5m apart: floe size 130x150m

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Station	Main pack ice line #2	Temperature: -10 °C
	Ice beacon #4759	Winds: 330 at 10knts
PI-L2	1600 GMT, March 8, 1992	North Lat: 51 51.7
	Bags/holes 12.5m apart	West Long: 54 33.4
	Floe size 250mx300m	

	Snow(cm)	Freeboard(cm)	Ice(cm)	
PI-L2.01	3(w)	+2	55	ridge (orange bag)
PI-L2.02	2(w)	+2	39	
PI-L2.03	2(w)	+2	35	
PI-L2.04	2(w)	+2	37	
PI-L2.05	2(w)	+2	36	
PI-L2.06	3(w)	+2	36	(clothes)
PI-L2.07	3(w)	+2	37	
PI-L2.08	2(w)	+2	36	
PI-L2.09	2(w)	+2	36	
PI-L2.10	2(w)	+2	36	
PI-L2.11	2(w)	+2	36	
MEAN	2	2	38	
PI-L2.12	2(w)	+2	36	(40m from 11)
PI-L2.13	2(w)	+2	85	(100m from 11)
PI-L2.14	---	---	13	(thin ice)

Station	Pack Ice Stn.#4	Temperature: -10 °C
	at bag #5 (PI-L2.05)	Winds: 330 at 10knts
PI-S4	March 8, 1992	North Lat: 51 51.7
		West Long: 54 33.4

	bottle#	Salinity	Location/Depth
PI-S4.01	10857	3.0	dry snow in ridge
PI-S4.02	10860	40.0	wet 2cm snow layer
PI-S4.03	10859	7.0	10-15 cm
PI-S4.04	10858	8.0	25-30 cm

- -

Station	Pack Ice ridge line #3	Temperature: -10 °C
	Ice beacon #4759	Winds: 330 at 10knts
PI-L3	1630 GMT, March 8, 1992	North Lat: 51 51.7
	Holes 1.5m apart	West Long: 54 33.4

	Snow(cm)	Ice(cm)		Snow(cm)	Ice(cm)
PI-L3.01	2(w)	37	PI-L3.05	--	140 (ridge)
PI-L3.02	2(w)	41	PI-L3.06	2(w)	44
PI-L3.03	2(w)	44	PI-L3.07	2(w)	41
PI-L3.04	--	52 (ridge)	PI-L3.08	2(w)	38

- -

Station	Pack Ice Stn #5	Temperature: -10 °C
	Ice beacon #4759	Winds: 330 at 10knts
PI-S5	1630 GMT, March 8, 1992	North Lat: 51 51.7
	Extra ice holes	West Long: 54 33.4

	Snow(cm)	Ice(cm)	Location*
PI-S5.01	2(w)	38	W at 75m
PI-S5.02	2(w)	36	SW at 75m
PI-S5.03	2(w)	38	SSW at 50m
PI-S5.04	2(w)	28	SSE at 50m
PI-S5.05	2(w)	45	SSE at 75m

* relative to main line with orange bag L2.01 as South and L2.11 as North

AIRPORT LAKE SURFACE CALIBRATION DATA

Station		
AL-L1	Airport Lake Snow Line #1 Snow depths 1.0m apart March 7, 1992 Marker bags 30m apart	Temperature: -5 °C Winds: 300 at 45knts North Lat: 51 22.6 West Long: 56 04.7

	Snow(cm)		Snow(cm)
AL-L1.00	0	AL-L1.25	174
AL-L1.01	8	AL-L1.26	202
AL-L1.02	11	AL-L1.27	220
AL-L1.03	20	AL-L1.28	220
AL-L1.04	30	AL-L1.29	220
AL-L1.05	39	AL-L1.30	161
AL-L1.06	44	AL-L1.31	140
AL-L1.07	55	AL-L1.32	120
AL-L1.08	63	AL-L1.33	130
AL-L1.09	68	AL-L1.34	125
AL-L1.10	75	AL-L1.35	125
AL-L1.11	83		
AL-L1.12	95		
AL-L1.13	105		
AL-L1.14	116		
AL-L1.15	123		
AL-L1.16	130		
AL-L1.17	136		
AL-L1.18	140		
AL-L1.19	146		
AL-L1.20	147		
AL-L1.21	150		
AL-L1.22	155		
AL-L1.23	159		
AL-L1.24	176		

Station	Airport Lake Snow Line #2	Temperature: -5 °C
	Snow depths 1.0m apart	Winds: 300 at 45knts
AL-L2	March 7, 1992	North Lat: 51 22.6
	Marker bags 30m apart	West Long: 56 04.7

