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DANISH NATIONAL
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Airborne Lidar Measurements of Sea Ice North of Greenland and Ellesmere Island 2004

GreenICe/SITHOS/CryoGreen/A76 Projects
Final Report

N.S. Dalå, R. Forsberg, K. Keller, H. Skourup, L. Stenseng, S. M. Hvidegaard

Danish National Space Center
Technical report No. 1, 2005

THE DANISH NATIONAL SPACECENTER IS A RESEARCH CENTER
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TABLE OF CONTENTS

1 INTRODUCTION

In May 2004 an airborne lidar campaign was carried out north of Ellesmere Island and Greenland by the Geodynamics Dept. of KMS (National Survey and Cadastre, Denmark: Kort og Matrikelstyrelsen; from Jan 1, 2005, the Geodynamics Dept. is part of the Danish National Space Center). The primary aim of the survey was to collect sea ice freeboard heights from a swath laser system, continuing laser data acquired yearly in the region since 1998, and the measurement of heights of the Greenland inland ice margin along the west coast of Greenland, in order to measure reference heights for detection of future changes.

The KMS2004 airborne laser campaign was supporting several projects:

1) The establishment of an ice camp at approx. 85°N, 65°W for the EU GreenICE project. Flights to and from the ice camp were utilized for ice swath profiling in the GreenICE project.

2) Long-range laser flights in the region north of Greenland, as part of the EU SITHOS project. These flights repeated flight lines from 1998, 2001, 2002 and 2003 in order to study changes in sea ice thickness and dynamics, as well as provided a first opportunity to underfly the NASA ICESat laser satellite.

3) Prelaunch CryoSat calibration and validation experiments on the Greenland ice sheet (CryoVex04), in cooperation with ESA and British glaciologists, extended with Greenland ice sheet margin laser flights in the CryoGreen national project (a cooperative project with GEUS and DTU).

4) Support for a bathymetric pilot project of the Danish UNCLOS A76 project, providing aircraft resources and basic information on sea ice applicable for judging possibilities for operations with icebreakers.

This report primarily describes the airborne operations, acquired data and the results of the scanning laser sea-ice freeboard measurements of the KMS2004 campaign (the measurements of land ice will be detailed in a future report).

The KMS2004 campaign additionally performed continental ice cap surveys over the Hans Tausen ice cap and over the Lyngmark ice cap and smaller glaciers of Disko Island. Ice sheet profiles were measured along the EGIG line, along the West Greenland ice sheet margin, along the ice sheet margin of the Humboldt Glacier, over the Steenstrup Glacier and the Petermann Glacier.

Overall the KMS2004 lidar flights generated as the primary data set around 15 GB of raw laser data at 1 m resolution.

2 AIRBORNE OPERATIONS

The lidar and radar measurements were carried out in the period April 20 to May 26, 2004. The airborne survey was performed using a chartered Air Greenland Twin Otter aircraft (registration: OY-POF), operating primarily from Kangerlussuaq (Sdr. Strømfjord) in Greenland and the military airfield at Alert, Canada. The field operations of the airborne survey proceeded as follows:

1st Campaign April 2004 (CryoVex04 EGIG line support and CryoGreen ice margin flights):

April 13-14	KMS team Kristian Keller and Lars Stenseng and UK glaciology team (Liz Morris, Jeff, Peter Nienow, Dough Mair, Sebastian Veit) arrives in Kangerlussuaq, Greenland. Both teams start to unpack.
April 15-18	Flights cancelled due to bad weather at EGIG line position T5.
April 19	UK team 'put out' on the ice sheet.
April 20	Laser test and calibration flight – Kangerlussuaq.
April 21	Survey flight Kangerlussuaq to Ilulissat via T12. Survey flight out of Ilulissat – landing T5.
April 22	Survey flight out of Ilulissat – landing at T41 and T21.
April 23	Survey flight Ilulissat to Kangerlussuaq. Landing for refuelling in Upernavik. Equipment in aircraft was uninstalled.

2nd Campaign May 2004 (GreenICE/SITHOS/§76 flights):

May 3	Survey equipment installed and tested in aircraft in Air Greenland hangar in Kangerlussuaq, Greenland.
May 4	Test and calibration flight, Kangerlussuaq. Flight from Kangerlussuaq to Thule Air Base. Survey on the West Greenland ice sheet margin from 76 N to Thule Air Base.
May 5	Flight from Thule Air Base to Alert, Canada. Survey along the ice sheet margin South of Humboldt Glacier and North along the Petermann Glacier to Kennedy Canal and Fort Conger.
May 6-9	Establishment of the GreenICE floating ice camp (85N 65W).
May 10-12	Four return survey flights from Alert to the ice camp.
May 13	No flights.
May 14	Survey of Hans Tausen Icecap.
May 15	Survey from Qaanaaq to Alert through the Kennedy Canal via Hans Ø.
May 16-19	No survey flights – due to bad weather (fog).
May 20-21	Cargo picked up at the camp. Last load out of ice camp on May 21.
May 22	Ice thickness and freeboard measured by drilling off the coast of the runway, Alert. Rough conditions, many ridges.
May 23	Survey flight track out of Alert on the way to Station Nord.
May 24	Measuring corners of spinnaker building and runway by GPS.
May 25	Survey flight to cover ICESat tracks. Partly cloud-free north of Greenland.
May 26	Flight from Alert to Kangerlussuaq (fuel: Qaanaaq and Ilulissat). Survey on Humboldt Glacier and the West Greenland ice sheet margin - Lyngmark icecap and glacier on Disko Island.
May 27	Scientific equipment dismounted in Kangerlussuaq and shipped back to Denmark.

Fig. 1. Left: Twin-Otter at Alert; Right: Hans Island in the Nares Strait between Ellesmere Island and Greenland, overflown and measured by laser scanning on May 5 enroute to Alert.

More than 140 airborne hours was flown during the KMS04 campaign, including the transits from and to the aircraft base at Kangerlussuaq, Greenland, cf. Table 1. The flown tracks are shown in Fig. 2.

Table 1. Flights of 2004 by Julian day and date

Date/JD	Flight	Track	Off bloc	Take off UTC	Landing UTC	On bloc	Airborne	Survey operator
1904/110	SFJ-T5	cargo + 2 pax	09:21	09:25	10:53	10:58	1:28	No survey
	T5-SFJ		11:07	11:12	12:44	12:47	1:30	No survey
	SFJ-T5	cargo + 2 pax	13:30	13:35	14:58	15:03	1:23	No survey
	T5-SFJ		15:15	15:20	16:55	17:00	1:35	No survey
	SFJ-T12	cargo + 3 pax	17:32	17:38	19:14	19:19	1:36	No survey
	T12-T5	1 pax	19:27	19:32	20:03	20:08	0:31	No survey
	T5-SFJ		20:09	20:14	21:45	21:50	1:31	No survey
2004/111	SFJ-T12		09:55	10:00	11:45	11:50	1:45	No survey
	T12-JAV		11:58	12:02	13:08	13:12	1:06	No survey
	JAV-T5		13:48	13:52	14:39	14:44	0:47	No survey
	T5-SFJ		14:48	14:43	16:20	16:24	1:27	No survey
	SFJ-SFJ	Blue building	19:59	20:03	20:46	20:51	0:52	KRK/LS
2104/ 112	SFJ-T12-JAV		10:50	10:55	12:55	13:00	2:00	LS/KRK
	JAV-T5		14:25	14:29	15:24	15:29	0:55	LS/KRK
	T5-JAV		15:40	15:45	16:37	16:42	0:52	LS/KRK
2204/ 113	JAV-T41		10:21	10:26	13:10	13:15	2:44	KRK
	T41-T21		13:38	13:43	14:44	14:47	1:01	KRK
	T21-JAV		15:06	15:11	16:48	16:50	1:37	KRK
2304/ 114	JAV-JUV		09:49	09:54	15:48	15:53	5:54	KRK
	JUV-JAV		16:19	16:24	21:02	21:07	4:38	KRK
0405/125	SFJ test	Blue building	10:04	10:09	10:31	10:36	0:22	KRK/HES
	SFJ-TAB	S7-S11	11:47	11:52	17:48	17:53	5:56	KRK/HES
0505/126	TAB-YLT	A1-A5	13:07	13:12	17:01	17:06	4:49	KRK/HES
0605/127	YLT-ICE	Reco	15:05	15:10	16:37	16:42	1:27	No survey
	ICE-YLT		18:02	18:07	19:19	19:24	1:12	No survey
	YLT-ICE	Cargo	21:03	21:08	22:28	22:33	1:20	No survey
	ICE-YLT		22:57	23:02	00:11	00:16	1:09	No survey

0705/128	YLT-ICE	Cargo	18:07	18:12	19:25	19:30	1:13	No survey
	ICE-LT		20:04	20:09	21:23	21:28	1:14	No survey
	YLT-ICE	Cargo+3pax	22:11	22:16	23:26	23:31	1:10	No survey
	ICE-YLT		00:20	00:25	01:38	01:43	1:13	No survey
0905/130	YLT-ICE	Cargo	13:36	13:41	14:59	15:04	1:18	No survey
	ICE-YLT		15:30	15:35	16:43	16:48	1:08	No survey
	YLT-ICE	Cargo 3 pax	17:28	17:33	18:52	18:57	1:19	No survey
	ICE-YLT		19:39	19:44	20:53	20:58	1:09	No survey
	YLT-ICE	Cargo 2 pax	21:38	21:43	22:56	23:01	1:13	No survey
	ICE-YLT		23:28	23:33	00:41	00:46	1:08	No survey
1005/131	YLT-ICE	Fuel	13:35	13:40	15:00	15:05	1:20	No survey
	ICE-YLT	2pax	16:07	16:12	17:21	17:26	1:09	No Survey
	YLT-ICE	Fuel	18:30	18:35	19:59	20:04	1:24	No Survey
	ICE-YLT		22:33	22:38	23:54	23:59	1:16	KRK
1105/132	YLT-ICE	G3-G2	16:38	16:43	19:44	19:49	3:01	HES/KRK
	ICE-YLT		20:18	20:23	21:37	21:42	1:14	HES/KRK
1205/133	YLT-ICE	H1-H3	17:37	17:42	19:54	19:59	2:12	HES/KRK
	ICE-YLT	H4 1 pax	20:25	20:30	22:21	22:26	1:51	HES/KRK
	YLT-ICE	8 pax	22:59	23:04	00:25	00:30	1:21	HES
	ICE-YLT	7 pax	01:00	01:05	02:33	02:38	1:28	HES
1405/135	YLT-YLT	P1-P13	13:19	13:24	18:16	18:21	4:52	HES/KRK
	YLT-ICE		19:51	19:56	21:05	21:10	1:09	No survey
	ICE-YLT	2pax	21:40	21:45	23:09	23:14	1:24	No survey
	YLT-TAB	1pax	01:06	01:11	04:26	04:31	3:15	No survey
1505/136	TAB-NAQ	1pax	17:57	18:02	18:31	18:36	0:29	No survey
	NAQ-YLT	NS1-NS5 4pax	20:36	20:41	23:35	23:40	2:54	RF
1905/140	YLT-YLT	ICE	18:01	18:06	20:47	20:52	2:41	No Survey
2005/141	YLT-ICE		21:07	21:12	22:37	22:42	1:25	No survey
	ICE-YLT	cargo+3pax	23:17	23:22	00:37	00:42	1:15	No survey
	YLT-ICE		01:14	01:19	02:40	02:45	1:21	No survey
	ICE-YLT	cargo	03:29	03:34	04:50	04:55	1:16	No survey
	YLT-ICE		05:19	05:24	06:45	06:50	1:21	No survey
	ICE-YLT	cargo+1pax	07:29	07:34	08:49	08:54	1:15	No survey
2105/142	YLT-ICE		22:23	22:28	23:47	23:52	1:19	No survey
	ICE-YLT	cargo	00:44	00:49	02:03	02:08	1:14	No survey
	YLT-ICE		02:24	02:29	03:50	03:55	1:21	No survey
	ICE-YLT		05:01	05:06	06:23	06:28	1:17	No survey
2205/143	YLT-ICE	4pax DPC	17:38	17:43	19:07	19:12	1:24	No survey
	ICE-YLT	4pax DPC	22:02	22:07	23:23	23:28	1:16	No survey
2305/144	YLT-YLT	F1-F4	14:20	14:25	20:07	20:12	5:42	RF/HES
2405/145	YLT-NAQ	5+3 pax GI+DPC	14:50	14:55	17:34	17:39	2:39	No survey
	NAQ-YLT		18:10	18:15	20:40	20:45	2:25	No survey
2505/146	YLT-YLT	ICESat	16:41	16:46	22:46	22:51	6:00	RF/HS
2605/147	YLT-NAQ	2 KMS+1 DPC	11:25	11:30	14:52	14:57	3:22	RF/HS
	NAQ-JAV	Ice margin	15:21	15:26	21:09	21:14	5:43	RF/HS
	JAV-SFJ	Disko survey	21:27	21:32	23:52	0:02	2:20	RF/HS
TOTAL							140:30	
TOTAL including block time (53 flights @ 0:10)							152:20	

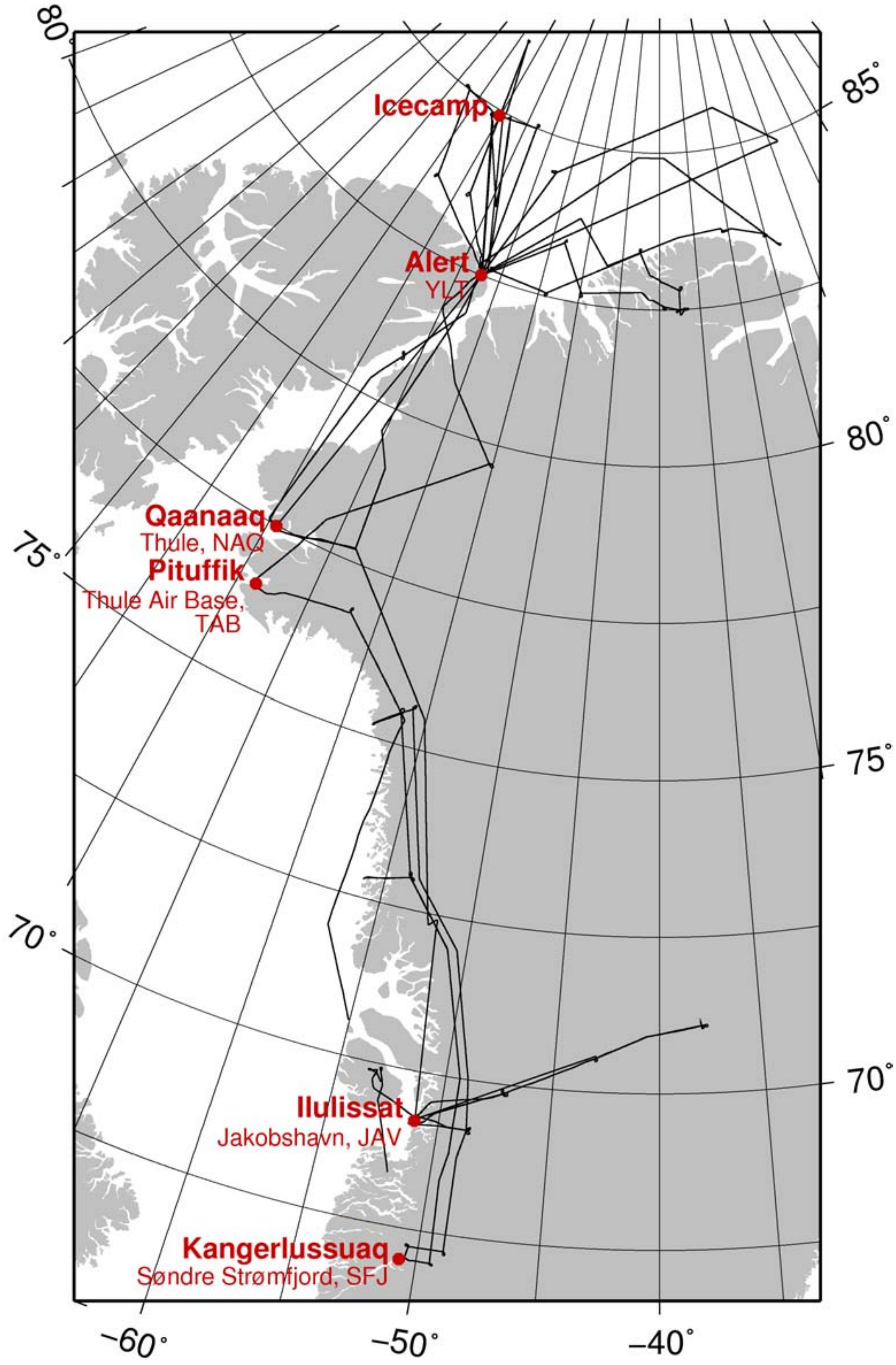


Fig. 2. Flight tracks flown during KMS2004 airborne lidar campaigns, including support for ESA CryoVex04 and the GreenICE ice camp.

3 HARDWARE INSTALLATION

The KMS laser scanner, GPS and INS equipment were installed in the aircraft in a similar fashion to the 2001 and 2002 installations, with the only difference that the INS instrument was placed next to the laser scanner (see fig. 10). This placement was chosen to protect the instrument from the cargo inside the cabin.

The instruments were powered by 28 V DC of the Twin Otter aircraft, converted into12, 24 and 220 V AC by a specially designed power/conditioner system (including backup batteries), designed for KMS by Greenwood Engineering, Denmark.

4 OVERVIEW OF ACQUIRED DATA AND PROCESSING

The basic principle of the measurement of ice freeboard height, F, relies on laser measurements of range to the surface, r^{laser}, combined with precise kinematic GPS aircraft positioning, attitude determination by INS, and a geoid model; to first order, neglecting measurement errors and dynamic sea-surface topography, the freeboard is given by

$$F = h^{GPS} - r^{laser} \cos p \cos r - N \tag{1}$$

The GPS height h^{GPS} of the aircraft is determined by differential GPS relative to several ground base stations; the range r^{laser} from the aircraft to the surface is measured by a scanning laser; pitch p and roll r by an inertial navigation system, and the geoid height N is obtained from a model based on gravity measurements from previous projects, compiled in the Arctic Gravity Project (Forsberg and Kenyon, 2004).

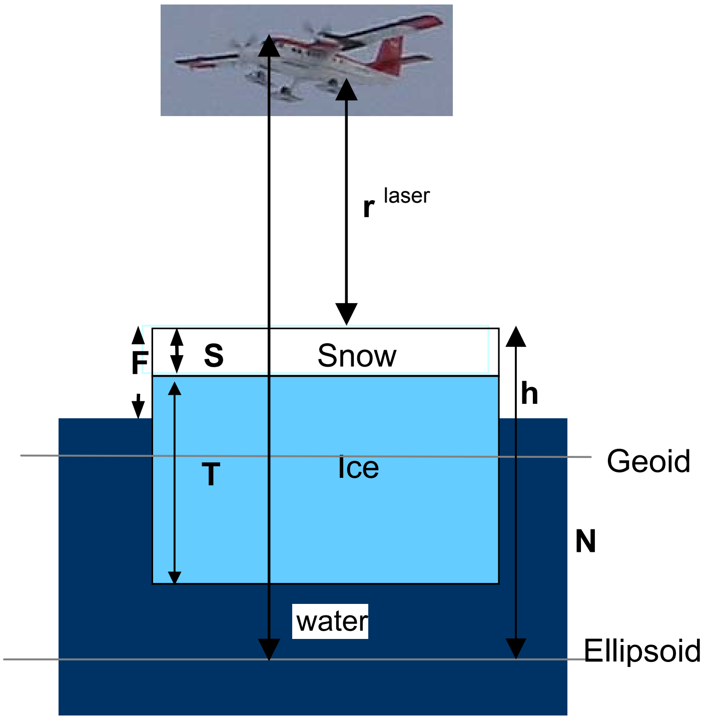


Fig. 3. Principle of freeboard determination. The conversion of freeboard, F, to thickness, T, is approximately a constant (~6.0 in April/May – Wadhams et. al., 1992) depending on densities and snow depth, S.

4.1 GPS data and processing

Kinematic GPS is the key positioning method for the aircraft. GPS dual-frequency phase data were logged at 1 Hz using 1-2 reference ground receivers at one or more reference sites, and 3 aircraft receivers (Trimble, Ashtech and Javad type). The aircraft GPS receivers are named AIR1 (Trimble, 4000-SSI), AIR2 (Ashtech, Z-extreme) and AIR3 (Javad, Legacy). AIR1 and AIR2 share the front GPS antenna; AIR3 the rear GPS antenna. Antenna offsets were unchanged from earlier installations in OY-POF, cf. table 5.

Data were logged internally in receivers during flights, and downloaded upon landing on laptop computers. Data were backed-up on CD-ROMs.

4.1.1 GPS reference stations

Reference GPS stations were mounted on roofs or on tripods in the field at Kangerlussuaq, SFJ; Ilulissat, JAV and Alert, YLT; the reference points were generally not marked. Available data are indicated in Table 2.

Table 2. GPS aircraft and reference data collected during GreenICE/SITHOS 04

JD/Date	AIR1	AIR2	AIR3	EGI	SCANNER	PHOTO	JAV1	YLT	SFJ1	THU3	REMARKS
2004/111	X	X	X(1)	X	X				X		
2104/112a	X	X(2)	X	X	X				X		
2104/112b	X	X(3)	X	X(4)	X		X		X		
2204/113	X	X(5)	X	X	X		X		X		
2304/114	X	X	X	X	X		X		X		
0405/125a	X	X	X	X	X				X		Test Flight
0405/125b	X	X	X	X	X					X	
0505/126	X	X	X	X	X	(X)				X	
1005/131	X	X	X	X	X			X			
1105/132	X	X	X	X	X			X			
1205/133a	X	X	X	X	X			X			
1205/133b	X	X	X	X	X			X			
1405/135	X	X	X	X	X	X		X			
1505/136	X	X	X	X	X			X		X	
2305/144	X	X	X	X	X	X		XX			
2505/146	X		X	X	X	X		XX			
2605/147a	X	X	X	X	X				X	X	
2605/147b	X	X	X	X	X				X		

(1) Fuse in power rack blown; data gap 468 sec.
(2) GPS stopped due to unknown reason; data gap 56 sec.
(3) GPS stopped twice due to unknown reason; data gap 256 sec. and 106 sec.
(4) Problems with EGI – data from flight split in 8 parts.
(5) GPS stopped twice due to unknown reason; data gap 70 sec. and 115 sec.

Fig. 4. The reference GPS in Kangerlussuaq, SFJ1.

The GPS reference coordinates were computed using the online processing service SCOUT provided by Scripps orbit and permanent array center (SOPAC). In SCOUT raw RINEX data are processed relative to the three nearest IGS stations and the coordinates are referenced to the ITRF2000 system to the mean epoch of measurements at an accuracy level of few cm.

The GPS solutions for the aircraft antennas were done on a single baseline basis to available reference stations using the GPSurvey software (vers. 2.35), using precise IGS orbits. An example is shown in Fig. 7. Generally several solutions were made, and a "best" solution, with fewest dropouts and cycle slips, was selected as the basic GPS aircraft solution. These solutions are generally estimated to be accurate to the 20-50 cm level r.m.s. The accuracy is dependant on the distance between the reference station and the aircraft and on the number of satellites and their geometry. The number of satellites was usually quite high, often around 8-10, with some limited periods with fewer satellites.

Fig. 5. The GPS references in Alert, YLT1 in front, YLT2 on top of the leftmost building

Table 3. GPS reference stations used for GreenICE/SITHOS 2004

Location	Name – site
Kangerlussuaq	SFJ1 - meteorological hut, Trimble
Ilulissat, Jakobshavn	JAV1 – antenna on roof of airport building, Trimble
Alert	YLT1a and YLT1b – antenna on ground NW of the "Hilton" and "Spinaker" buildings, Trimble. YLT2 – antenna on roof of the "Hilton" building, Ashtech
Pituffik, Thule Air Base	THU3 – KMS permanent GPS station, Trimble.

Fig. 6. The reference GPS station in Ilulissat, JAV1.

Table 4. GPS reference coordinates

Station	**Lat (dms)**	**Lon (dms)**	**h(el)**
SFJ1	67 00 21.64284	-50 42 09.71231	72.001
JAV1	69 14 25.36075	-51 03 56.63796	58.927
YLT1a (up to and including JD 135)	82 30 44.06286	-62 19 45.05685	50.122
YLT1b (from JD 136 and forward)	82 30 44.19441	-62 19 45.44823	51.170
YLT2 JD 144	82 30 40.95356	-62 19 14.50999	50.417
YLT2 JD 146	82 30 40.95328	-62 19 14.50668	50.408

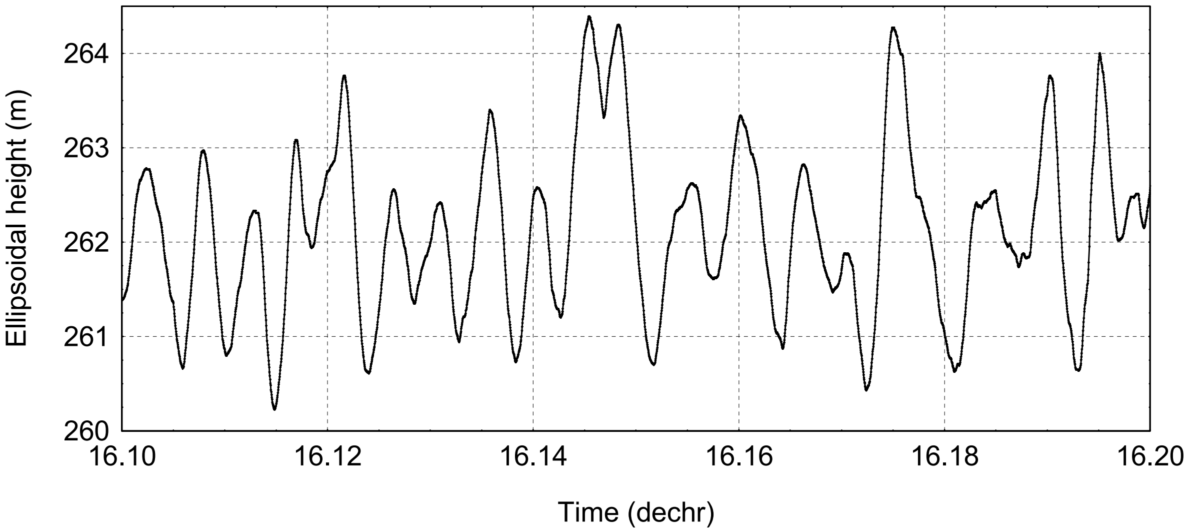


Fig. 7. Example of GPS aircraft height (JD 144), showing phugoid motion due to the autopilot feedback system. The regular phugoid motion is useful for time calibration.

4.2 Inertial attitude and position data

A Honeywell medium-grade inertial navigation system with embedded GPS (H764-G "EGI") was used throughout the flights to record inertially integrated position, velocity and attitude information. 50 Hz inertial data were logged on a laptop PC in binary format through a 1553 mil-spec communications bus. Both free inertial and Kalman filtered GPS-integrated inertial data were logged on most flights. Data volume per flight was typically 50 MB/hour.

The INS data processing consists of the following steps:

1) Reading and reformatting the original EGI binary 1553 data. The data are in this process averaged to 10 Hz to obtain more manageable file sizes (this has no impact on the final quality of the laser data). A specially developed Fortran programme "*readegi*" does this task.

2) Combination of the INS and GPS. "Draping" of the INS-integrated heights onto the GPS heights is done by modelling the function

$$\varepsilon = h^{GPS} - h^{INS} \tag{2}$$

by a low-pass filtered smooth correction curve, which is added to the INS results. In this way a smooth GPS-INS file is obtained, which will preserve the GPS solutions, but otherwise fill-in the gaps in data with INS information. The programme for this is "*gpsegi*".

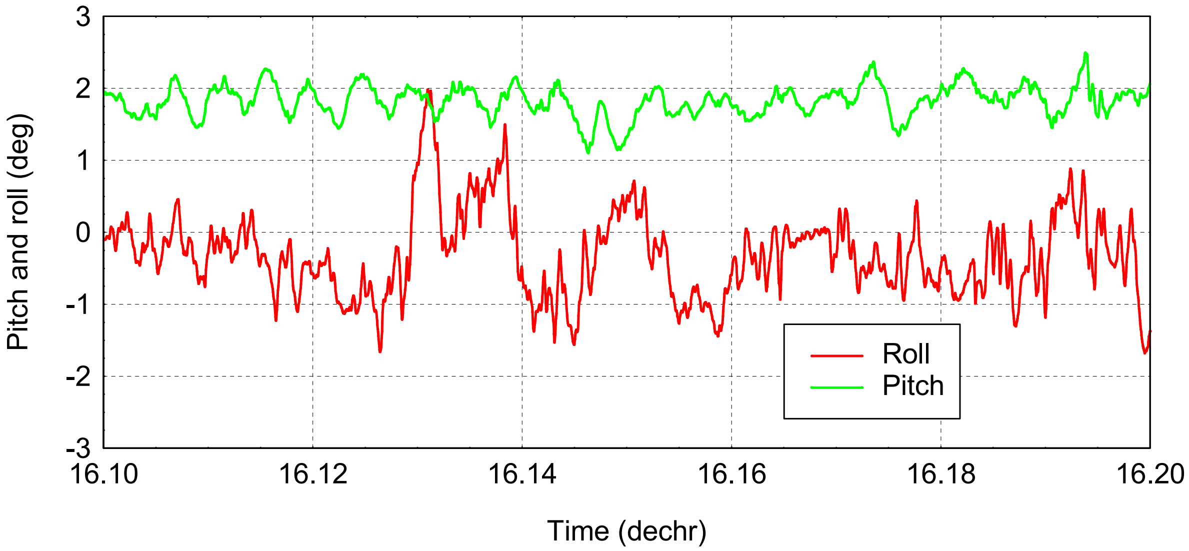


Fig. 8. Example of pitch (green) and roll (red) from INS; JD144.

Figure 8 shows roll and pitch of a small part of a typical flight. The merged GPS-INS files are typically denominated ".pos"-files, and contain the following information:

thr, lat, lon, h, pitch, roll, heading

where *thr* is the time, *lat, lon, pitch, roll* and *heading* in degrees. The raw INS files are typically in the data archives called names of form "05231409.ddk" where 05231409 is date/time information (May 5th at 14:09).

4.3 Scanning laser data and processing

During the KMS2004 operations all laser measurements were done with a Riegl scanning laser of type LMS-Q140i, which provides cross-track scans at a user selectable frequency, with range accuracy better than 5 cm. The laser operates in the near-infrared wavelength band, and has a scan angle of 60°, giving a swath width roughly identical to the flight elevation above ground (for the installation in the Twin-Otter a small fraction of the outermost scans were shaded by the fuselage due to a limited hole size in the Twin-Otter). The principle is outlined in figure 9.

The KMS Riegl laser scanner (lidar) data was logged as hourly files on a stand-alone laptop computer. The lidar files are time tagged by a 1 pps signal from the AIR1 GPS receiver, with start time of the scans given by the operator as a file name. Nominally files cover about 1 hr of data, at 40 scans/second and 208 measurements per scan. During changeover between files 1-2 min of data are typically lost. No data were taken in fog. Start and stop time of the lidar files acquired are listed in Appendix 3.

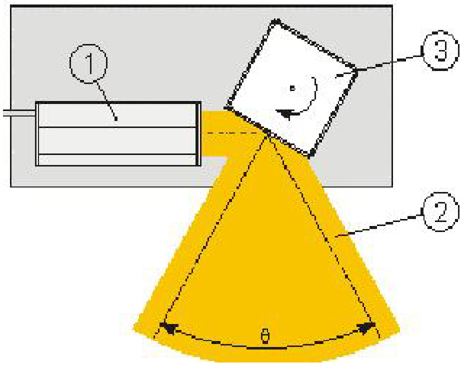


Fig. 9. Scanning lidar principle. A laser (1) provides a swath (2) by reflection in a rotating mirror (3)

Files were logged in text or binary (".2dd") formats, yielding file sizes of 200-300 MB. Data were written directly on CD's after the flights. Occasionally recorded by error, text-format logged files were converted into binary format as part of the processing, and no text-format files should be left in the raw data collections used for processing.

A note of caution: Unfortunately the Riegl logging system does not allow the recording of the integer seconds. There is therefore a risk of lack of synchronization between laser and GPS/INS at integer seconds, corresponding to translations at multiples of approximately 60 m on the ground. Usually these offsets are easily detected by visual inspection of plots of crossing scans.

Fig. 10. Left: Riegl laser scanner with attached heating pads (left) and EGI instrument (back right). Right: Aircraft hole photographed from below, with scanner mirror and below the lenses of single beam laser altimeter (backup instrument). The web camera was mounted just left of the two lenses.

The routine processing of the lidar data into ellipsoidal surface heights involves two steps:

1) Reading the raw Riegl scanner files, and recovering GPS time, laser mirror angle α and measured range r, and interpolating corresponding GPS coordinates and pitch, roll, heading (p,r,a) for the GPS-EGI output file.

2) Using three-dimensional geometry to compute coordinates of the ground laser reflection point by computing the coordinate vector (Δx, Δy, Δz) in a local-level system (N,E,U) from the aircraft GPS antenna position to the ground point position (not taken the misalignment into account):

$$\begin{aligned}
\Delta x &= cosa*cosp*dx_l + (cosa*sinp*sinr-sina*cosr)*dy + (cosa*sinp*cosr+sina*sinr)*dz \\
\Delta y &= -sina*cosp*dx_l - (sina*sinp*sinr+cosa*cosr)*dy + (cosa*sinr-sina*sinp*cosr)*dz \\
\Delta z &= sinp*dx_l - cosp*sinr*dy - cosp*cosr*dz \qquad (3)
\end{aligned}$$

where (dx,dy,dz) are the offsets in the aircraft body system:

x positive to the front of the aircraft $dx = -sin(a)*r + dx_l$
y positive to the right of the aircraft $dy = cos(a)*r + dy_l$
z positive down $dz = sin(p)*r + dz_l$ *(4)*

In the above equations the aircraft GPS antenna offset (dx_l, dy_l, dz_l) will depend on the GPS antenna used. The used offsets are listed in table 5, cf. fig. 13.

Table 5. The (dx, dy, dz) offsets. The lever arm from the GPS antennas to the origin of the laser scanner:

to laser scanner	dx (m)	dy (m)	dz (m)
from AIR1/AIR2 (front)	- 3.70	+ 0.52	+ 1.58
from AIR3 (rear)	+ 0.00	- 0.35	+ 1.42

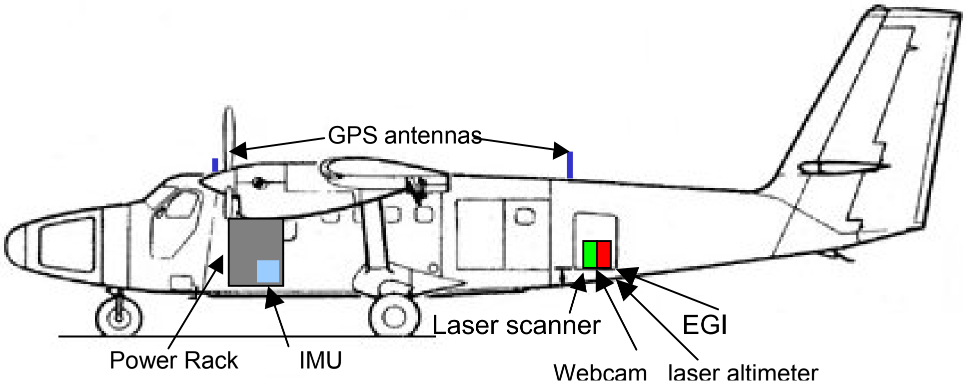


Fig. 11. GPS antenna offset vectors to the laser scanner.

The laser scanner has an inherent unknown orientation when installed in the aircraft. Whereas the roll offset r_0 are easily found by regression over level surfaces (e.g. water), the determination of pitch and heading offsets p_0 and a_0 are normally determined by a 4-leaf-clover overflight of known GPS-positioned objects. Buildings in Kangerlussuaq and near the airstrip Alert were used for this purpose.

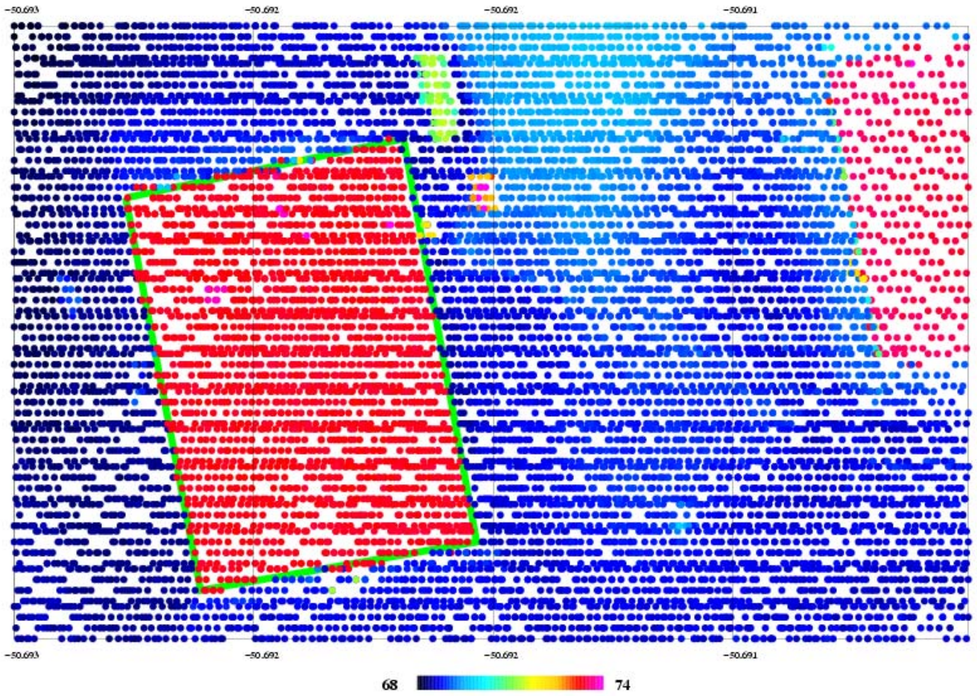


Fig. 12. Laser scan on JD125 over Kangerlussuaq storage building, measured by GPS for calibration of offset angles, units in meters.

During processing of the lidar data it was soon clear that the offset angles changed during the campaign. The equipment was uninstalled on JD114 and reinstalled JD125 and a new set of angles was found from over flights over the Kangerlussuaq building. During the days 127 to 130 the aircraft was used for service flights to the ice camp, and the lidar may have been hit during loading or unloading of cargo. The same may have happened on the days 131, 132 and 133 when heavy cargo was brought to the ice camp on survey flights. On days without overflights of buildings, new sets of offset angles were found over thin level ice and in crossovers. The offset values are shown in table 6 together with the calibration method.

Table 6. Angle offsets for the lidar.

Angle offset ID	p_0	r_0	a_0	*Calibrated over*
A	*0.60*	*0.08*	*0.40*	*building in Kangerlussuaq(JD111)*
B	*0.20*	*-0.15*	*0.5*	*building in Kangerlussuaq (JD125)*
C	*0.35*	*0.00*	*0.50*	*building in Alert (JD135)*
D	*0.35*	*-0.07*	*0.50*	*thin level ice (JD132)*
E	*0.35*	*-0.06*	*0.50*	*thin level ice (JD147)*

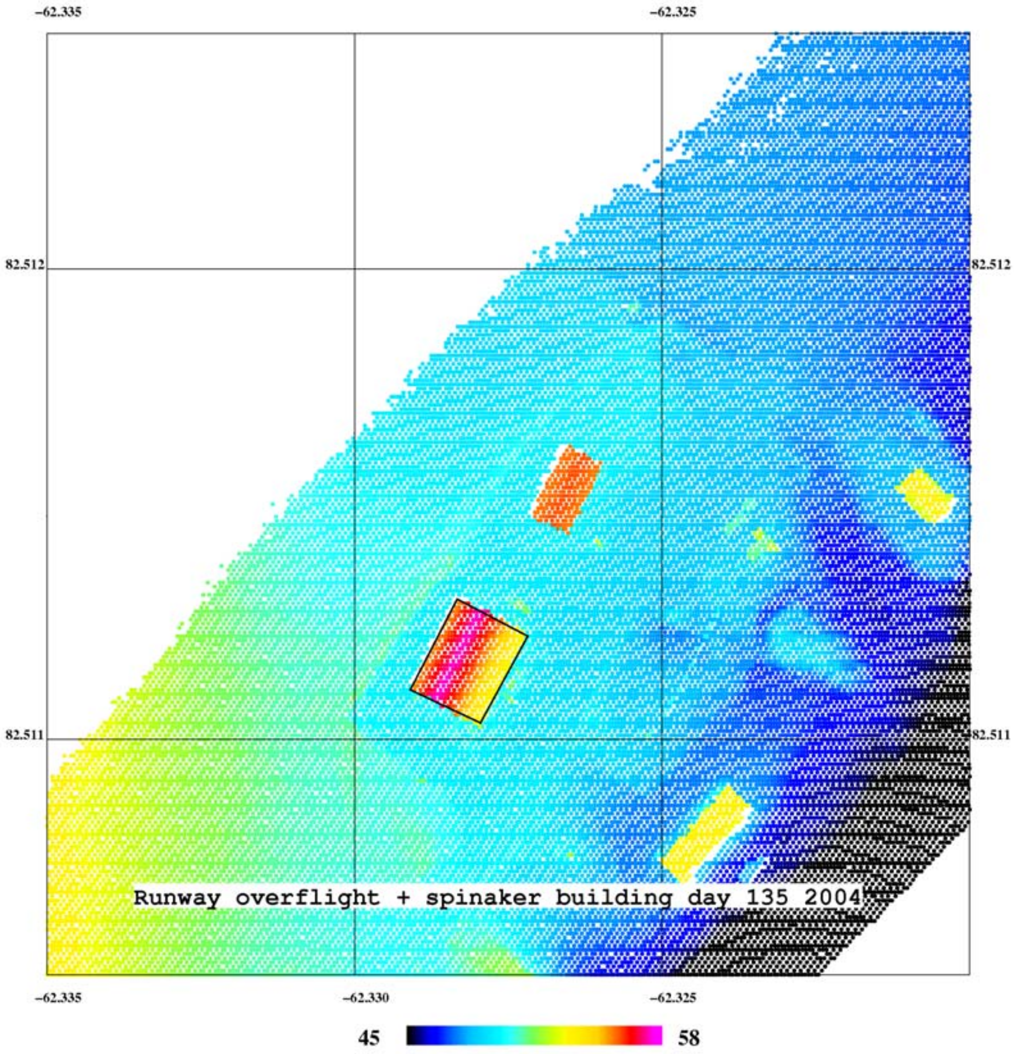


Fig. 13. Laser scan on JD135 over the “Spinaker” building at Alert, units in meters.