	Snow(cm)		Snow(cm)
AL-L2.00	0	AL-L2.25	168
AL-L2.01	0	AL-L2.26	168
AL-L2.02	0	AL-L2.27	168
AL-L2.03	0	AL-L2.28	205
AL-L2.04	0	AL-L2.29	220
AL-L2.05	6	AL-L2.30	220
AL-L2.06	15	AL-L2.31	220
AL-L2.07	23	AL-L2.32	220
AL-L2.08	32	AL-L2.33	220
AL-L2.09	51	AL-L2.34	220
AL-L2.10	68	AL-L2.35	190
AL-L2.11	82	AL-L2.36	180
AL-L2.12	91	AL-L2.37	180
AL-L2.13	98	AL-L2.38	180
AL-L2.14	109	AL-L2.39	180
AL-L2.15	120	AL-L2.40	180
AL-L2.16	127	AL-L2.41	180
AL-L2.17	131	AL-L2.42	180
AL-L2.18	144	AL-L2.43	180
AL-L2.19	155	Al-L2.44	180
AL-L2.20	173	AL-L2.45	180
AL-L2.21	175		
AL-L2.22	171		
AL-L2.23	164		
AL-L2.24	172		

Real-time Airborne Electromagnetic Measurement of Sea Ice

J. Scott Holladay[*], James Lee, Ian St. John, Aerodat Ltd;
James R. Rossiter, Louis Lalumiere, Canpolar Inc.; and
Simon Prinsenberg, Bedford Institute of Oceanography

Summary

A new generation of airborne electromagnetic instruments which integrate EM sensors, data processing hardware and specialized inversion software has finally realized the goal of real-time measurement of sea ice thickness. The sensors are relatively small, lightweight implementations of conventional helicopter electromagnetic sounding systems, but incorporate a number of innovations critical to their mission, including wide frequency ranges, in-flight electronic calibration and real-time data inversion.

Two variations on this technology have been developed to date, for the U.S. and Canadian Governments respectively. This paper provides an overview of the Canadian system, known as *Ice Probe*, which was designed primarily for deployment from helicopters based on icebreakers, and discusses the results of its 1992 Labrador Sea trials. These trials were conducted in the vicinity of St. Anthony, Newfoundland as part of the Canadian Atlantic Storms II (CASP II) program of the Bedford Institute of Oceanography, and included validation measurements conducted over marked survey lines on land-fast and pack ice as well as long data collection traverses.

The validation program indicated that the system has an accuracy of approximately ±0.1 m ice thickness over flat ice in real time. These results were repeatable over the course of several days.

Introduction

The development of practical techniques for remote ice characterization, including the measurement of sea ice thickness and the identification of ice regime, has been a goal of the Transportation Development Centre (TDC) of Transport Canada since the late 1970's. Early efforts centred on impulse radar methods and were fairly successful in estimating the thickness of cold, undeformed first-year sea ice. By 1988, however, it had become clear that helicopter-borne airborne electromagnetic (EM) induction sounding was the most promising route for characterization of a wide range of ice types and conditions (Rossiter and Lalumiere, 1988), and TDC issued a contract to develop a dedicated EM ice sensor.

The TDC sea ice measurement system was conceived as an aid to autonomous route selection for Canadian Coast Guard icebreakers. While airborne and spaceborne sensors can image surficial features of ice with great accuracy, they cannot be used to estimate ice thickness. In addition, remote-sensing imagery can rapidly become out of date as ice conditions change, requiring the use of sensors carried on the ship for tactical route planning in ice-infested waters. Ice thickness and strength are key pieces of information required to choose routes effectively.

Other applications for which the sea ice measurement sensor will be useful include: icebreaker testing, ice monitoring during oil exploration, reconnaissance before construction of ice roads and other structures, oil rig safety monitoring, calibration of airborne and satellite synthetic aperture radar (SAR) data, ice thickness distribution estimates for global climate studies, air/ice/ocean climatic interaction studies, and estimation of sub-ice acoustic propagation and properties.

Principle of Operation

The technological basis for sea ice thickness measurement is the helicopter electromagnetic (EM) method (Palacky and West, 1991). A sensor package is towed in a bird about 30 m beneath the helicopter and between 15 and 30 m above the ice surface. Relatively low-frequency EM signals are transmitted by antennas in the sensor bird and excite eddy currents in nearby conductors. These currents in turn generate secondary EM fields which are measured by receivers also mounted in the bird to determine the distance between the bird and the ice-water interface, as seawater is the dominant conductor in the snow/ice/seawater environment.