The basic outcome of the lidar processing is ellipsoidal heights in WGS84. For use in sea ice freeboard estimation, a geoid model is subtracted from the computed ground heights. For the 2004 flights, as for the Cryovex-2003 flights, a geoid model, based on the Arctic Gravity Project and improved long-wavelength gravity field information from the GRACE satellite mission, has been used (Forsberg and Kenyon, 2004). The geoid – computed across the entire Arctic region north of 64°N – is shown in figure 14, and used for all sea-ice flight processing.

For the land ice, however, ellipsoidal heights were kept unchanged to ease comparisons with other GPS data and earlier acquired laser data.

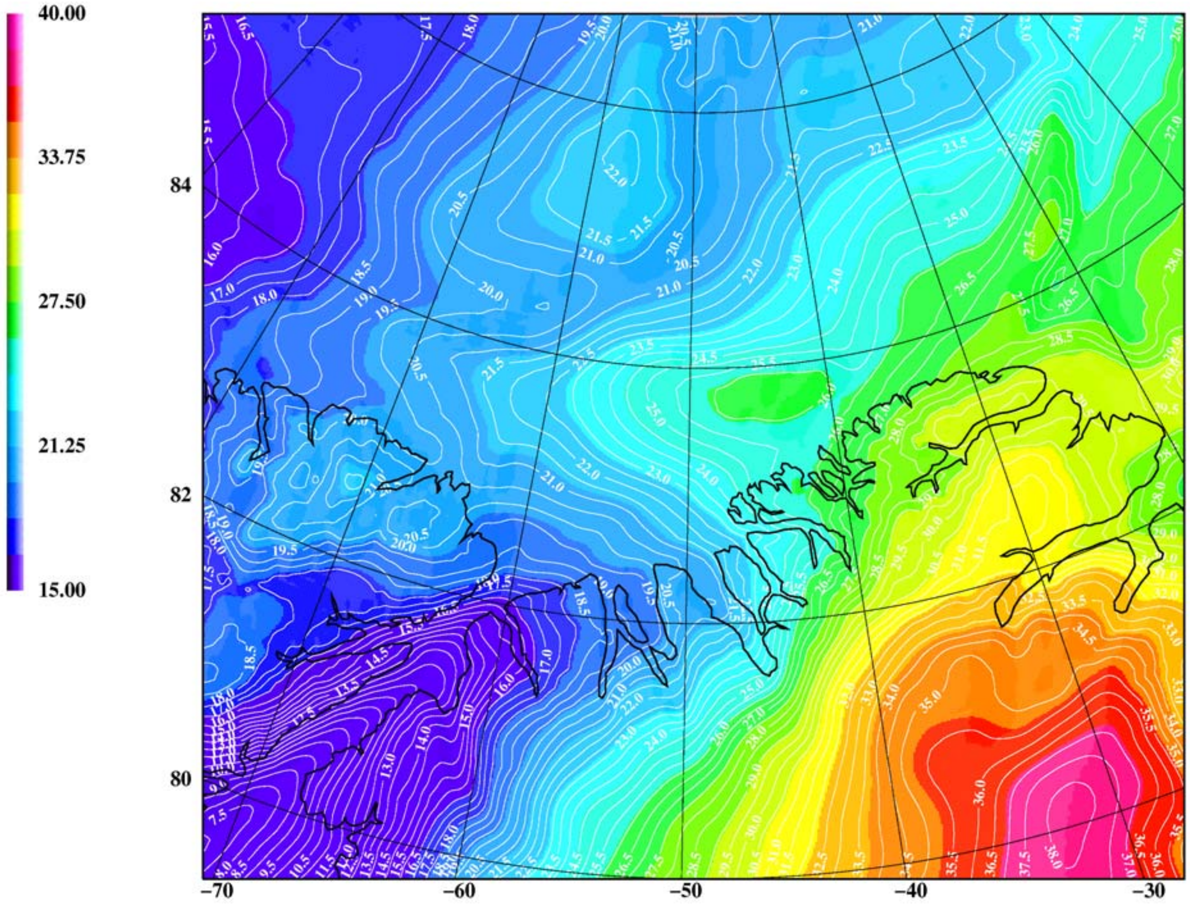


Fig. 14. ArcGP Feb 2004 geoid model used for reducing sea-ice lidar data. Units: meters.

The figures 15, 16 and 17 show some examples of full resolution sea ice and land ice lidar data after reduction for the geoid. The figures illustrate the high detail obtained in the lidar data, providing a clear representation of ridges and leads, and first-year and multi-year ice. The crossing tracks also illustrate the moving sea-ice, and that lidar for repeated flights in principle may be used to determine near-instantaneous ice velocities.

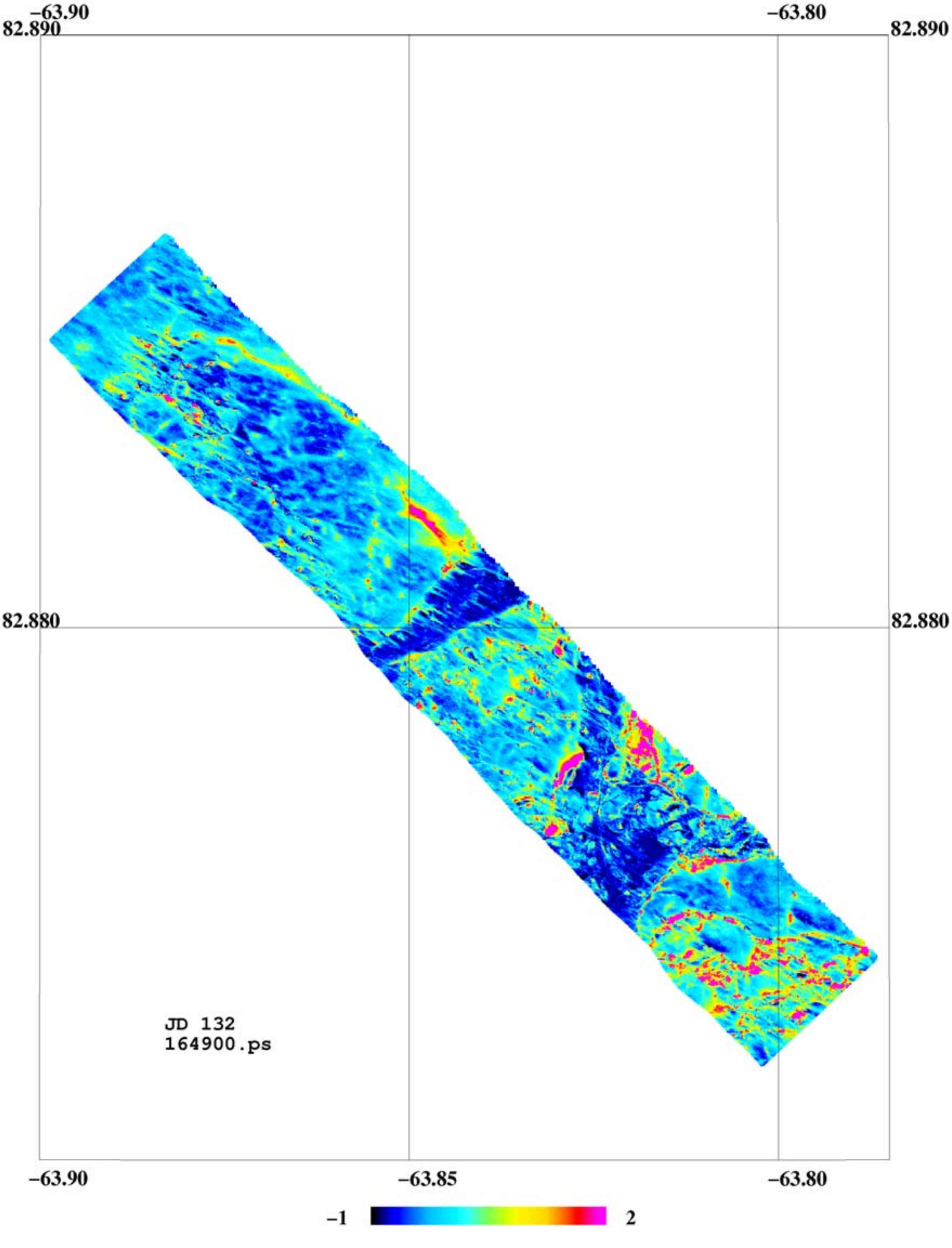


Fig. 15. Example of section of sea ice showing sastrugi on thin ice. Heights above geoid (m).

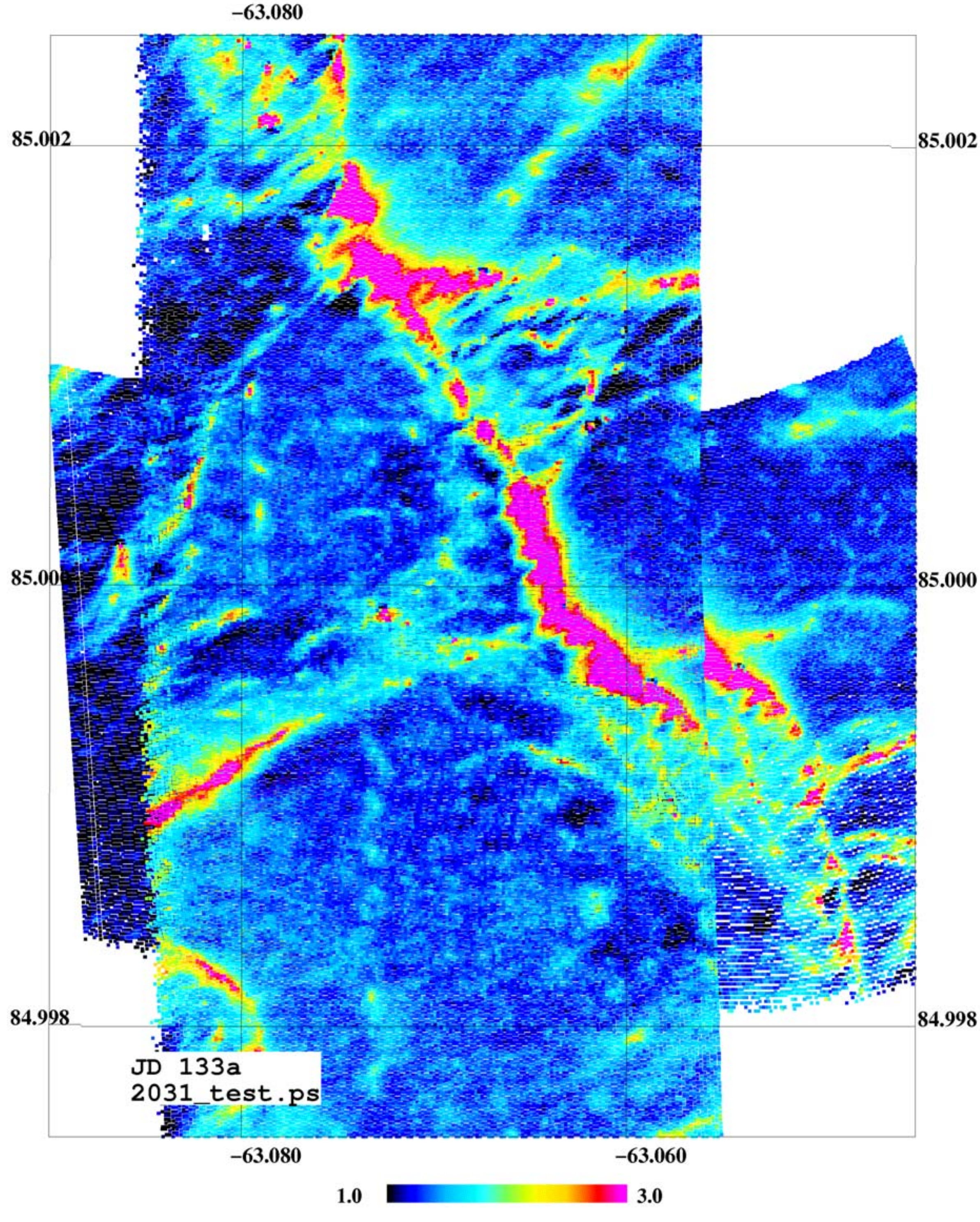


Fig. 16. Example of ice drift. The plot shows the ice drift towards West, when a North-South going flight line intersects an East-West going line after app. 5 minutes. Heights above geoid (m).

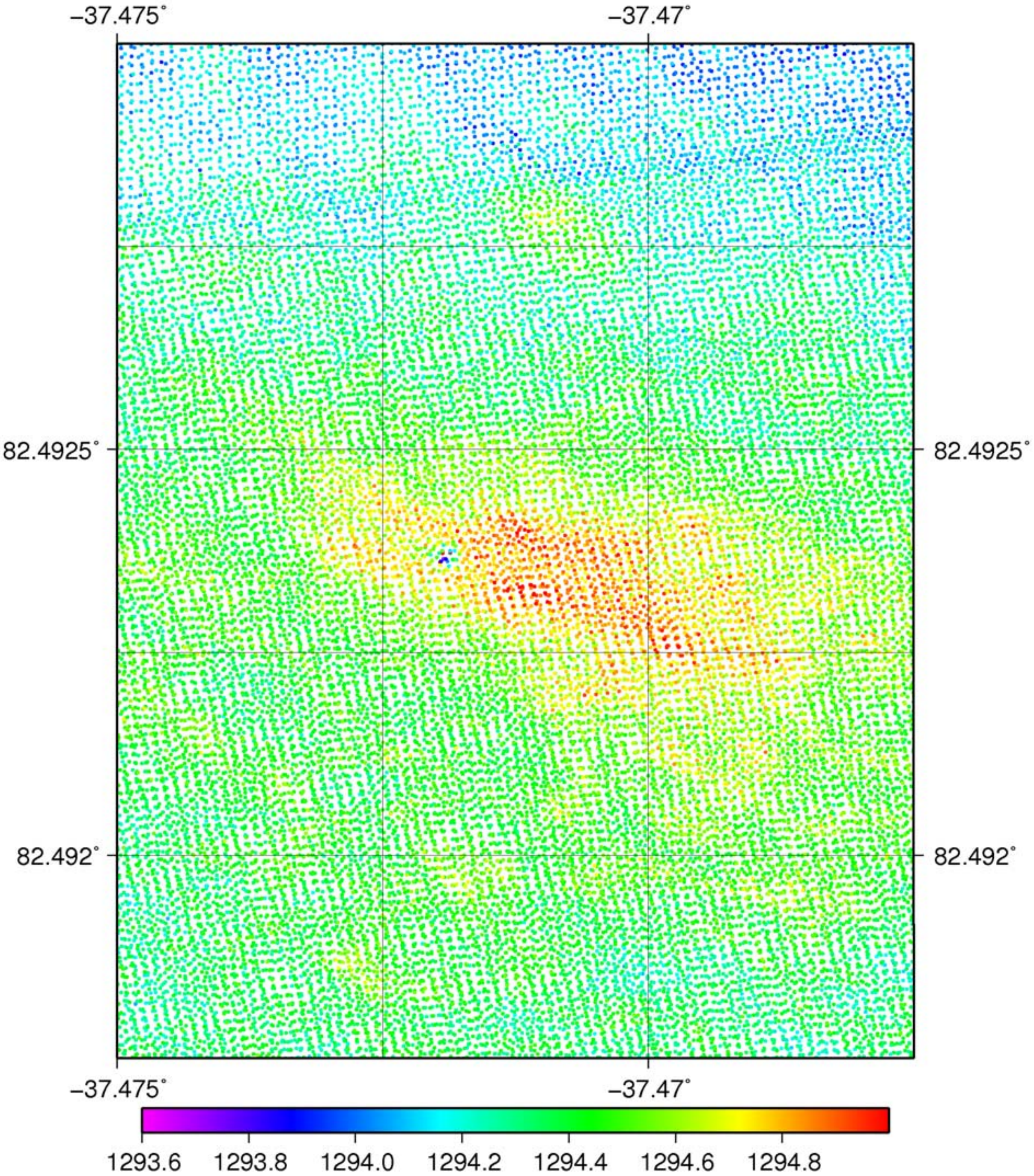


Fig. 17. Example of land ice ellipsoidal heights by laser from the Hans Tausen Ice Cap, Peary Land, North Greenland (the low spot in the middle is the loo from a 1995 glaciological field camp!).

4.4 Single beam laser

An Optech single beam laser altimeter was collecting data along with the Riegl laser scanner. The primary purpose of the single beam altimeter was to provide auxiliary laser data for comparison with the scanner, and detect offsets in the scanner due to the integer second offset problem. The laser altimeter can be seen in figure 10. The altimeter has a smaller range than the scanner, and was only used in a few cases to check for the offset timing.

4.5 Conversion of sea ice lidar results to freeboard heights

The lidar data over sea ice, processed as outlined in the previous section, are affected by systematic errors from GPS solutions, biases in geoid heights, and mean ocean dynamic topography, all of which implies that apparent freeboard heights F will be biased. This bias may be removed by “lowest-level” filtering. For the 2004 flights a generalized collocation version of the lowest-level filtering scheme - applied in Hvidegaard and Forsberg (2002) - has been used to routinely process “level 2” (5x5 averaged) lidar data into freeboard heights.

In the basic “standardized” method selected available lidar data – typically in a 1 hr segment – is subdivided into 0.01 hr intervals (corresponding to approx. 2 km). The minimal value in each interval is averaged over 0.04 hr intervals, and a “minimum surface” is fitted to the averaged minimal points by a trend surface

$$\Delta F = a + b^*t + s \tag{5}$$

Here a and b are constants, and s a stochastic signal modelled by least-squares collocation

$$s = C_{sx}C_{xx}^{-1}\underline{x} \tag{6}$$

where $\underline{x}$ is the vector of minimal values, and C the covariance matrices. A second-order Markov model covariance model

$$C(t) = C_0\,(1+\beta t)\, e^{-\beta t}, \quad \beta = 0.595\ t_{1/2} \tag{7}$$

was used throughout all processing, with a correlation length ($t_{1/2}$) of 0.04 hr and an assumed apriori noise of 0.2 m. The computations were done with a specially developed Fortran programme *“fitlinc”*.

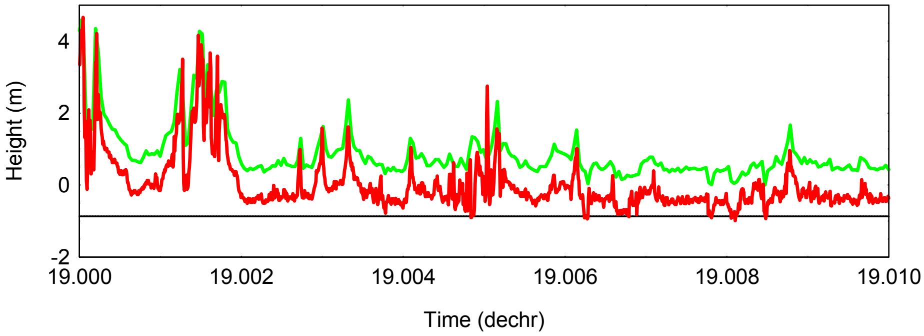


Fig. 18. Example of lowest level fitting of sea ice lidar data. Green: lidar results; lower, smooth curve (black): collocation minimum fit; red: freeboard heights. JD132.

The above principle corresponds to fitting a “smooth” curve to the lowest level. How to fit the curve, and the proper selection of covariance parameters are very much topics of ongoing research, and obviously a close function of ice properties, existence of outliers in the scanner data, and the nature of the local GPS and geoid errors. Figure 18 shows a typical example of the lowest-level curve estimation, and figure 19 shows an example of the estimated freeboard heights with associated freeboard distributions on the JD132 flight from Alert to the ice camp and back to Alert.