A laser profilometer (modified Optech G150) mounted in the bird measures the distance profile between the bird and the snow or ice surface. The difference between the bird-water and bird-snow distance profiles gives an "ice plus snow" thickness estimate. This methodology has been tested using a variety of EM equipment and processing techniques over both cold Arctic ice and relatively warm Labrador Sea ice (Holladay *et. al.*, 1990).

Data Inversion

The amplitude and phase of the secondary signal are a function of the EM system geometry, the distance between the bird and the seawater surface, the operating frequency, the ice conductivity and the seawater conductivity. This response can be numerically estimated in a precise and efficient manner for horizontally-layered ice and water layers of known thicknesses and conductivities (1D models), while approximating geometries found in pressure ridges and other ice features can require 2D or even 3D models. Using such models, the measured EM signals can be inverted on a point-by-point basis (1D case) or as profile or grid data (2D and 3D cases respectively) to yield estimates of the distance between the bird and the seawater surface. The 1D inversion technique has been developed to the point at which it can now be used for real-time inversion of survey data, providing excellent accuracy over relatively undeformed ice, but underestimating the depth of steep-sided ridge keels. While several inversion approaches are available (*e.g.* Kovacs *et. al.*, 1987a; Bergeron *et. al.*, 1987), we have used fast layered-halfspace model coupled to an efficient damped least-squares inversion routine which has proven both accurate and robust. We are currently interpreting 2D structures using lookup tables similar to those constructed by Liu and Becker (1990) using an inductive-limit numerical model (Liu *et. al.*,1991). Although full-scale 2D and 3D inverse modelling is not yet practical for real-time inversion systems where results must be produced within seconds of data acquisition, neural network techniques show promise for real-time inversion of 2D structure.

Sensor Characteristics

The frequencies and antenna configurations used in the TDC system are 2.5 Khz in the coaxial mode and 100 Khz in the horizontal coplanar mode, with transmitter-receiver antenna separations of 3.0 metres (see photograph in Fig. 1). The overall length of the bird is just under 4 metres, and its weight is about 125 kg. These frequencies, coil orientations and separations were chosen to optimize the capabilities of the system for ice thickness, conductivity and keel geometry estimation while controlling bird size and weight. The EM responses at both frequencies contribute to the accurate estimation of ice thickness, while the phase of the 100 Khz response is also sensitive to the apparent electrical conductivity of the sea ice, which is in turn related to the strength of the ice (Kovacs *et. al.*, 1987b).

Earlier studies successfully profiled sea ice using variations on standard helicopter EM systems. Novel features of the TDC EM subsystem include its calibration and signal processing technologies. The system performs continuous electronic self-calibration while in flight, which eliminates the cumbersome and inaccurate ground calibration techniques still required for conventional EM systems. All signal processing (apart from preamplification and the anti-alias filtering required prior to analog/digital conversion) is performed using high-speed, dedicated digital signal processors located within the bird. Placing the signal processing equipment within the bird is particularly useful in reducing noise and drift at high frequencies, and has the added benefit of making the bird "smart" enough that a spare bird can be directly substituted for a damaged or lost bird without the time-consuming reconfiguration process required for conventional systems.

The addition of a 500 MHz ground penetrating radar mounted in the bird permits the estimation of snow thickness independently of the EM-measured snow plus ice thickness (Rossiter *et. al.*, 1991). This information is useful in the estimation of breaking resistance and sliding friction of the ice and of the thermal conductivity.

Test Results

The system has been tested in the Canadian Arctic in 1991 (Holladay *et. al.*, 1992) and near St. Anthony, located at the tip of the Northern Peninsula of Newfoundland off Canada's Labrador Coast in March 1992. Three ~200 km long data collection missions were performed, traversing pack ice, patches of thin ice and fast ice near shore.

Ice and snow thicknesses, ice salinity and seawater conductivity were measured directly by auger, snow probe and conductivity meter along a set of marked survey lines (Fig. 2), which were then profiled repeatedly with the airborne system.

Fig. 3 is a composite of EM-derived ice thickness estimates for passes over lines PB-L1 and PB-L2 on fast ice near St. Anthony performed on March 6, merged with snow plus ice thicknesses observed on the surface at augered sites. At the time of this flight, cold, very windy winter conditions prevailed. The thicker ice at the left side of the figures is a rafted zone.

On March 11-12, the temperature rose sharply and rain fell for several hours, decreasing the average snow thickness by 0.13 m but having negligible effects on the ice thickness. Fig. 4 displays the EM-derived snow plus ice thickness estimates and surface measurements along PB-L1 and PB-L2, together with surface measurement results obtained on March 13. Fig. 5 compares radar-estimated snow depths with surface measurements of snow and snow plus ice thickness.