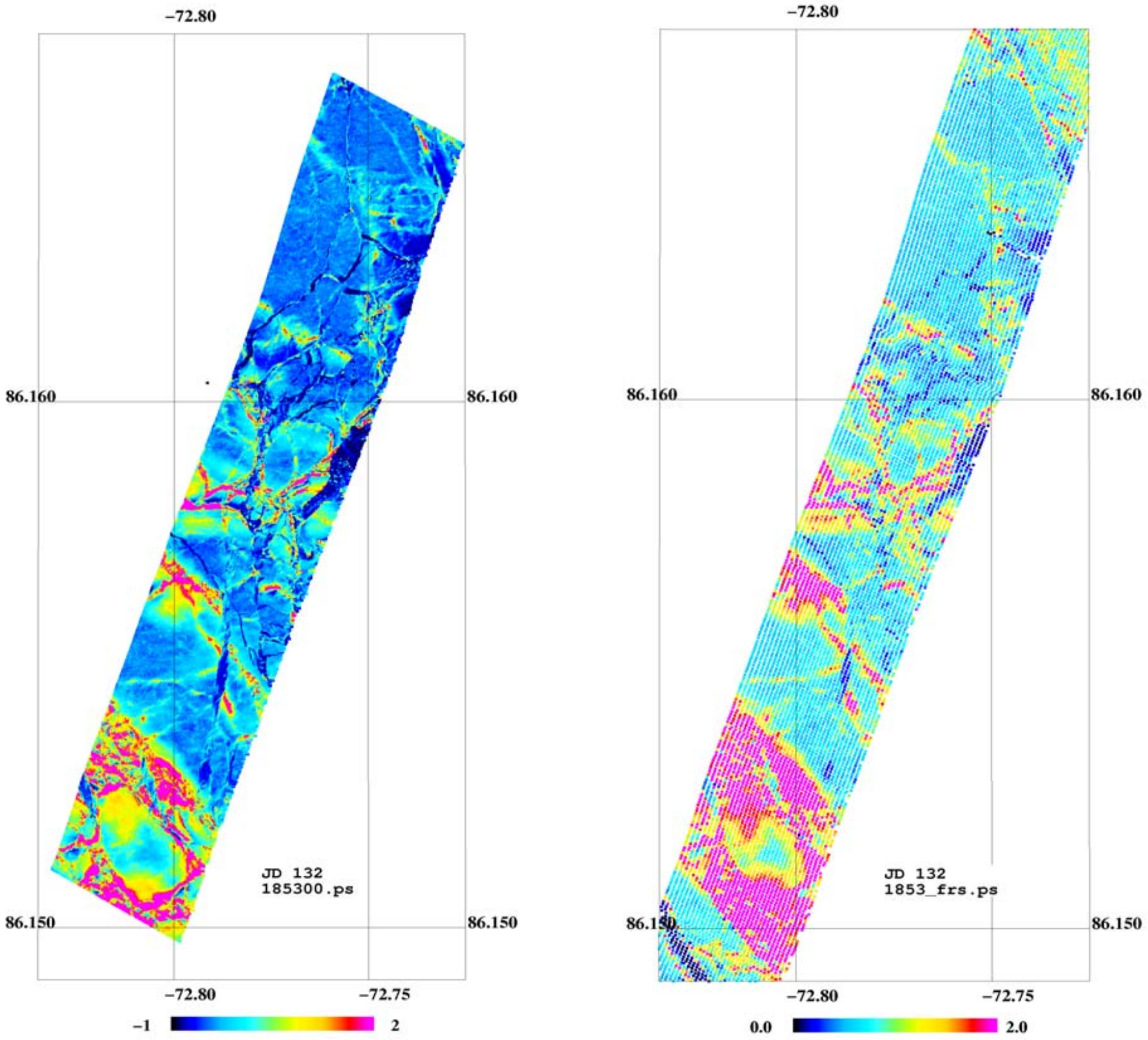
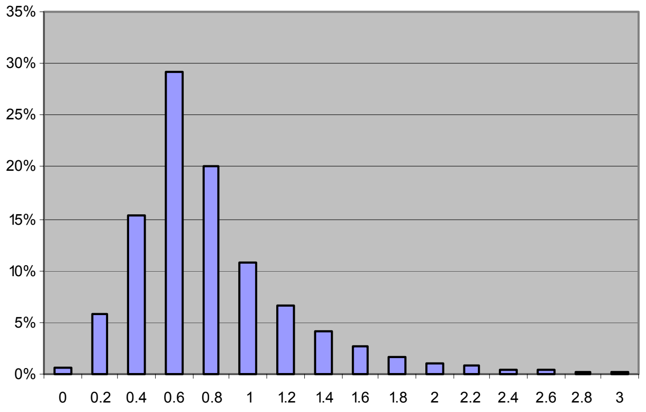


Fig. 19. Left: full-resolution lidar data (heights above geoid) from JD132 (May 11th) in a 0.01 hr interval. Right: the corresponding freeboard height data. Bottom: associated freeboard height distribution (units: meter).



Average ice thickness may be derived from the freeboard heights, by multiplication by a climatology-determined factor (approximately 6.0 in April/May – Wadhams et. al., 1992). This method relies on an assumption of isostatic balance between the height of the ice floe, including snow cover, and the buoyancy of the sea water surrounding the floe. The procedure applies to average sea ice properties on scales longer than typical floe sizes (> 100-200 m).

For the 2004 overall thickness map, all sea ice freeboard data have been averaged in approx. 4.5 km segments and transformed into total ice+snow thickness by a lowest-level polynomial fit. Results for all data are shown in figure 20. Note the low average sea ice thickness in the Lincoln Sea caused by a recent break up of ice in the Nares Strait that allowed ice to drift southwards through the channel prior to the observations.

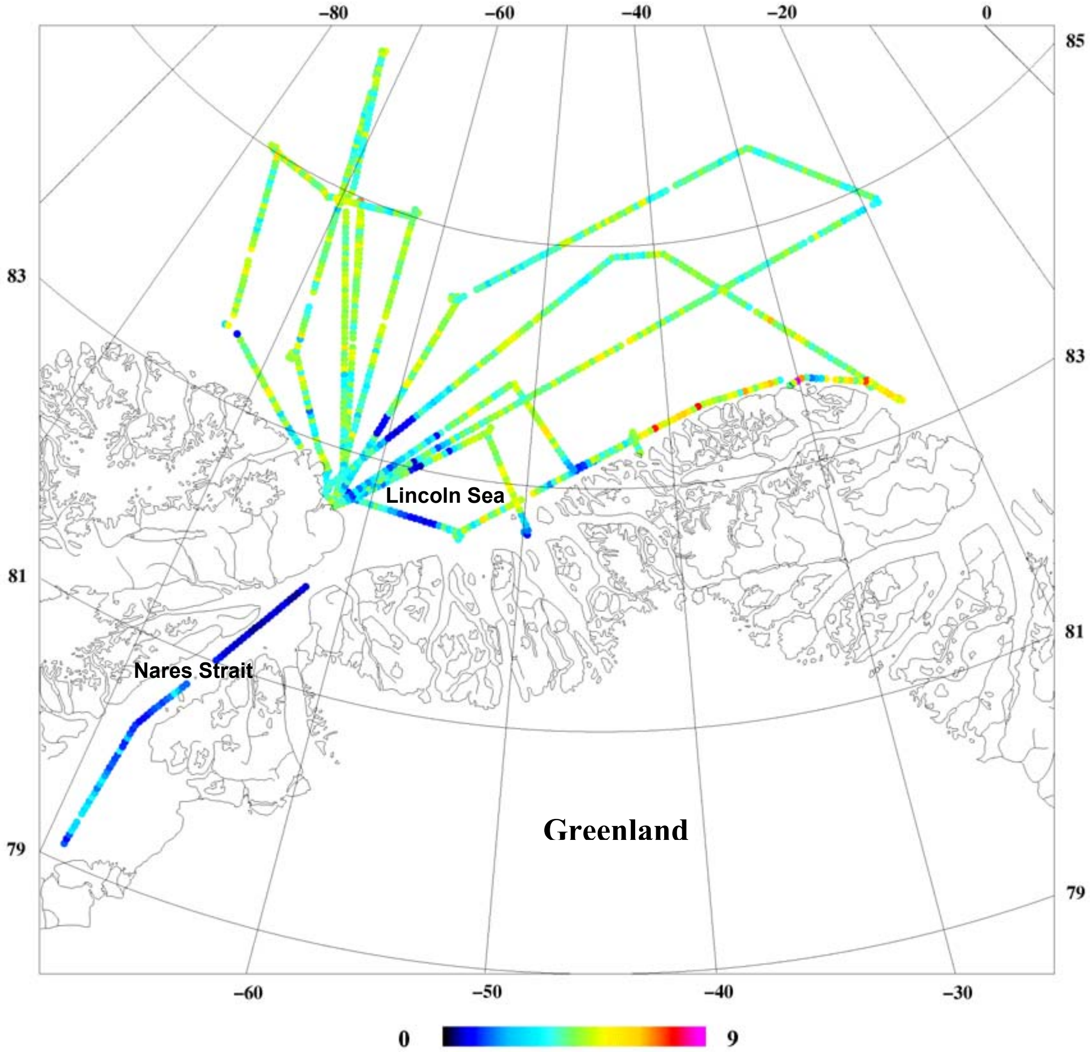


Fig. 20. Ice thickness from lidar measurements during the 2004 campaign. Unit: meter.

4.6 Ice drilling off Alert.

Limited reference measurements of sea-ice thickness, sea-ice freeboard and snow thickness were measured on polar pack ice floes off the runway at Alert on May 22. Due to very rough conditions, i.e. heavy ridging in the area and poor visibility, only four holes were drilled. The positions and measurements can be seen in the table and figure below. These are in the same area as similar drillings in 2002.

Table 7. Measurements of ice thickness, ice freeboard and snow depth off Alert by drilling. May 22 (JD 143).

Pt no	Lat	Lon	Snow Depth	Ice thickness	Ice freeboard
1	82 31.76	62 11.816	0.12 m	3.77 m	0.47 m
2	82 31.828	62 11.378	0.10 m	6 m+ (6.20?)	0.83 m
3	82 31.849	62 09.752	0.27 m	3.69 m	0.40 m
4	82 31.914	62 09.732	0.14 m	3.74 m	0.51 m

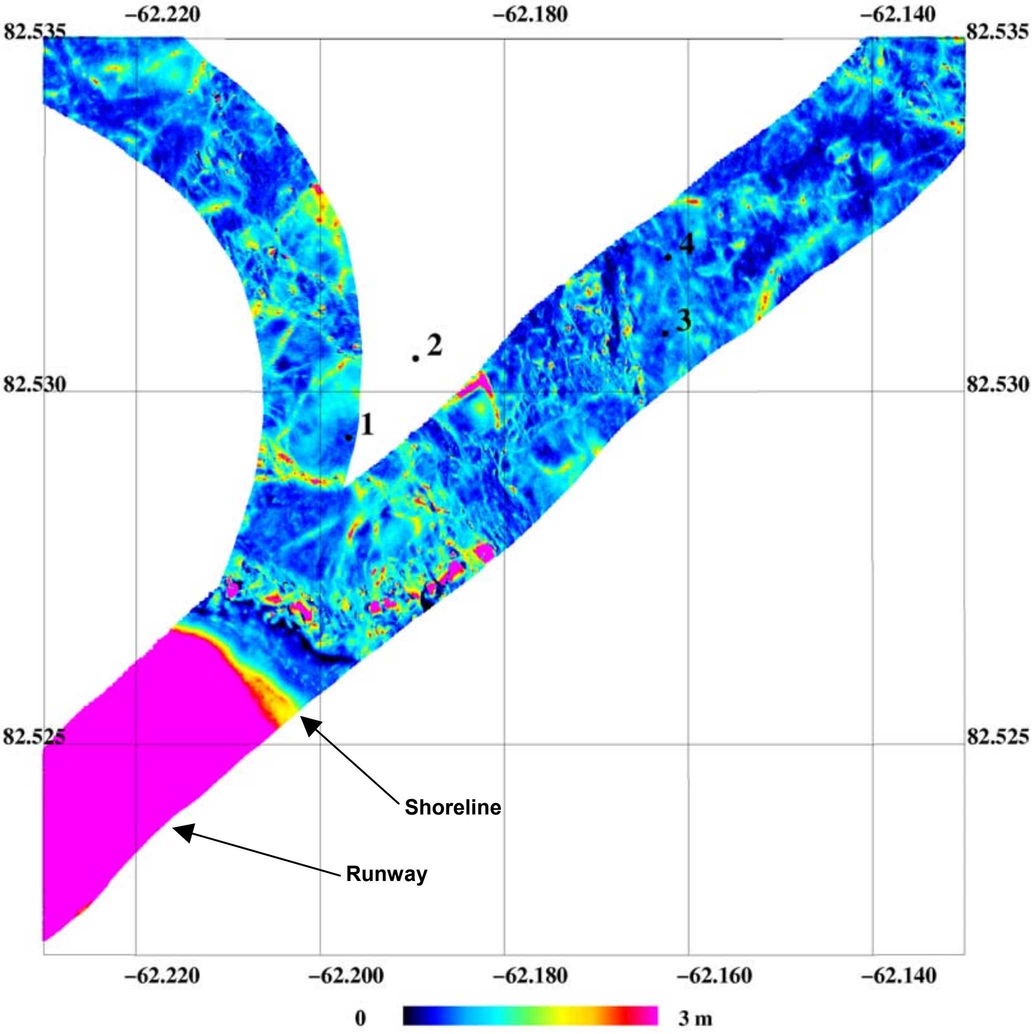


Fig. 21. Position of drilling sites points 1-4 off Alert and sea-ice freeboard heights extracted from scanner data on flight May 23 (JD 144).

Fig. 22. Ice drilling off Alert.

Fig. 23. Ice conditions in the area of the drilling sites off the runway, Alert.

4.7 Auxiliary data: Vertical digital photos

For verification and validation purposes a webcam was installed (looking nadir) in the aircraft next to the laser scanner. The webcam used was an AXIS 2100, which automatically recorded and stored the images on a laptop-PC every 2 seconds. The image resolution 604x480 (72 dpi) is on purpose rather low due to the large amount of data (~200 Mb) gathered at one flight. A photo example can be seen in figure 24, and a set of continuous photos with associated laser scanner data in figure 25. During operation the pictures were time-tagged and named after the logging computer internal clock time tags. The time offset found by comparing the images to GPS time by use of scanner data can be seen in appendix 9. The geo-located and time-tagged vertical photos are given along with the lidar data as final results of the 2004 campaign. Photos are available for four flights:

May 5	*Thule Airbase to Alert*
May 14	*Hans Tausen icecap*
May 23/25	*SITHOS flights*

The webcam was easy to operate and gave the opportunity to collect a continuous sequence of images overlapping in time, which is a great advantage compared to the digital camera used in 2003 (K. Keller et al., 2003). Unfortunately the webcam needed a large contrast, e.g. clear sky or dark open leads in between the ice floes, to produce images of high quality.

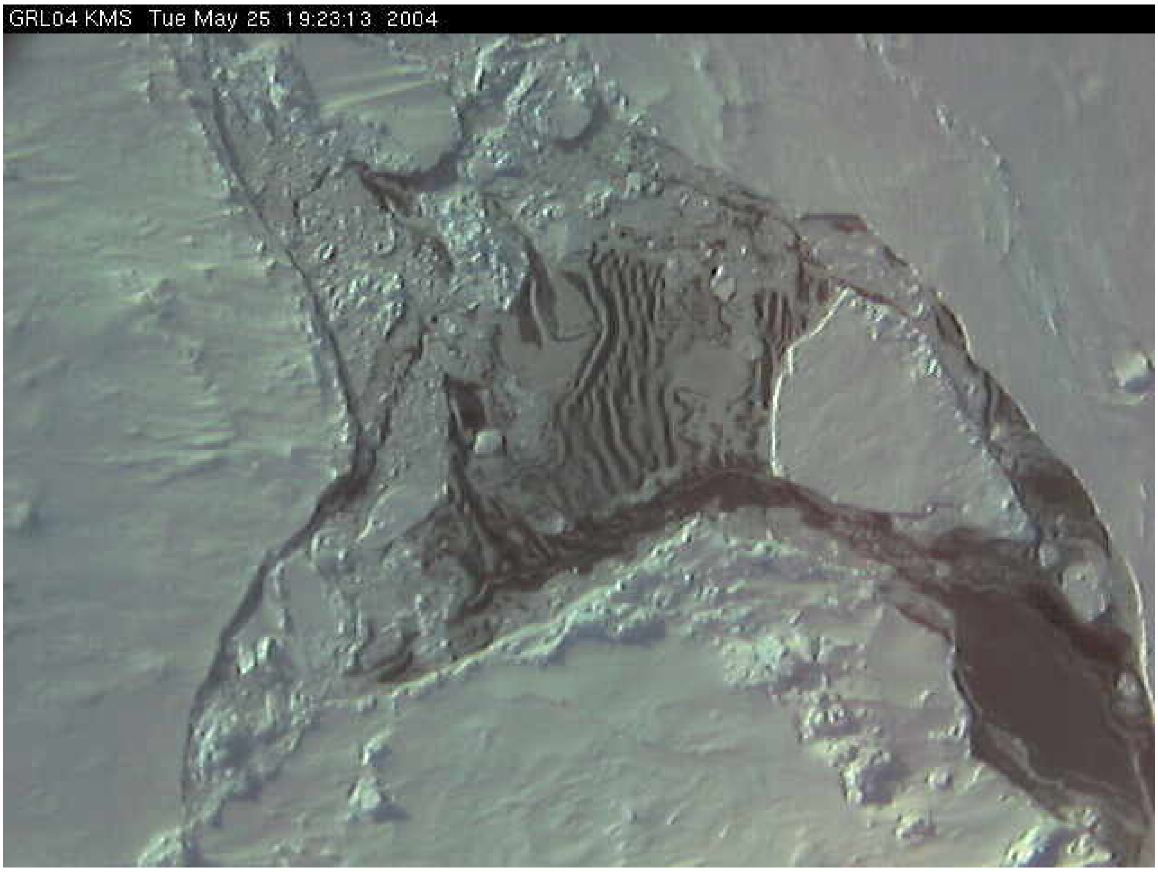


Fig. 24. Example of vertical photo with leads with new ice, size of image approx.150x200 m

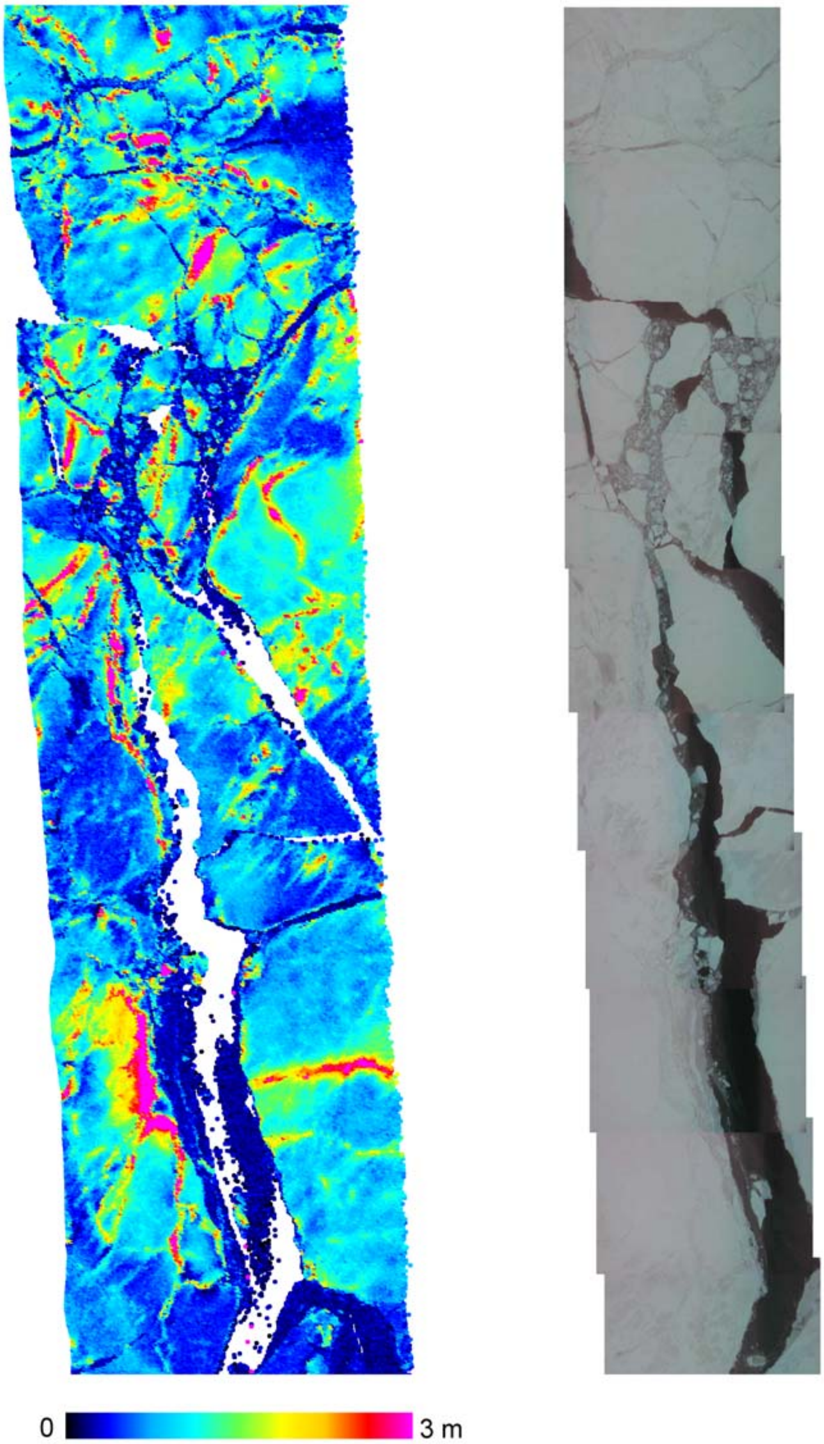


Fig. 25. Example of coincident scanner data (left) versus vertical photo (right). May 23 JD144 15.415-15.425 UTC.

5 UNDERFLIGHT OF ICESat

As part of the field campaign an under flight of NASA's space borne laser altimeter ICESat was carried out. Two near coincident tracks were flown on May 25 (JD 146), see figure below. The high-resolution airborne swath laser data provide detailed mapping of ridges and leads, and thus provides an opportunity to understand ICESat waveform characteristics for different sea-ice types and settings.

Unfortunately a timing error for the aircraft scheduling gave an 8 hour delay in the under flight compared to the ICESat passage. However, by luck the ice both along the western and eastern flight tracks showed essentially no movement in the period due to calm wind conditions, as verified by drift vectors estimated from Envisat SAR interferometry.

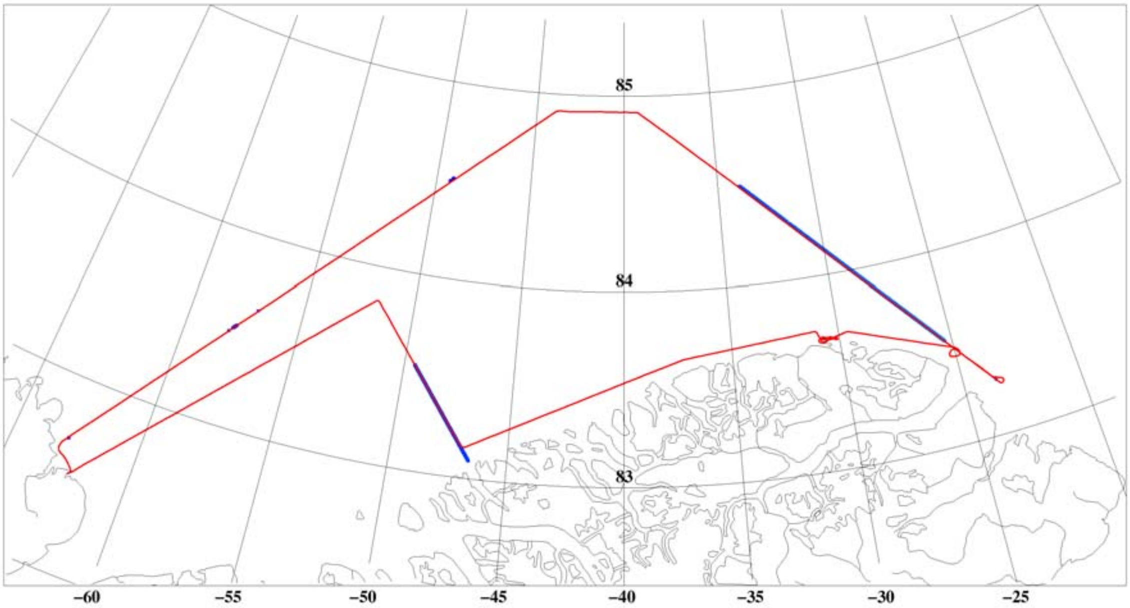


Fig. 26.The red line is the flight track of May 25. The blue lines are the cloud-free near-coincident ICESat sub tracks from the same day.

Preliminary work shows good correlation between the two data sets, but also indicate the ICESat freeboards to be underestimated by ~25 cm, see Figure 27. The offset is believed to originate from an overestimation of the lowest-level fit as the heights under consideration are averaged over the relative large ICESat footprint ~70 m.

The smoothing across the ICESat footprint can also be detected in the freeboard distributions, see Figure 28. Here the thinnest ice classes and ridges are almost absent in the ICESat freeboard distribution, but present in the laser scanner freeboard distribution.

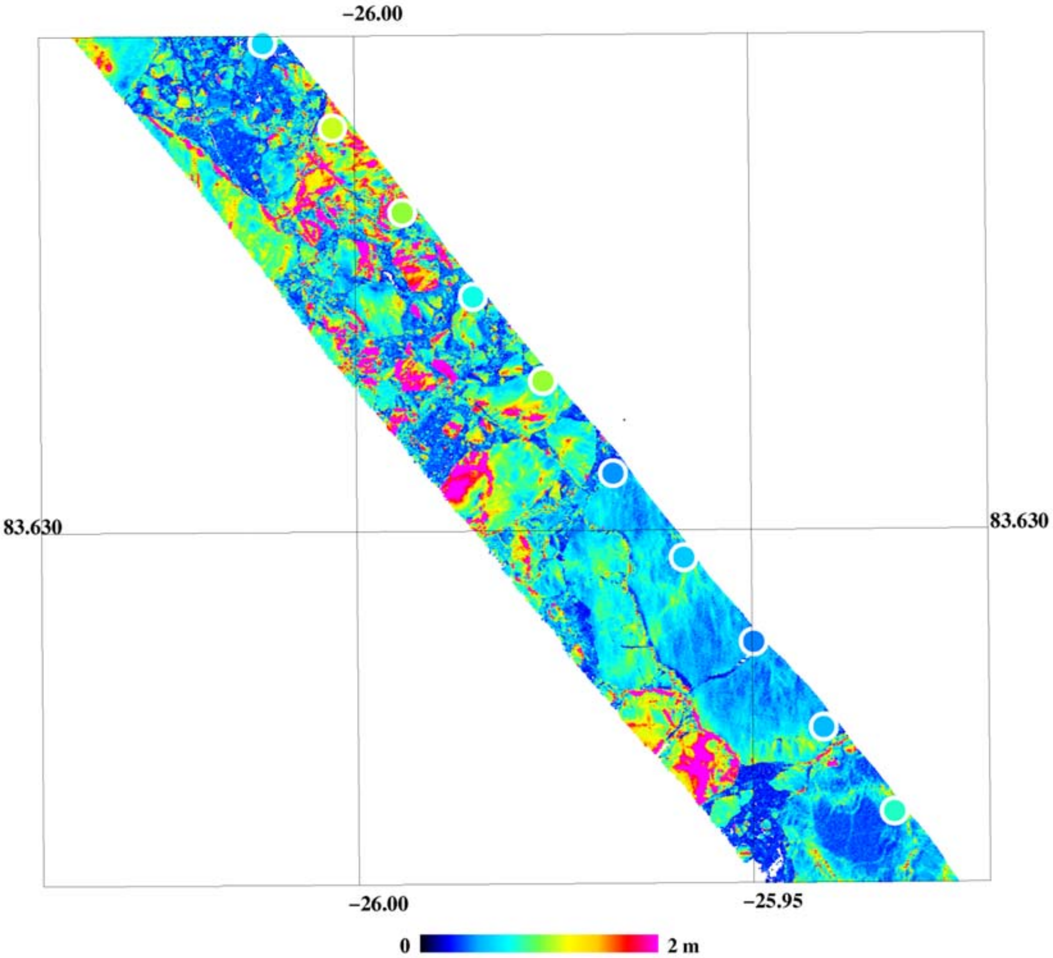


Fig. 27. Lidar swath (width approx. 250 m) after lowest-level filtering - ICESat measurements shown with circles – same color coding. A good qualitative agreement is seen.

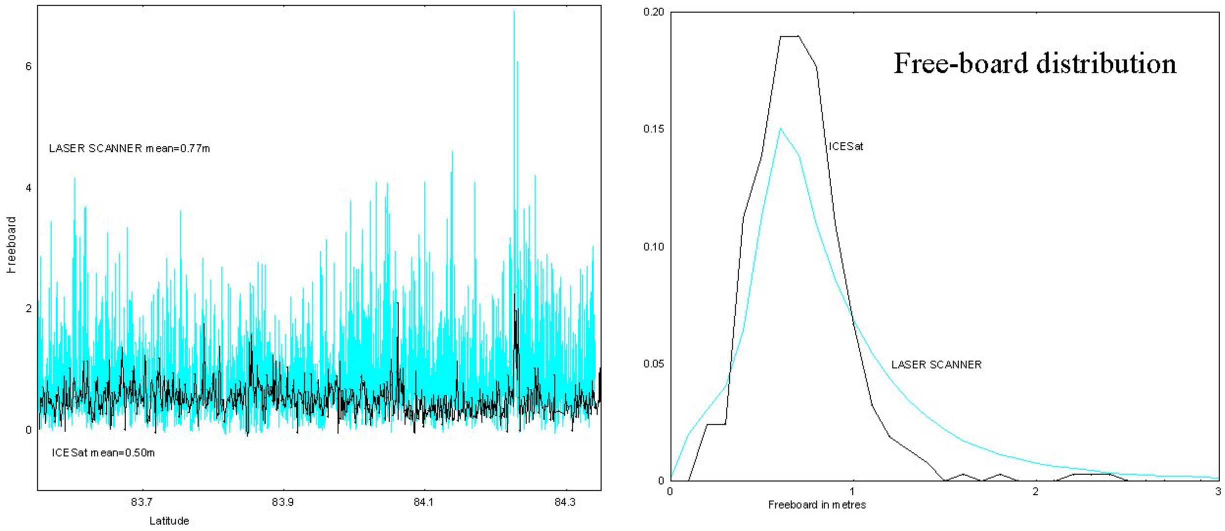


Fig. 28. Left: Freeboard heights from ICESat (black) and the vertical part of laser scanner data (cyan). The mean value of the laser scanner freeboard is ~25 cm higher than the mean value based on ICESat freeboard, when using the lowest level filtering method. Right: Freeboard distribution.

6 GreenICE drifting ice camp

The laser flights of 2004 was done in connection with the support of the GreenICE ice camp, established on May 7, 2004, aimed to be a low cost, 14 day temporary camp for doing a variety of different research, including coring of ocean bottom sediments (GEUS), making a seismic profile (Univ. of Bergen), installing tilt meter buoys for ice thickness measurement tests (SAMS), as well as general climatological and sea-ice in-situ drilling studies (GEUS and AWI). For details of the GreenICE project see www.greenice.org.

A major purpose of the ice camp activities was also to collect simultaneous helicopter EM and Twin-Otter laser scanner data. AWI brought for this purpose an EM sensor, which measures ice thickness when towed under a helicopter (cf. the picture on the front page). Unfortunately the coincident laser-EM flights could not be carried out due to a long period of bad weather, and a medical evacuation of one of the AWI participants, who had an accident during ice drilling at camp.

The establishment of the GreenICE camp by the support of the same Twin-Otter that made laser measurement flights, shows the versatility and efficiency of this kind of joint operation with a Twin-Otter. The GreenICE camp was established on May 7 by an advance team associated with Defense Research Establishment Atlantic (DREA) and the KMS participants (K. Keller and H. Skourup). The first position by handheld GPS was found to be 85.021 N 64.868 W. An aircraft runway was found on a refrozen lead 1.20 m in thickness, and the camp established on a multiyear ice floe of 3.5 m in thickness. The ice camp was maintained for 14 days and drifted almost 100 km in a western direction during this period, cf. figure 31. A total of 16 Twin-Otter flights from Alert were used to supply and demobilize the camp during the operations.

Fig. 29. GreenICE camp. The tents on the multi-year floe is the main camp, while the tents at the right near the runway house the seismic equipment.

Fig. 30. GreenICE camp. Tents and other equipment provided by DREA Canada (J. Milne)

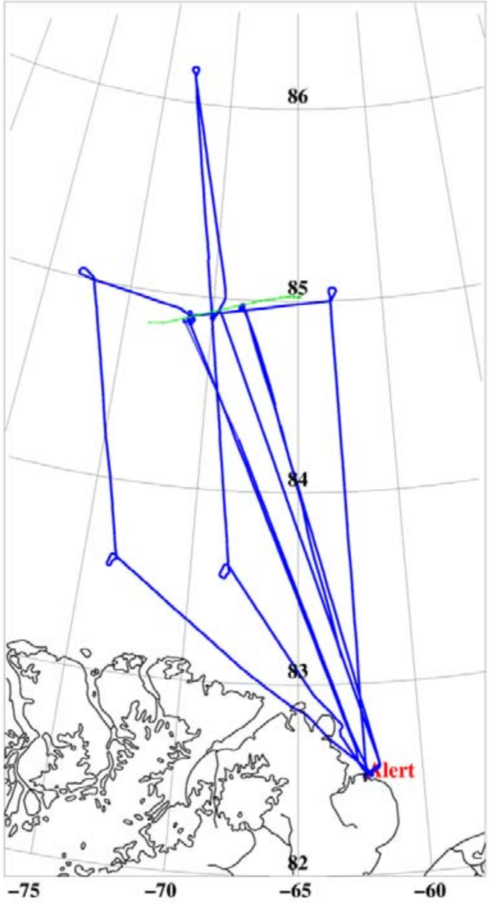


Fig. 31. Laser flights around GreenICE camp. The green line shows the westward drift of camp.

7 CONCLUSIONS

The 2004 KMS (DNSC) laser flights were successful in securing a wealth of baseline laser measurements over the inland ice of Greenland, as well as over sea-ice north of Greenland, at a relatively modest cost and manpower effort. The 2004 survey also shows that it is possible to combine laser sea-ice measurements with the major transport and logistic tasks of establishing a temporary ice camp in the Arctic Ocean, utilizing the “empty” return flights during mobilization. The 2004 flight project also supported the “pilot project” of the Danish UNCLOS §76 project, making test measurements of bathymetry on the sea-ice off Alert and at the GreenICE camp location.

The measurements over the inland ice included measurements in the marginal zone of north-western Greenland, as well as a resurvey of the Hans Tausen ice cap in northern Greenland. The purpose of the inland ice measurements was to provide baseline data for detection of ice elevation changes, as well as provide data for calibration and validation of satellites (ICESat and CryoSat). A fully automatized climate station was later installed by GEUS along an airborne laser track near Upernavik as part of the same project. The laser measurements of the EGIG line region was thus done in connection with support of British scientists doing CryoSat pre-launch surface measurements.

The sea-ice measurements provided repeated and new sea-ice freeboard data from a region of the Arctic Ocean with very heavy ice conditions. The derived ice thickness data and associated statistics of ridges and leads will provide useful information for the planned seismic and bathymetric operations by aircraft and icebreakers in the coming years in connection with the Danish §76-projects, as well as providing pre-launch ice data, to be repeated during the calibration and validation phase of the ESA CryoSat mission, presently scheduled for launch in September 2005. The (partially) successful laser under flight of ICESat over Arctic Ocean sea-ice, the first such effort internationally, is an example of the potential of detailed airborne measurements in understanding the satellite signals.

Acknowledgements

We thank G. Stewart, CDN Forces, for providing access to Alert. Martin Doble (SAMS) and R. Abbot (VECO) provided logistical support for the flights, in connection with the preparation of the GreenICE camp. Air Greenland pilots are thanked for good cooperation during the laser flights and establishment of the GreenICE camp. We thank B. Schutz, Univ. of Texas, for the ICESat orbit information. The ICESat data used for the comparisons in Figures 27-28 were obtained from NASA-GSFC (Y. Donghui and J. Zwally; the 2004 data are at present not yet available through the National Snow and Ice Data Center). L. Toudal, DTU, provided the Envisat SAR interferometry ice drift vectors for the ICESat tracks.

Support for the 2004 flights were provided by the Danish Natural Science Research Council (logistic support for CryoSat validation), the Danish Environmental Agency (Miljøstyrelsen) and KMS (§76 support) and the European Union (GreenICE and SITHOS projects).

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Appendix 1. Airborne altimetry log CRYOVEX 2003

All times in UTC.

JD 111 20/4-04 Test and calibration flight SFJ

195500	New scan file 105500.2dd
2000	Taxi to runway
2003	Take off
~2005	Javad fuse couples out
~2007	Javad fuse coupled back in
202708	New scan file 202800.2dd
2046	Landing
204630	Scan file closed

JD 112 21/4-04 SFJ - T12 – JAV+ JAV – T5 - JAV

1045	INS aligned, Pure set to GPS-FG
1049	taxi to runway
1055	take off
110030	new scanfile 110030.2dd
1105	over ice, dist. 300 m
111249	frozen meltwater lake
1113	ice shelf
1126	right turn teardrop
1130	on line N
1137	frozen meltwater river
115030	new scanfile 115030.2dd
1154	low bat detected (Trimble)
1220	right turn teardrop
1225	on line to JAV
1248	open water
125130	new scan file 125130.2dd (Note: 5 sec. sync.)
1300	Landing JAV

JAV - T5 - JAV

1427	Taxi to runway
1429	Take off
143300	New scan file 143300.2dd
1438	Trimble: Low bat. detected
1515	Clockwise teardrop over T5
~1530	Landed at T5. GPS continued logging. Picked up Carl E. B.
154300	New scan file 154300.2dd
1545	Take off
1637	Landing Jacobshavn.
1639	Taxi to block.

JD 113 22/4-04 JAV – T41 – T21 - JAV

1026	Take off JAV
103130	New scanner file
1043	clouds
1046	500 ft
1048	1000 ft
110830	T1
1118	T5
1120	800 ft
1127	stop scanner
112800	new scanner file
1139	T12
1225	stop scanner file
122800	new scanner file
1139	T12
1225	stop scanner file
122600	new scanner file
130015	T41 pass twice
130405	
1305	stop scanner file + INS new file
1310	T41 on ground
	unloading depot for UK1
1343	Take off T41
134500	new scanner file, INS ok
143330	T21 pass twice
143730	T21 pass
1444	on ground T21
150800	new scanner file
1511	take off
1544	T21
1602	T5
1605	stop scanner file
160600	new scanner file (+ 1 sec???)
1648	on ground JAV

EGI file stopped 2 hours earlier probably due to PC-error. EGI/INS PC changed to KRK PC.

JD 114 23/4-04 JAV - N4 - N_line - JUV - S_line - SFJ

0945	all OK (not Trimble power cable??)
0954	take off JAV
101300	new scanner file
1020	N4 pass twice
111220	stop scanner file
111300	new scanner file
	laser alt OK 300 m
1135	N6
12002	N7
120500	new scanner file
1303	new scanner file
1302	N8 ?
1305	N8 ?
1340	S10-S9-S10-S6-JUV
1401	stop scanner file
140200	new scanner file
	turbulence
1457	stop scanner file
145800	new scanner file
1521	S6
1548	on ground JUV (sun +5)
1624	take off
1627	new scanner file
1649	S6 pass twice
	speed over ground 65 knots !
172500	new scanner file
	Sorte Nunatak 71 20N; 50 24W
1822	new scanner file
191800	swiss camp
191900	new scanner file
192400	new scanner file
1944	Trimble mem full
201700	new scanner file

203945	road to VW-track
204330	S1 pass (twice?)
205950	Blue building (SFJ)
2102	on ground SFJ

JD 125 4/5-04 Test + SFJ -> Thule

Test

0950	start Ok
0955	javad start
10.00	All OK
100500	new scanner file
1009	takeoff, 4 passes over blue building:
1012	10.20 West bound
1016	10.27 North bound
1019	10.31 East bound
1024	10.40 South bound
1026	Lake Ferguson
1031	on ground, INS pos OK

SFJ -> Thule TAB

1145	start, INS pos way off
1152	take off
1156	INS pos OK
	IFR to JUV (Upernavik) clouds
1346	All ok
1611	S7, 800 ft alt.
161730	new scanner file, restart scanner PC!
1701	S11
180200	new scanner file 170200 ???
1730	stop
1753	on ground TAB

JD 126 5/5-04 TAB - A1 - A5 - ALT

INS PC too cold!, KKs PC used.