Discussion

Comparison of the surface measurements with the EM-derived snow plus ice thickness estimates indicates that the EM results are well within the target accuracy level of ±0.2 m: the mean and standard deviations for differences between the EM and surface measurements in Figs. 3 and 4 are -0.06 and 0.07 m, respectively.

Excellent correspondence is seen between passes executed at different speeds and altitudes and on different days over the validation lines, demonstrating the independence of flight conditions and stability of system calibration which are essential to an operational ice sensor. It is also evident from a comparison of Fig. 3 with Fig. 4 that the system has faithfully reproduced the 0.13 m average reduction in snow plus ice thickness.

The rafted section at the eastern end of the E-W lines is clearly visible on the profiles, and its estimated thickness matches the March 13 surface measurements accurately. It is too wide for significant 2D effects to be visible, except at the edges of the rafted zone where some smoothing is observed.

The snow thickness estimated using the impulse radar on March 13 (shown in Fig. 5) follows the surface measurements closely, despite the above-freezing conditions prevailing on March 11-13.

Conclusions

The Canadian Coast Guard has identified a number of requirements that an optimal ice measurement system must fulfil, including:

1. provision of automated, real-time thickness information for most types of sea ice;
2. ice thickness accuracy of ±5% or 0.2 m over the range from 0.2 to 15 m;
3. bolt-on, bolt-off installation for most small helicopters;
4. robust, easy-to-maintain, modular design; and
5. operation by non-specialist personnel.

The system described here is designed to meet these requirements: the results obtained to date indicate that the first four have already been achieved. Future efforts will focus on improving the user interface to simplify system operation and on obtaining further experience in a variety of operational conditions.

Acknowledgements

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Figure 1: Photograph of the sensor bird on an ice floe in the Labrador Sea. The survey helicopter is visible in the background.

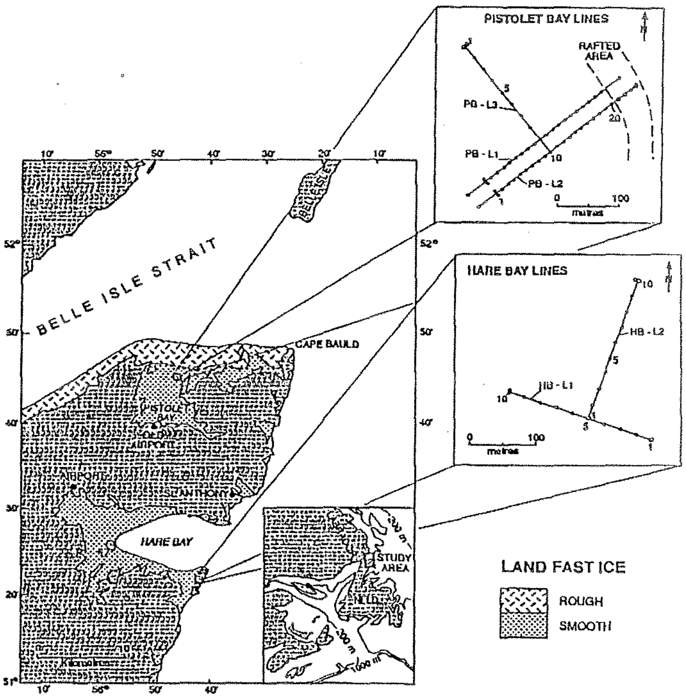

Figure 2: Location and site maps for the St. Anthony survey. Survey results and ground truth for Pistolet Bay lines PB-L1 and PB-L2 are profiled in Figs. 3-5.