1240	Power on
1255	All OK - scanner
1302	scanner restarted, OK
1312	Take off
1358	INS pos OK
140100	A1, New scanner filef
150100	New scanner file
1520	A3 - tear drop
155400	New scanner file
1548	Webcam started
1614	Grounding line
1617	A5
1635	Fort Conger, inland
1701	On ground Alert

JD 131 10/5-04/4-03 YLT - ICECAMP - YLT

1835	Take off
1910	3xGPS, INS, scanner OK
1914	NAVINS
192800	New scanner file 1000 ft
1959	On ground icecamp
2003	Stop, power on
2003	New INS file, align
2225	NAVINS
2230	Start engine no. 2
223500	New scanner file
2238	Take off
231530	New scanner file
2346	Descending to YLT
2354	On ground YLT

JD 132 11/5-04 YLT - G3 - G2 - ICECAMP - YLT

1641	3xGPS and scanner OK.
	INS position unstable
	No data laser altimeter
1643	Take off YLT
164900	New scanner file
1729	Tear drop
1735	Wide open lead (83 40 N 68 18 W)
175100	New scanner file
185300	New scanner file
1942	New INS file, scanner log closed
1944	On ground ice camp
2023	Take off ice camp
202600	New scanner file
2136	scanner stopped
2137	On ground YLT

JD 133 12/05-04 - YLT - H1 - H2 - H3 - ICECAMP - H4 - YLT

1733	Power on INS not aligned
1742	Take off
1749	All OK
175100	New scanner file
1832	Fog
1834	Tear drop
1839	700 ft
1843	Testing laser altimeter - bad
185700	New scanner file
1922	Tear drop
1951	Approaching ice camp
	scanner stopped
	new INS file
1954	On ground ice camp
2030	Take off ice camp
203100	new scanner file
2103	tear drop
213200	new scanner file
2215	Approach to landing YLT
2217	new INS file
	scanner stopped
2221	On ground YLT
	Power off

YLT - ICECAMP - YLT

2254	Power on
	INS not aligned, 3xGPS OK
2304	Take off
2307	scanner started
230900	New scanner file
0012	Approaching ice camp

0021	scanner stopped new INS file
0025	On ground ice camp
0056	INS, 3xGPS OK
0105	Take off ice camp
010900	new scanner file
0232	scanner stopped
0233	On ground YLT

JD 135 14/5-04 YLT - P1 - P13 - Hans Thausen iskappe - YLT

1300	Power on INS not aligned, 3xGPS OK
1324	Take off scanner started
132800	New scanner file
1331	tear drop P1
1331	webcam started (app. 10 sec offset)
1345	datalogger started
1348	800 ft
1403	tear drop P2
142800	new scanner file
1458	tear drop P3
152800	new scanner file
1552	tear drop
1603	tear drop
1619	tear drop
162800	new scanner file
1659	tear drop
1727	tear drop
172800	new scanner file
1810	overflight runway 80 kn 500 ft
1816	On ground YLT

JD 136 15/05-04 YLT-TAB, TAB-NAQ - NS1 - NS4 - Hans Ø - NS5 - YLT

YLT-TAB-NAQ (Medivac flt – Chr. Haas AWI)

NAQ-YLT via ULS and Hans Oe

2040	start taxi, Qaanaaq
2042	take off
2102	start logging, ice cap
2121	Inglefield outer coast
2140	new log file
2213	overhead Canadian ULS
2235	Hans Oe crossings
2311	end of line, close file
2335	landing Alert

JD 144 23/5-04 YLT - F1 - F4 - YLT

1420	Start engine x 2
1423	start scanner (-logging)
1424	Take off
142900	New scanner filef
1529	Tear drop F1 800 ft
154000	New scanner file
164100	New scanner file
1702	F2
1738	WP F3
174200	New scanner filef
1757	Low clouds 500 ft
1805	climb 800 ft
184700	New scanner file
195200	New scanner file
2003	runway overflight
2007	On ground Alert

JD 145 24/5-04 Local survey of Spinaker building (north of Hilton) in Alert.

Four corners: 1 NW, 2 SW, 3 SE, 4 NE
GPS antenna held at corner of roof

GPS runway survey by car.
GPS antenna height: 2,36 m (measured to antenna plane)

JD 146 25/5-04YLT – YLT (ICESAT underflight)

1628	Power on
164430	1st scanner file
1646	Take off
1658	(RF camera time 1858)
175800	New scanner file
190000	New scanner file
1952	Tear drop
200500	New scanner file
211100	New scanner file
221330	New scanner file
2246	Landing

JD 147 26/5-04 YLT – NAQ – JAV + JAV – Lyngmark Ice Cap - SFJ

1113	power on
1130	take off
130930	first scan file
1411	new scan file
1428	fog
1451	scanner stopped
1453	landing Qaanaaq (NAQ)
1526	take off
160600	new scanner file
1658	data logger run time error - file system full
1711	new scan file
1816	do
1920	close systems, clouds
2114	landing JAV

JAV – Lyngmark Ice Cap - SFJ

2128	INS realigned
2131	take off JAV
2149	new scanner file
2218	do
2357	landing SFJ

Appendix 2. Waypoints GreenICE/SITHOS 2004

Point ID	Lat (degrees)	Lon (degrees)	Lat (ddmmss)			Lon(ddmmss)			Notes
S1	67.010	-49.440	67	00	36.0 N	49	26	24.0 W	N/S profile of ice margin West Greenland
S2	68.340	-49.570	68	20	24.0 N	49	34	12.0 W	
S3	68.800	-49.340	68	48	00.0 N	49	20	24.0 W	
S4	70.000	-49.340	70	00	00.0 N	49	20	24.0 W	
S5	72.000	-51.000	72	00	00.0 N	51	00	00.0 W	
S6	73.000	-53.700	73	00	00.0 N	53	42	00.0 W	
S9	75.200	-58.250	73	12	00.0 N	53	15	00.0 W	Steenstrup Glacier
S10	75.500	-56.670	75	30	00.0 N	56	40	12.0 W	
S11	76.750	-62.000	76	45	00.0 N	62	00	00.0 W	
N0	67.225	-50.400	67	13	30.0 N	50	24	00.0 W	N/S profile of ice margin West Greenland
N1	67.230	-48.955	67	13	48.0 N	48	57	18.0 W	
N2	67.985	-48.965	67	59	06.0 N	48	57	54.0 W	
N3	68.740	-48.975	68	44	24.0 N	48	58	30.0 W	
N4	69.200	-48.710	69	12	00.0 N	48	42	36.0 W	
N5	70.000	-48.960	70	00	00.0 N	48	57	36.0 W	
N6	72.000	-50.500	72	00	00.0 N	50	30	00.0 W	
N7	73.000	-53.200	73	00	00.0 N	53	12	00.0 W	
N8	75.600	-56.000	75	36	00.0 N	56	00	00.0 W	
J1	69.200	-48.710	69	12	00.0 N	48	42	36.0 W	Jakobshavn Glacier
J2	69.200	-50.000	69	12	00.0 N	50	00	00.0 W	
J3	69.150	-51.250	69	09	00.0 N	51	15	00.0 W	
T1	69.73130556	-48.132777	69	43	52.7 N	48	07	58.0 W	EGIG (NASA)
T3	69.77441667	-47.731166	69	46	27.9 N	47	43	52.2 W	
T5	69.85127778	-47.253111	69	51	04.6 N	47	15	11.2 W	
T12	70.17580	-45.34555	70	10	32.9 N	45	20	40.4 W	
T21	70.54386111	-43.024861	70	32	37.9 N	43	01	29.5 W	
T41	71.07869444	-37.919972	71	04	43.3 N	37	55	11.9 W	

A1	78.0000	-66.0000	78	00	00.0 N	66	00	00.0 W	
A2	79.2833	-58.3333	79	17	00.0 N	58	20	00.0 W	
A3	79.6833	-55.3333	79	41	00.0 N	55	20	00.0 W	
A4	80.7500	-60.7333	80	45	00.0 N	60	44	00.0 W	Peterman Glacier
A5	81.2500	-62.4166	81	15	00.0 N	62	25	00.0 W	
NS3	80.2658	-68.3666	80	15	57.0 N	68	22	00.0 W	
NS4	80.4403	-67.8516	80	26	25.1 N	67	51	06.0 W	
HansØ	80.8260	-66.4560	80	49	33.6 N	66	27	21.6 W	
NS5	81.8378	-62.3666	81	50	16.1 N	62	22	00.0 W	
M1	72.4000	-52.3000	72	24	00.0 N	52	18	00.0 W	
M2	75.5000	-55.1250	75	30	00.0 N	55	07	30.0 W	
M3	77.7200	-63.3800	77	43	12.0 N	63	22	48.0 W	
M4	79.0700	-63.7000	79	04	12.0 N	63	42	00.0 W	
M5	79.6079	-65.2873	79	36	28.4 N	65	17	14.3 W	
G2	83.6090	-68.2350	83	36	32.4 N	68	14	06.0 W	North of Ellesmere Island
G3	86.1260	-72.8570	86	07	33.6 N	72	51	25.2 W	
H1	83.0910	-67.5313	83	05	27.6 N	67	31	52.7 W	North of Ellesmere Island
H2	83.6030	-73.5132	83	36	10.8 N	73	30	47.5 W	
H3	85.0000	-77.2363	85	00	00.0 N	77	14	10.7 W	
H4	85.0000	-63.0693	85	00	00.0 N	63	04	09.5 W	
p1	82.6139	-61.1485	82	36	50.0 N	61	08	54.6 W	Hans Tausen icecap
p2	82.5525	-54.0406	82	33	09.0 N	54	02	26.2 W	
p3	83.3985	-42.6432	83	23	54.6 N	42	38	35.5 W	
p4	83.0500	-41.2663	83	03	00.0 N	41	15	58.7 W	
p5	82.8000	-37.4700	82	48	00.0 N	37	28	12.0 W	
p6	82.4920	-37.4700	82	29	31.2 N	37	28	12.0 W	
p7	82.4186	-37.4830	82	25	07.0 N	37	28	58.8 W	
p8	82.4920	-36.9000	82	29	31.2 N	36	54	00.0 W	
p9	82.4920	-37.4700	82	29	31.2 N	37	28	12.0 W	

p10	82.5469	-39.4104	82	32	48.8 N	39	24	37.4 W	
p11	82.7695	-42.5880	82	46	10.2 N	42	35	16.8 W	
p12	82.6616	-49.8110	82	39	41.8 N	49	48	39.6 W	
p13	83.3977	-53.2549	83	23	51.7 N	53	15	17.6 W	
F1	84.4433	-57.2183	84	26	36.0 N	57	13	06.0 W	
F2	85.6466	-28.8733	85	38	48.0 N	28	52	24.0 W	
F3	84.8416	-18.4416	84	50	30.0 N	18	26	30.0 W	
F4	82.5100	-62.3266	82	30	36.0 N	62	19	36.0 W	
E1	82.7500	-62.5000	82	45	00.0 N	62	30	00.0 W	E1-E2 ICESat track
E2	84.9100	-43.9000	84	54	36.0 N	43	54	00.0 W	
E3	84.9100	-39.1500	84	54	36.0 N	39	09	00.0 W	E3-E4 ICESat track
E4	83.5000	-25.0500	83	30	00.0 N	25	03	00.0 W	
E5	83.6900	-29.4000	83	41	24.0 N	29	24	00.0 W	
E6	83.7200	-31.6000	83	43	12.0 N	31	36	00.0 W	
E7	83.6465	-37.3000	83	38	47.4 N	37	18	00.0 W	
E8	83.1500	-46.9800	83	09	00.0 N	46	58	48.0 W	E8-E9 ICESat track
E9	83.8334	-51.7430	83	50	00.2 N	51	44	34.8 W	E9-E10 ICESat track
E10	82.6400	-61.5000	82	38	24.0 N	61	30	00.0 W	
G1	69.6878	-53.2832	69	41	16.0 N	53	16	59.4 W	Lyngmark icecap – Disko Island
G2	69.7415	-53.3388	69	44	29.4 N	53	20	19.6 W	
G3	69.8838	-53.1831	69	53	01.7 N	53	10	59.1 W	
G4	69.8756	-53.4176	69	52	29.3 N	53	25	03.2 W	
G5	69.7841	-52.7115	69	50	34.8 N	53	10	30.0 W	
G6	69.8624	-53.0000	69	51	44.6 N	53	00	00.0 W	
G7	69.6743	-52.8128	69	40	27.5 N	52	48	46.1 W	
G8	69.4341	-52.8833	69	26	02.8 N	52	53	00.0 W	

Appendix 3. GreenICE 2004 laser scanner files

JD	File name	2dd format	Start (dechr)	Stop (dechr)	Comments
111 – April 20	195500.2dd	T	19.916	20.417	Test flight SFJ
	202800.2dd	T	20.468	20.784	5 sec. reset
112a – April 21	110030.2dd	T	11.000	11.819	SFJ-T12-JAV
	115030.2dd	T	11.833	12.815	
	125130.2dd	T	12.883	12.949	5 sec. reset
112b – April 21	143300.2dd	T	14.550	15.438	JAV-T5-JAV
	154300.2dd	T	15.716	16.622	
113 – April 22	103130.2dd	T	10.516	11.442	JAV-T41-T21-JAV
	112800.2dd	T	11.466	12.416	
	122600.2dd	T	12.433	13.087	
	134500.2dd	T	13.750	14.630	
	150800.2dd	T	15.133	16.078	
	160600.2dd	T	16.100	16.464	
	162900.2dd	T	16.483	16.817	
114 – April 23	101300.2dd	T	10.216	11.207	JAV-N4-N_line-JUV-S_line-SFJ
	111300.2dd	T	11.216	12.071	
	120500.2dd	T	12.083	13.016	
	130300.2dd	T	13.050	14.016	
	145800.2dd	T	14.966	15.817	
	162700.2dd	T	16.450	17.400	
	172500.2dd	T	17.416	18.352	
	182200.2dd	T	18.366	19.306	
	191900.2dd	T	19.316	19.388	
	192400.2dd	T	19.400	20.252	
	201700.2dd	T	20.283	21.083	
125 – May 4	100500.2dd	T	10.083	10.517	SFJ test flight SFJ-TAB
	161730.2dd	T	16.283	17.011	
	170200.2dd	T	17.033	17.500	
126 – May 5	140100.2dd	T	14.017	14.973	TAB- Peterman Glacier - YLT
	150100.2dd	T	15.017	15.874	
	155400.2dd	T	15.900	16.675	
131 – May 10	192800.2dd	T	19.467	19.976	YLT-ICECAMP-YLT
	223500.2dd	T	22.583	23.243	
	231530.2dd	T	23.255	23.898	
132 – May 11	164900	Txt	16.817	17.798	YLT-ICECAMP-YLT
	175100	Txt	17.850	18.825	
	185300.2dd	T	18.883	19.707	
	202600.2dd	T	20.433	21.570	
133a – May 12	175100.2dd	T	17.850	18.918	YLT-ICECAMP-YLT
	185700.2dd	T	18.950	19.853	
	203100.2dd	T	20.517	21.492	
	213200.2dd	T	21.533	22.271	
133b – May 12	230900.2dd	T	23.150	24.349	YLT-ICECAMP-YLT
	010900.2dd	T	01.150	02.533	
135 – May 14	132800.2dd	T	13.467	14.426	YLT- Hans Tausen Ice Cap - YLT
	142800.2dd	T	14.467	15.417	
	152800.2dd	T	15.467	16.452	
	162800.2dd	T	16.467	17.436	
	172800.2dd	T	17.467	18.269	
136 – May 15	210200.2dd	T	21.033	21.647	NAQ- Hans Ø-YLT
	214000.2dd	T	21.667	23.211	
144 – May 23	142900.2dd	T	14.483	15.623	YLT-YLT
	154000.2dd	T	15.667	16.649	
	164100.2dd	T	16.683	17.675	
	174200.2dd	T	17.700	18.771	
	184730.2dd	T	18.788	19.852	
	195200.2dd	T	19.867	20.181	

146 – May 25	164430.2dd	T	16.738	17.956	YLT-YLT ICESat track
	175800.2dd	T	17.966	18.983	
	190000.2dd	T	19.000	20.062	
	200500.2dd	T	20.083	21.172	
	211100.2dd	T	21.183	22.207	
	221330.2dd	T	22.221	22.775	
147a – May 26	130930.2dd	T	13.155	14.163	YLT-NAQ NAQ-JAV
	141100.2dd	T	14.183	14.850	
	160600.2dd	T	16.100	17.168	
	171100.2dd	T	17.183	18.248	
	181600.2dd	T	18.266	19.362	
147b – May 26	214900.2dd	T	21.816	22.275	JAV- Lyngmark Ice Cap - SFJ
	221630.2dd	T	22.275	22.276	
	221800.2dd	T	22.300	22.983	

Appendix 4. Overview of GPS data processing

Date	JD	Flight	Reference	Mobile	file name	start (GPSs)	end (GPSs)	start (dech)	end (dech)	var. ratio	ref. var.	Comments
20-04-2004	**111**		**SFJ1**	**1**	**111a1s1.p**	**244203**	**247991**	**19,831**	**20,883**	**4,9**	**1,179**	**No gaps**
				2	111a2s1.p	244261	247950	19,847	20,871	6,3	1,325	No gaps
				3a	111a3as1.p	244298	245139	19,857	20,091	32,5	0,913	No gaps
					111a3bs1.p	245607	247878	20,221	20,851	3,5	1,683	3 gaps of in total 60 sec's
21-04-2004	**112**	**a**	**SFJ1**	**1**	**112a1s1.pa**	**297335**	**305964**	**10,589**	**12,986**	**3.2**	**8.461**	**No gaps !**
				2a	112a2as1.pa	297451	301685	10,622	11,798	7.8	2.100	No gaps !
				2b	112a2bs1.pa	301741	305980	11,813	12,991	1.5	4.216	No gaps !
				3	112a3s1.pa	297389	305978	10,604	12,990	2.4	12.443	No gaps !
		b	SFJ1	1	112a1s1.pb	309557	319352	13,984	16,705	1.3	14.272	1 gap of in total 111 sec's
				2a	112a2s1.pb1	309601	312075	13,997	14,684	2.7	40.644	1 gap of in total 112 sec's
				2b	112a2s1.pb2	312331	315585	14,755	15,659	2.6	4.248	No gaps !
				2c	112a2s1.pb3	315691	319375	15,688	16,712	1.4	3.519	No gaps !
				3	112a3s1.pb	309557	319365	13,984	16,709	1.2	13.984	1 gap of in total 111 sec's
			JAV1	1	112a1j1.pb	309557	319352	13,984	16,705	1.6	3.704	1 gap of in total 111 sec's
				2a	112a2j1.pb1	309601	312075	13,997	14,684	1.4	3.197	1 gap of in total 112 sec's
				2b	112a2j1.pb2	312331	315585	14,755	15,659	1.7	8.412	No gaps !
				2c	112a2j1.pb3	315691	319375	15,688	16,712	1.6	2.268	No gaps !
				3	**112a3j1.pb**	**309557**	**319365**	**13,984**	**16,709**	**6.1**	**1.873**	**1 gap of in total 111 sec's**
22-04-2004	**113**		**SFJ1**	**1**	**113a1s1.p**	**381556**	**406495**	**9,984**	**16,912**	**1,1**	**9,398**	
				2a	113a2s1.p1	381601	388730	9,997	11,976	1,1	7,879	
				2b	113a2s1.p2	388801	395765	11,997	13,931	1,6	5,492	
				2c	113a2s1.p3	395881	406485	13,964	16,908	2,5	6,604	
				3	113a3s1.p	381566	406487	9,987	16,909	1,9	6,032	2 gaps of in total 306 sec's
			JAV1	1	113a1j1.p	381556	406495	9,984	16,911	1,2	5,547	1 gap of in total 108 sec's
				2a	113a2j1.p1	381601	388730	9,997	11,976	1,7	2,018	
				2b	113a2j1.p2	388801	395765	11,997	13,931	1,9	15,066	
				2c	113a2j1.p3	395881	406485	13,964	16,908	1,2	4,643	1 gap of in total 109 sec's
				3	113a3j1.p	381566	406487	9,987	16,909	1,1	5,430	4 gaps of in total 415 sec's

23-04-2004	114		SFJ1	1	114a1s1.p	467213	503051	9,781	19,736		277534,188	7 gaps of in total 379 sec's
				2	**114a2s1.p1**	**466741**	**505647**	**9,650**	**20,458**	**1,1**	**31,303**	**4 gaps of in total 213 sec's**
				2	**114a2s1.p2**	**505663**	**508085**	**20,462**	**21,135**	**1,1**	**1,785**	**No gaps**
				3	114a3s1.p1	467200	505647	9,778	20,458	1,1	31,430	5 gaps of in total 459 sec's
				3	114a3s1.p2	506066	508081	20,574	21,134	1,3	1,120	6 gaps of in total 1108 sec's
Test flyvning SFJ				3	125a3s1.pt	208719	210876	9,974	10,573		0.840	No gaps !
04-05-2004	125		SFJ1	1	125a1s1.p	214884	238081	11,686	18,130	1.1	29.616	2 gap's of in total 468 sec's
				2a	125a2as1.p	215011	221165	11,722	13,431	1.1	12.213	1 gap of in total 112 sec's
				2b	125a2bs1.p	221221	238070	13,447	18,127	1.2	60.028	No gaps !
				3	125a3s1.p	214912	238069	11,694	18,127	1.1	29.537	1 gap of in total 113 sec's
			THU2	1	125a1t2.p							Floating
				2	125a2t2.p							Floating
				3	125a3t2.p							Floating
			THU3	1	125a1t3.p	214884	238081	11,686	18,130	1.1	18.917	3 gap's of in total 530 sec's
				2a	125a2at3.p	215011	221165	11,722	13,431	1.1	19.100	1 gap of in total 114 sec's
				2b	125a2bt3.p	221221	238070	13,447	18,127	1.1	8.310	No gaps !
				3	**125a3t3.p**	**214912**	**238069**	**11,694**	**18,127**	**2.3**	**7.929**	**1 gap of in total 112 sec's**
05-05-2004	126		THU3	1	126a1t3.p	305470	321279	12,849	17,241	1,2	1,484	One gap of 43 sec's at 17,14
				2a	126a2at3.p	305221	312480	12,780	14,796	1,3	1,983	No gaps
				2b	126a2bt3.p	312541	320909	14,813	17,138	1,3	4,516	No gaps
				3	**126a3t3.p**	**305147**	**320965**	**12,759**	**17,153**	**6,2**	**1,493**	**No gaps**
10-05-2004	131		YLT	1								Bad data
				2								Bad data
				3	**131a3y1.p**	**154616**	**172777**	**18,945**	**23,990**	**1,8**	**4,935**	**One gap of 229 sec's**
				3	131a3y1.p2	154616	172777	18,945	23,990	1,8	5,132	One gap of 229 sec's