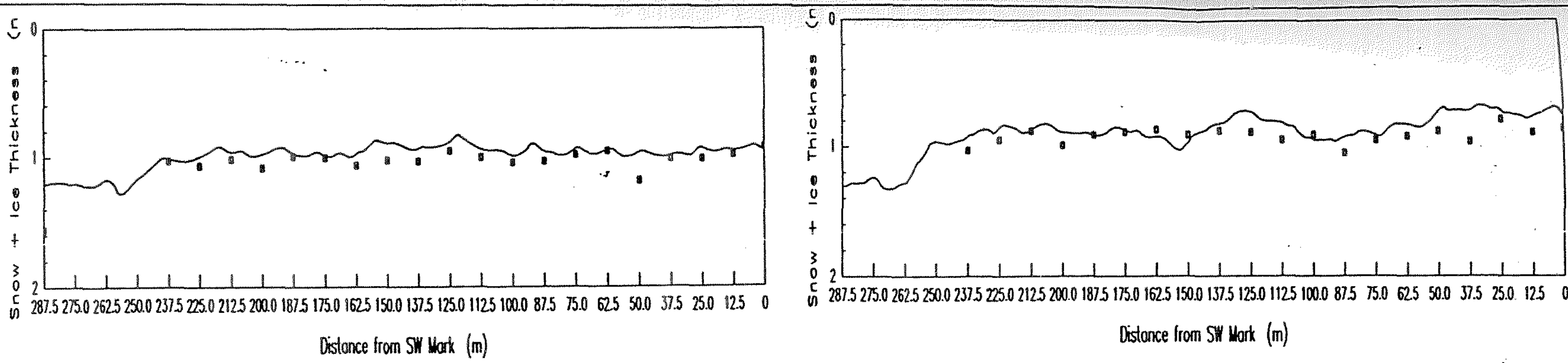

Figure 3: Ice thickness estimates obtained with the system over PB-L1 (left) and PB-L2 (right) on March 6, plotted with surface measurements of snow plus ice thicknesses. The thicker ice to the left is a rafted zone.

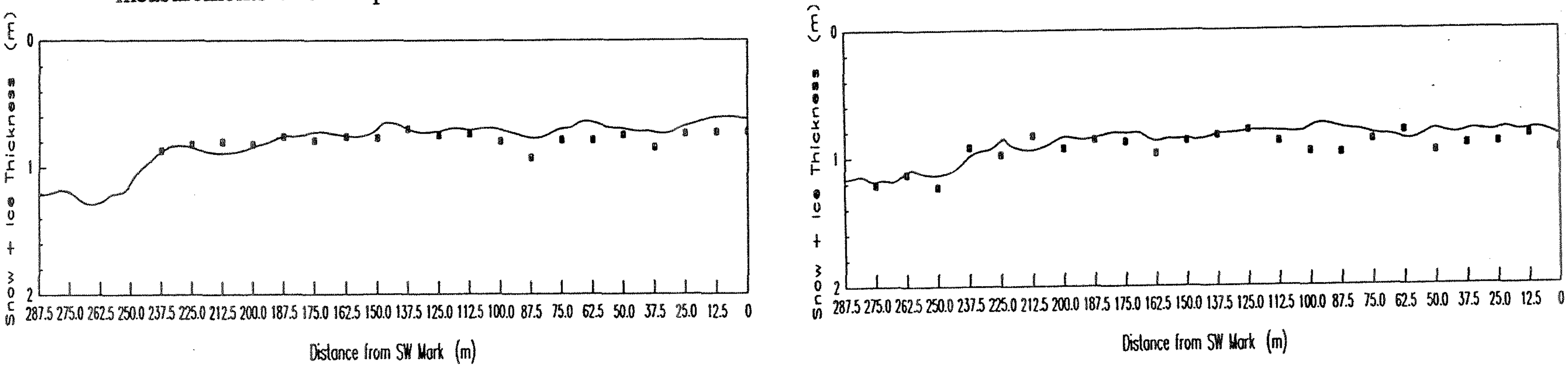

Figure 4: Ice thickness estimates obtained over the same lines as in Fig. 3, on March 13, following 2 days of warm weather and rainfall. The average snow plus ice thickness was reduced by 0.13 m, a change accurately reflected in the EM results.

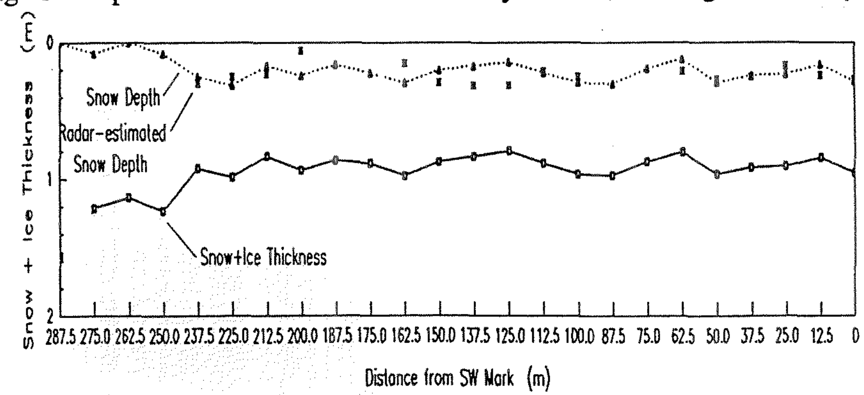

Figure 5: Preliminary comparison of observed and radar-estimated snow depth along PB-L2 on March 13. The snow plus ice thickness is included as a reference.