11-05-2004	132		YLT1a	1	132a1y1a.p1	232116	244343	16,473	19,869	1.2	4.606	No gaps !
					132a1y1a.p2	244657	250982	19,957	21,714	1.3	20.998	No gaps !
				2	**132a2y1a.p1**	**232261**	**244251**	**16,513**	**19,844**	**1.2**	**4.474**	**No gaps !**
					132a2y1a.p2	244637	250950	19,951	21,705	3.6	5.678	No gaps !
				3a	132a3ay1a.p	231761	242772	16,374	19,433	1.2	2.911	No gaps !
				3b	**132a3by1a.p**	**242944**	**250940**	**19,481**	**21,702**	**9.7**	**1.274**	**No gaps !**
12-05-2004	133	a	YLT1a	1	133a1y1a.pa1	322260	332669	17,513	20,404	4.1	0.964	No gaps !
					133a1y1a.pa2	332769	340160	20,432	22,485	1.5	14.525	No gaps !
				2	133a2y1a.pa1	322321	332669	17,530	20,404	10.8	0.854	No gaps !
					133a2y1a.pa2	332733	340070	20,422	22,460	1.6	9.399	No gaps !
				3	**133a3y1a.pa**	**322370**	**340298**	**17,544**	**22,524**	**1.6**	**6.612**	**No gaps !**
		b	YLT1a	1	133a1y1a.pb	341807	350130	22,943	1,255	2.1	13.106	No gaps ! Short ref. File
				2	133a2y1a.pb	342151	350130	23,038	1,255	1.9	12.202	No gaps ! Short ref. File
				3	**133a3y1a.pb**	**341587**	**350130**	**22,882**	**1,255**	**1.1**	**7.137**	**No gaps ! Short ref. File**
14-05-2004	**135**		**YLT1a**	**1**	**135a1y1a.p**	**478865**	**498032**	**13,014**	**18,339**	**1.8**	**5.338**	**No gaps !**
				2	135a2y1a.p	479881	498062	13,297	18,347	1.2	5.444	No gaps !
				3	135a3y1a.p	478807	498080	12,998	18,352	1.5	4.566	No gaps !
15-05-2004	136		YLT1b	1	136a1y1b.p	589024	604787	19,614	23,993	1.2	5.722	No gaps !
				2	**136a2y1b.p**	**589051**	**604365**	**19,622**	**23,876**	**2.6**	**3.136**	**No gaps !**
				3	136a3y1b.p	589010	604689	19,610	23,966	1.1	3.031	No gaps !
			THU3	1	136a1t3.p	589024	604787	19,614	23,993	2.2	4.169	No gaps !
				2	136a2t3.p	589051	604365	19,622	23,876	2.8	4.184	No gaps !
				3	136a3t3.p	589010	604689	19,610	23,966	1.8	7.066	No gaps !
23-05-2004	144		YLT1b	1	144a1y1b.p	51155	72129	14,206	20,032	1.7	2.367	No gaps !
				2a	144a2ay1b.p	51061	66040	14,180	18,341	2.4	2.735	No gaps !
				2b	144a2by1b.p	66151	72120	18,372	20,030	3.5	1.404	No gaps !
				3	144a3y1b.p	51018	72120	14,168	20,030	2.0	2.244	1 gap of in total 330 sec's
			YLT2 144	**1**	**144a1y2.p**	**51155**	**72934**	**14,206**	**20,256**	**1.7**	**2.620**	**No gaps !**
				2a	144a2ay2.p	51061	66040	14,180	18,341	1.1	3.555	No gaps !
				2b	144a2by2.p	66151	72910	18,372	20,249	5.1	0.961	No gaps !
				3	144a3y2.p	51018	72895	14,168	20,245	2.0	5.532	1 gap of in total 330 sec's

24-05-2004	145		YLT1b	c1	145c1y1b.p	143581	144360	15,880	16,096	11.7	0.394	No gaps ! RUNWAY ALERT !
25-05-2004	**146**		**YLT1b**	**1**	**146a1y1b.p**	**232108**	**255323**	**16,471**	**22,919**	**11.3**	**1.316**	**No gaps !**
				3	146a3y1b.p	232012	255228	16,444	22,893	6.5	1.298	1 gap of in total 317 sec's
			YLT2	1	146a1y2.p1	232108	238458	16,471	18,235	1.2	17.214	No gaps !
					146a1y2.p2	238477	255323	18,240	22,919	1.2	15249.125	1 gap of in total 9 sec's
				3	146a3y2.p1	232012	238458	16,444	18,235	1.3	15.726	No gaps !
					146a3y2.p2	238477	255228	18,240	22,893	1.3	361404.438	2 gap's of in total 327 sec's
26-05-2004	147	a	THU3	**1**	**147a1t3.pa**	**299653**	**330659**	**11,233**	**19,846**	**1.3**	**2.553**	**No gaps !**
				2a	147a2at3.pa	300001	307875	11,330	13,517	1.8	5.227	No gaps !
				2b	147a2bt3.pa	307951	332505	13,538	20,359	1.5	5.223	No gaps !
				3	147a3t3.pa	299653	331962	11,233	20,208	1.4	4.091	1 gap of in total 39 sec's
		b	SFJ1	1	147a1s1.pb	336623	345660	21,503	0,013	1.3	42.759	No gaps !
				2	**147a2s1.pb**	**335971**	**345660**	**21,322**	**0,013**	**1.2**	**14.691**	**No gaps !**
				3a	147a3as1.pb	335889	341373	21,299	22,822	1.4	34.257	No gaps !
				3b	147a3bs1.pb	343467	345660	23,404	0,013	1.2	35.650	No gaps !

Appendix 5. Overview of INS data processing

Date	JD	Flight	file name	GPS file	start	end	GPS antenna	Comments
20-04-2004	111		04201956.pos	111a1s1.p	19.950	20.800	1	
21-04-2004	112	a	04211041.pos	112a1s1.pa	10.700	12.960	1	
		b	04211431.pos	112a3j1.pb	14.530	16.650	3	Merge of 4 EGI-files GAPS:
								14.6023-14.6072
								15.4258-15.4288
								15.7351-15.7382
22-04-2004	113		04221005.pos	113a1s1.p	10.089	13.096	1	
			04221337.pos	113a1s1.p	13.625	14.637	1	No EGI-files after 14.637 :-(
23-04-2004	114		04230936.pos	114a2s1.p	9.669	15.836	2	GPS file merged of 114a2s1.p1+114a2s1p2
			04231617.pos	114a2s1.p	16.343	21.120	2	gap between GPS-files: 20.458-20.462
04-05-2004	125	test	040504a.pos	125a1s1.pt	9.897	10.546	1	
			05041346.pos	125a3t3.p	13.775	17.961	3	
05-05-2004	126		05051246.pos	126a3t3.p	12.830	17.119	3	
11-05-2004	131		05101905.pos	131a3y1.p	19.174	19.986	3	
			05101956.pos	131a3y1.p	22.000	23.951	3	Gap 22.626-22.633
12-05-2004	132		05111629.pos	132a2y1a.p1	16.560	19.710	2	
			05111939.pos	132a3by1a.p	19.760	21.670	3	
12-05-2004	133	a	05121724.pos	133a3y1a.pa	17.464	19.866	3	Gaps in EGI-file between 19.83-19.84???
			05121948.pos	133a3y1a.pa	19.869	22.280	3	
		b	05122250.pos	133a3y1a.pb	22.897	24.359	3	
			05130018.pos	133a3y1a.pb	00.362	01.255	3	No GPS data after 01.255 - short reference file

Appendix 6. Overview of lidar data processing

JD	File name	2dd format	Start (dechr)	Stop	Route	Processing comments	Test (cross-test, building or runway)
111 – April 20	195500.2dd	T	19.916	20.417	Test flight SFJ 5 sec. reset	Offset angles: A	Building: OK!
	202800.2dd	T	20.468	20.784			
112a – April 21	110030.2dd	T	11.000	11.819	SFJ-T12-JAV	Offset angles: A	Cross over land ice: OK
	115030.2dd	T	11.833	12.815			
	125130.2dd	T	12.883	12.949	5 sec. reset		
112b – April 21	143300.2dd	T	14.550	15.438	JAV-T5-JAV	Offset angles: A	Cross over land ice: OK
	154300.2dd	T	15.716	16.622			
113 – April 22	103130.2dd	T	10.516	11.442	JAV-T41-T21-JAV	Offset angles: A	Cross over land ice:
	112800.2dd	T	11.466	12.416			
	122600.2dd	T	12.433	13.087			
	134500.2dd	T	13.750	14.630			
	150800.2dd	T	15.133	16.078			
	160600.2dd	T	16.100	16.464			
	162900.2dd	T	16.483	16.817			
114 – April 23	101300.2dd	T	10.216	11.207	JAV-N4-N_line-JUV-S_line-SFJ	Offset angles: A	Cross over land ice: OK
	111300.2dd	T	11.216	12.071			
	120500.2dd	T	12.083	13.016			
	130300.2dd	T	13.050	14.016			
	145800.2dd	T	14.966	15.817			
	162700.2dd	T	16.450	17.400			
	172500.2dd	T	17.416	18.352			
	182200.2dd	T	18.366	19.306			
	191900.2dd	T	19.316	19.388			
	192400.2dd	T	19.400	20.252			
	201700.2dd	T	20.283	21.083			
125 – May 4	100500.2dd	T	10.083	10.517	SFJ test flight SFJ-TAB	Offset angles: B	Building: OK!
	161730.2dd	T	16.283	17.011			
	170200.2dd	T	17.033	17.500			
126 – May 5	140100.2dd	T	14.017	14.973	TAB- Petermann Glacier -YLT	Offset angles: B	No cross or building
	150100.2dd	T	15.017	15.874			
	155400.2dd	T	15.900	16.675			
131 – May 10	192800.2dd	T	19.467	19.976	YLT-ICECAMP-YLT	Offset angles: C	Crosstest with JD 146 ok near Alert
	223500.2dd	T	22.583	23.243			
	231530.2dd	T	23.255	23.898			

132 – May 11	164900 175100 185300.2dd 202600.2dd	Txt Txt T T	16.817 17.850 18.883 20.433	17.798 18.825 19.707 21.570	YLT-ICECAMP-YLT	Offset angles: D Offset angles: D Offset angles: D Offset angles: C	Crosstest ok
133a – May 12	175100.2dd 185700.2dd 203100.2dd 213200.2dd	T T T T	17.850 18.950 20.517 21.533	18.918 19.853 21.492 22.271	YLT-ICECAMP-YLT	Offset angles:C	Crosstest ok
133b – May 12	230900.2dd 010900.2dd	T T	23.150 01.150	24.349 02.533	YLT-ICECAMP-YLT	Offset angles: C	
135 – May 14	132800.2dd 142800.2dd 152800.2dd 162800.2dd 172800.2dd	T T T T T	13.467 14.467 15.467 16.467 17.467	14.426 15.417 16.452 17.436 18.269	YLT- Hans Tausen Ice Cap -YLT	Offset angles: C	5 cross: OK
136 – May 15	210200.2dd 214000.2dd	T T	21.033 21.667	21.647 23.211	NAQ- Hans Ø-YLT	Offset angles: C	
144 – May 23	142900.2dd 154000.2dd 164100.2dd 174200.2dd 184730.2dd 195200.2dd	T T T T T T	14.483 15.667 16.683 17.700 18.788 19.867	15.623 16.649 17.675 18.771 19.852 20.181	YLT-YLT	Offset angles: C	
146 – May 25	164430.2dd 175800.2dd 190000.2dd 200500.2dd 211100.2dd 221330.2dd	T T T T T T	16.738 17.966 19.000 20.083 21.183 22.221	17.956 18.983 20.062 21.172 22.207 22.775	YLT-YLT ICESat track	Offset angles: C	Cross-test with JD 131 ok near Alert
147a – May 26	130930.2dd 141100.2dd 160600.2dd 171100.2dd 181600.2dd	T T T T T	13.155 14.183 16.100 17.183 18.266	14.163 14.850 17.168 18.248 19.362	YLT-NAQ NAQ-JAV	Offset angles: E	Land ice
147b – May 26	214900.2dd 221630.2dd 221800.2dd	T T T	21.816 22.275 22.300	22.275 22.276 22.983	JAV- Lyngmark Ice Cap - SFJ	Offset angles: E	Land ice

Appendix 7. Structure of data directories

The raw and processed data of from the KMS2004 campaign is provided on DVD's as the raw data files, and a "level 2" (5 x 5 average) lidar data of laser scanner heights and freeboard heights, produced by the methods outlined in Sect. 4.3.

It should be pointed out that the final, detailed processed lidar data are way too voluminous (around 40 GB) to make much sense in providing as files. Instead jobs are provided which allows the direct production of detailed lidar files for any period of the acquired lidar data (cf. Appendix 3) by a Fortran executable ("*readsca9* < RS.INP"). Examples of data and plots are given in the files for a short (0.01 hour~36 sec) full-resolution section of the lidar data.

Description of delivered file types:

*.pos	Combination of GPS and INS data.
*.2dd	Raw scanner data in binary format.
*.scn	High-resolution (~0.01 hour interval) processed scanner data in ASCII format.
*.ver	High-resolution (~0.01 hour interval) processed vertical data in ASCII format.
*.ps	Postscript figure of high-resolution scanner data.
*_5x5.scn	Low-resolution processed scanner data in ASCII format.
*_5x5.ver	Low-resolution vertical data in ASCII format.
*_5x5.ps	Postscript figures of low-resolution scanner data.
*_5x5.frb	Low-resolution freeboard profile.
*_5x5.frs	Low-resolution freeboard scan.
*_frs.ps	Postscript figure of low-resolution freeboard scan data.
*.jpg	Pictures from the vertical mounted camera.
ver_photo.pos	Time and position for pictures taken with the vertical camera.
*.png	Plot of the flight.

Available files for each day

	*.pos	*.2dd	*.scn	*.ver	*.ps	*_5x5.scn	*_5x5.ver	*_5x5.ps	*_5x5all.ps	*_5x5.frb	*_5x5.frs	*_frs.ps	*.jpg	ver_photo.pos	*.png	Comment
111	X															
195500		X														Test flight.
200655		X	X	X	X	X	X	X								Split into 195500 and 200655
202800		X														5 sec. reset (for internal use only)
GPS															X	
112a	X															
110030		X	X	X	X	X	X	X								Start time 110029
115030		X	X	X	X	X	X	X								
125130		X														5 sec. reset (for internal use only)
GPS															X	
112b	X															
143300		X	X	X	X	X	X	X								
154300		X	X	X	X	X	X	X								
GPS															X	
113	X															
103130		X	X	X	X	X	X	X								
112800		X	X	X	X	X	X	X								
122600		X	X	X	X	X	X	X								
134500		X	X	X	X	X	X	X								
150800		X														
160600		X														
162900		X														
GPS															X	
114	X															
101300		X	X	X	X	X	X	X								
111300		X	X	X	X	X	X	X								
120500		X	X	X	X	X	X	X								
130300		X	X	X	X	X	X	X								
145800		X	X	X	X	X	X	X								
162700		X	X	X	X	X	X	X								
172500		X	X	X	X	X	X	X								
182200		X	X	X	X	X	X	X								
191900		X	X	X	X	X	X	X								
192400		X	X	X	X	X	X	X								
201700		X	X	X	X	X	X	X								
GPS															X	
125	X															
100500		X														Test flight
161730		X	X	X	X	X	X	X	X							
170200		X	X	X	X	X	X	X								Original scanner filename is 180200
GPS															X	

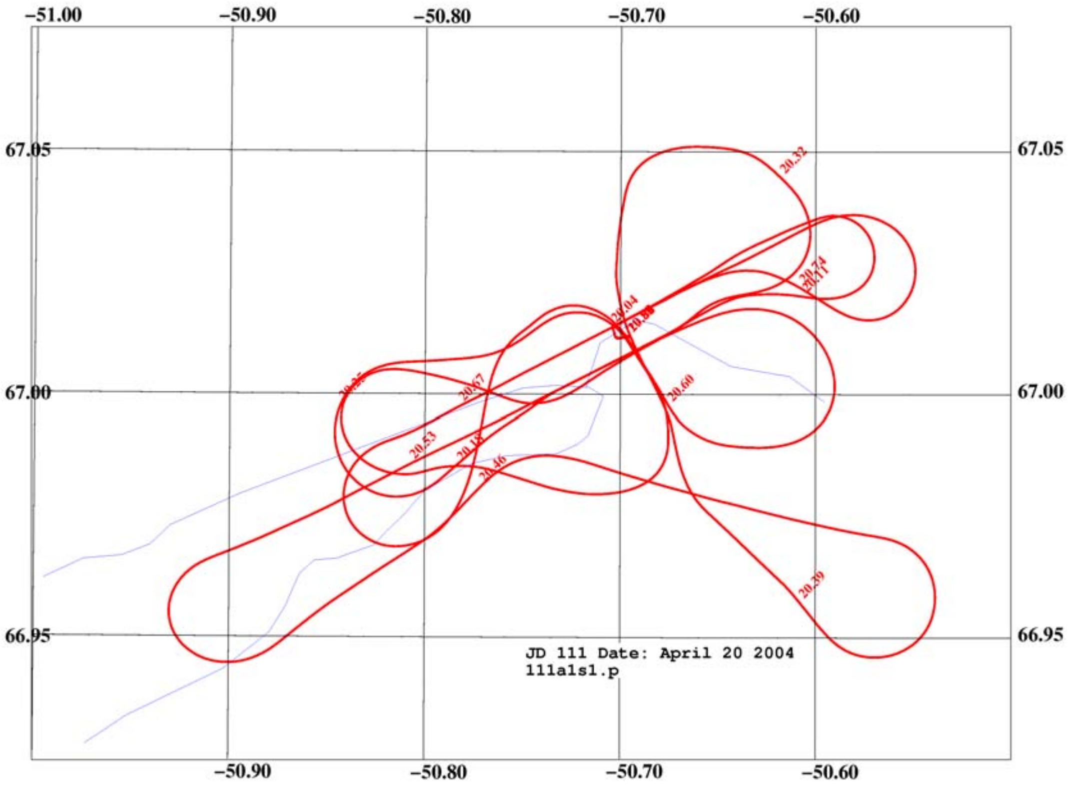
126	X															
140100		X	X	X	X	X	X	X	X							
150100		X	X	X	X	X	X	X	X							
155400		X	X	X	X	X	X	X	X							
GPS															X	
ver_photo													X	X		
131	X															
192800		X	X	X	X	X	X	X	X	X	X	X				
223500		X	X	X	X	X	X	X	X	X	X	X				
231530		X	X	X	X	X	X	X	X	X	X	X				
GPS															X	
132	X															
164900		X	X	X	X	X	X	X	X	X	X	X				
175100		X	X	X	X	X	X	X	X	X	X	X				
185300		X	X	X	X	X	X	X	X	X	X	X				
202600		X	X	X	X	X	X	X	X	X	X	X				
GPS															X	
133a	X															
175100		X	X	X	X	X	X	X	X	X	X	X				
185700		X	X	X	X	X	X	X	X	X	X	X				
203100		X	X	X	X	X	X	X	X	X	X	X				
213200		X	X	X	X	X	X	X	X	X	X	X				
GPS															X	
133b	X															
230900		X														
010900		X														
GPS															X	
135	X															
132800		X	X	X	X	X	X	X	X	X	X	X				
142800		X	X	X	X	X	X	X	X	X	X	X				
152800		X	X	X	X	X	X	X	X							
162800		X	X	X	X	X	X	X	X	X	X	X				
172800		X	X	X	X	X	X	X	X	X	X	X				
GPS															X	
ver_photo													X	X		
136	X															
210200		X	X	X	X	X	X	X	X	X	X					
214000		X	X	X	X	X	X	X	X	X	X					
GPS															X	
144	X															
142900		X	X	X	X	X	X	X	X	X	X	X				
154000		X	X	X	X	X	X	X	X	X	X	X				
164100		X	X	X	X	X	X	X	X	X	X	X				
174200		X	X	X	X	X	X	X	X	X	X	X				
184730		X	X	X	X	X	X	X	X	X	X	X				
195200		X	X	X	X	X	X	X	X	X	X	X				
GPS															X	

ver_photo													X	X		
146	X															
164430		X	X	X	X	X	X	X	X	X	X	X				
175800		X	X	X	X	X	X	X	X	X	X	X				
190000		X	X	X	X	X	X	X	X	X	X	X				
200500		X	X	X	X	X	X	X	X	X	X	X				
211100		X	X	X	X	X	X	X	X	X	X	X				
221330		X	X	X	X	X	X	X	X	X	X	X				
GPS															X	
ver_photo													X	X		
147a	X															
130930		X	X	X	X	X	X	X								
141100		X	X	X	X	X	X	X								
160600		X	X	X	X	X	X	X								
171100		X	X	X	X	X	X	X								
181600		X	X	X	X	X	X	X								
GPS															X	
147b	X															
214900		X	X	X	X	X	X	X								
221630		X														Short file, not processed.
221800		X	X	X	X	X	X	X								
GPS															X	

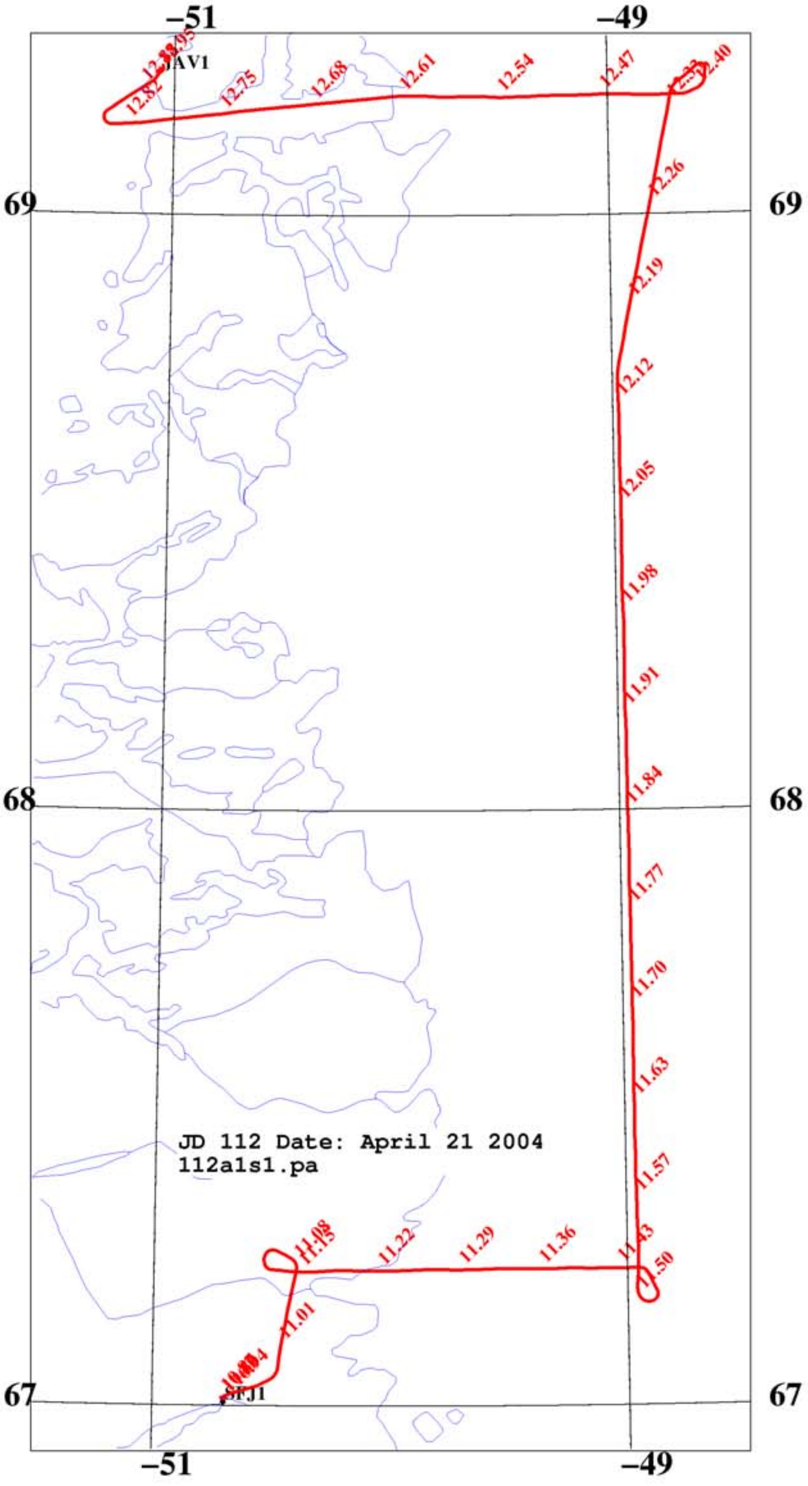
Appendix 8. Time tagging of digital vertical photos

JD	flight	GPS day of week	GPS-file	Picture interval	Offset (sec)	# photos	start (dech)	stop (dech)	Comment
126		3	126a3t3.p	1s	-7650	879	15.8000	16.0483	All sharp, though a little dark
		3	126a3t3.p	1s	-7648	150	16.1322	16.1753	All sharp, though a little dark
		3	126a3t3.p	2s	-7647	116	16.2988	16.3306	All sharp, though a little dark
		3	126a3t3.p	2s	0	843	16.3436	16.8108	All sharp, though a little dark
135	a	5	135a1y1a.p	2s	-18	8706	13.4325	18.3416	All sharp, though a little dark
144		0	144a1y2.p	2s	20	10558	14.3122	20.1822	Bad quality with poor contrast in e.g. clouds
146		2	146a1y1b.p	2s	28	10217	16.5625	22.8133	Bad quality with poor contrast in e.g. clouds

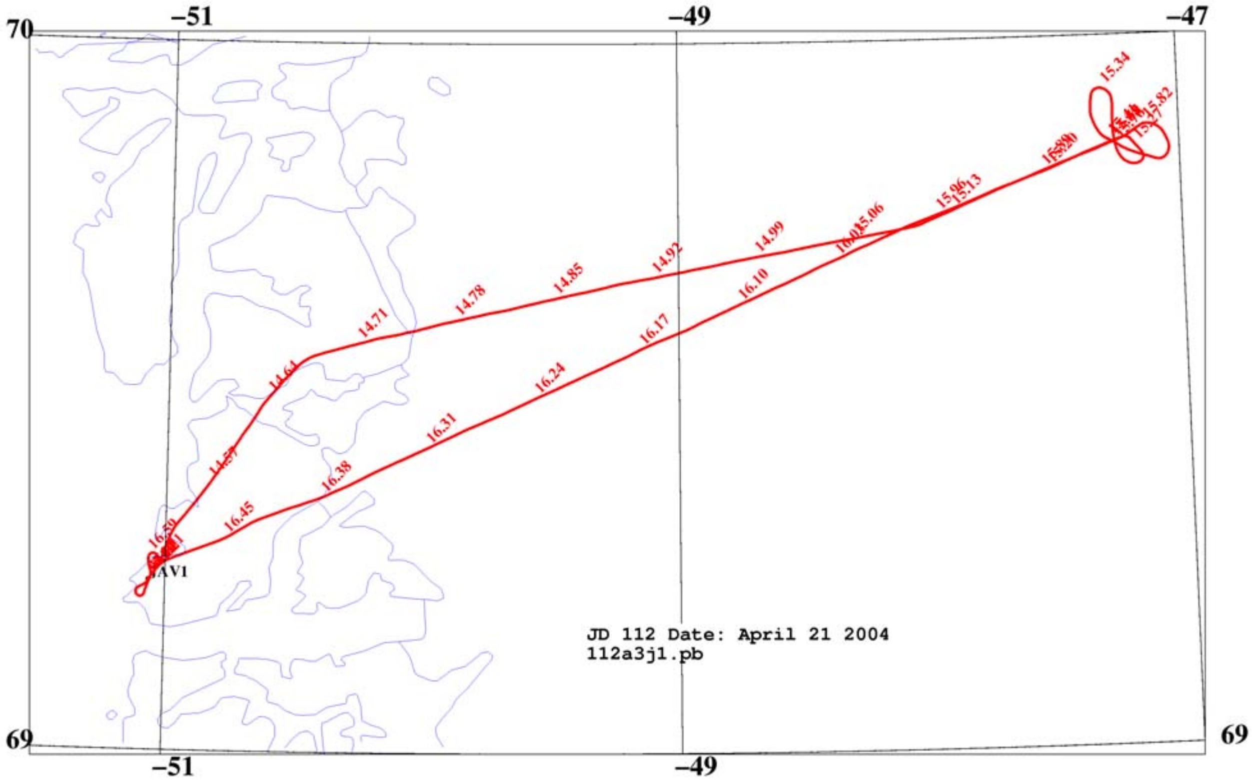
<u>Appendix 9.</u> GPS plots of daily flights
Time in UTC.



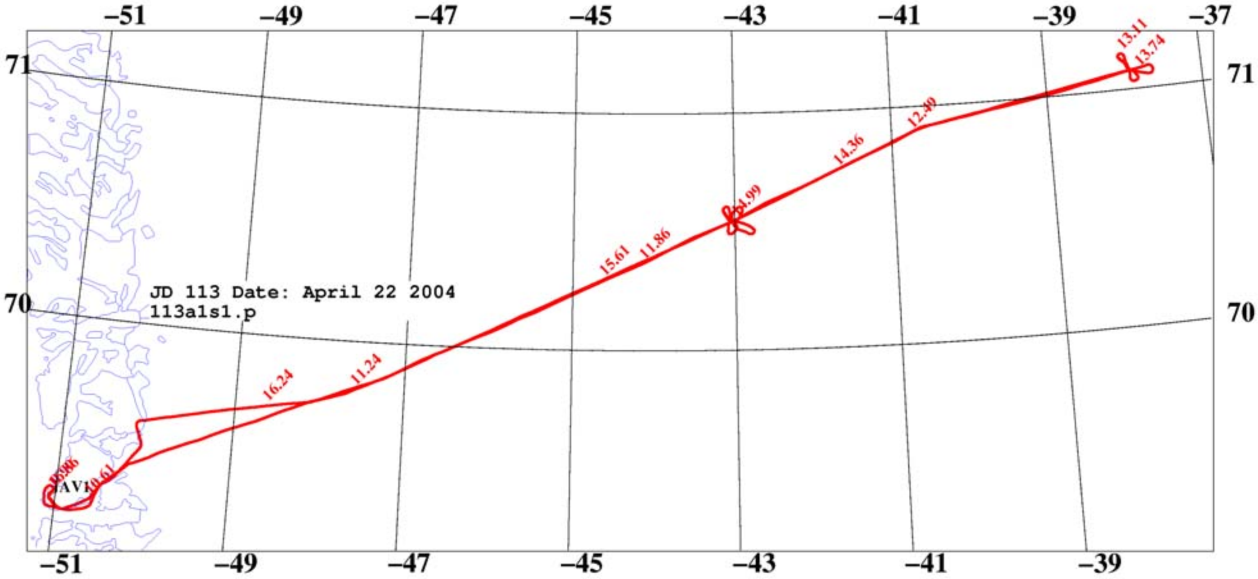
Flight track from April 20th, JD 111 Test flight around SFJ.



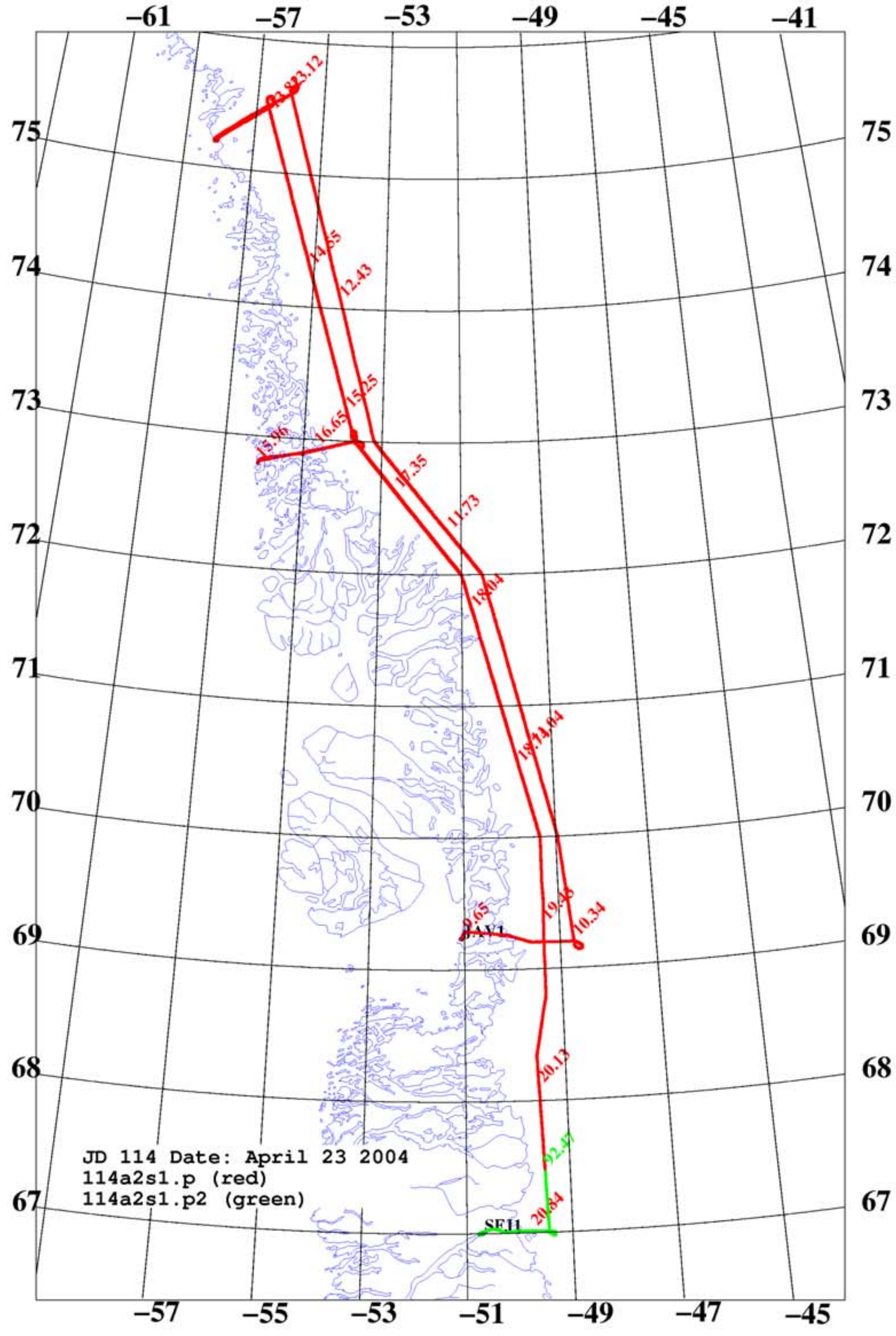
Flight tracks from April 21st, JD 112, first flight (112a), SFJ – T12 – JAV.



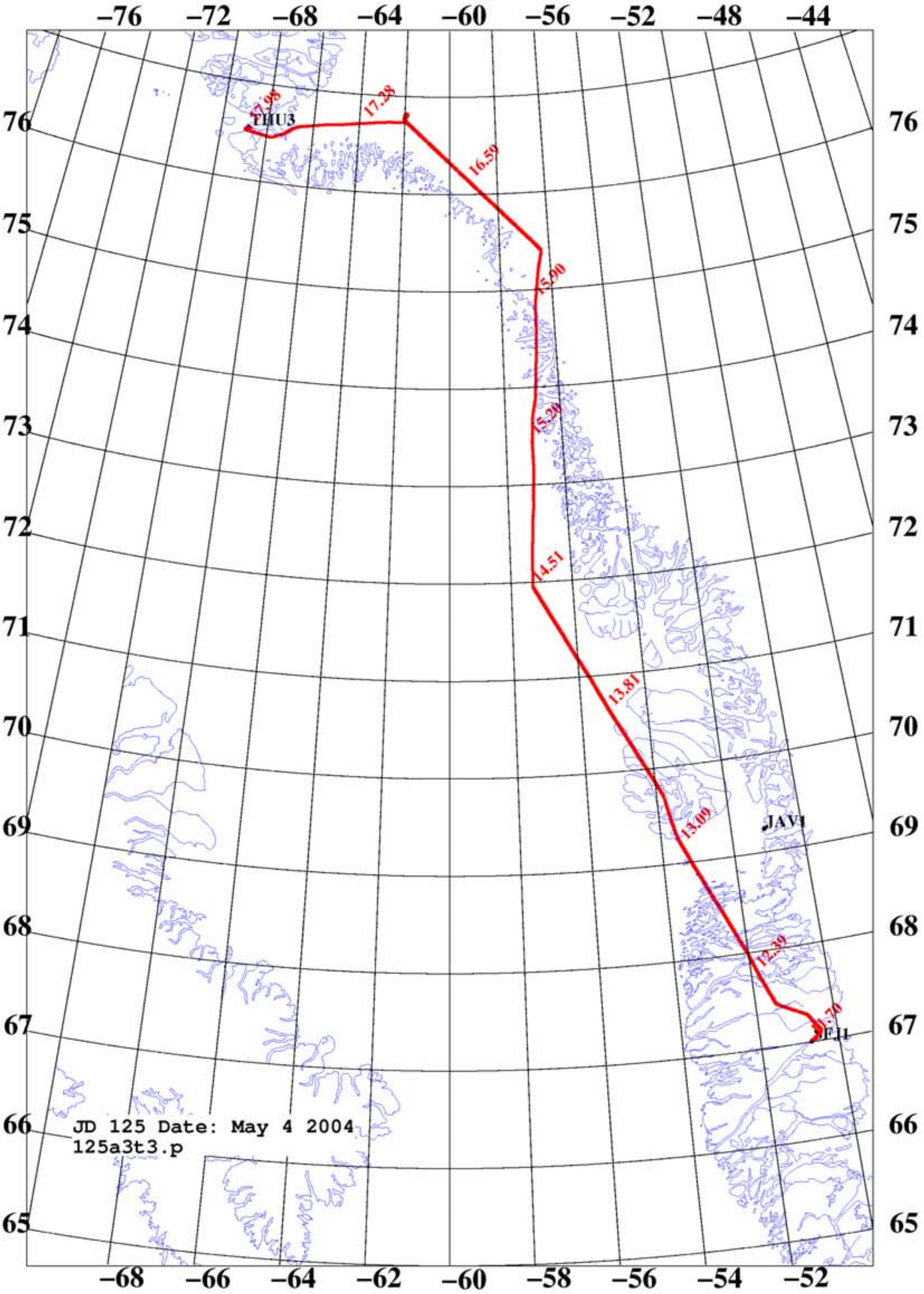
Flight tracks from April 21st, JD 112, second flight (112b), JAV – T5 - JAV.



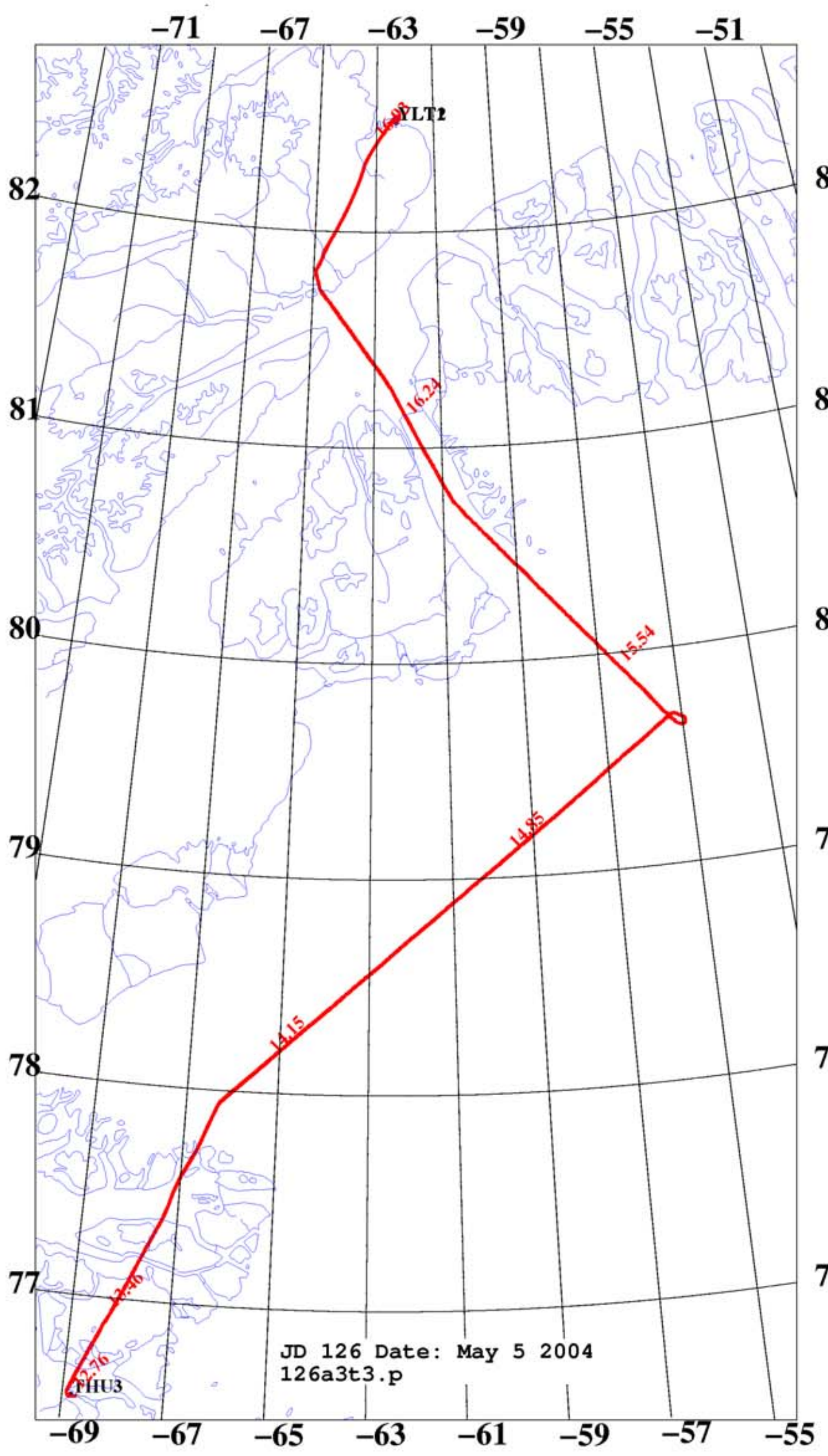
Flight track from April 22nd, JD 113, JAV – T41 – T21 – JAV.



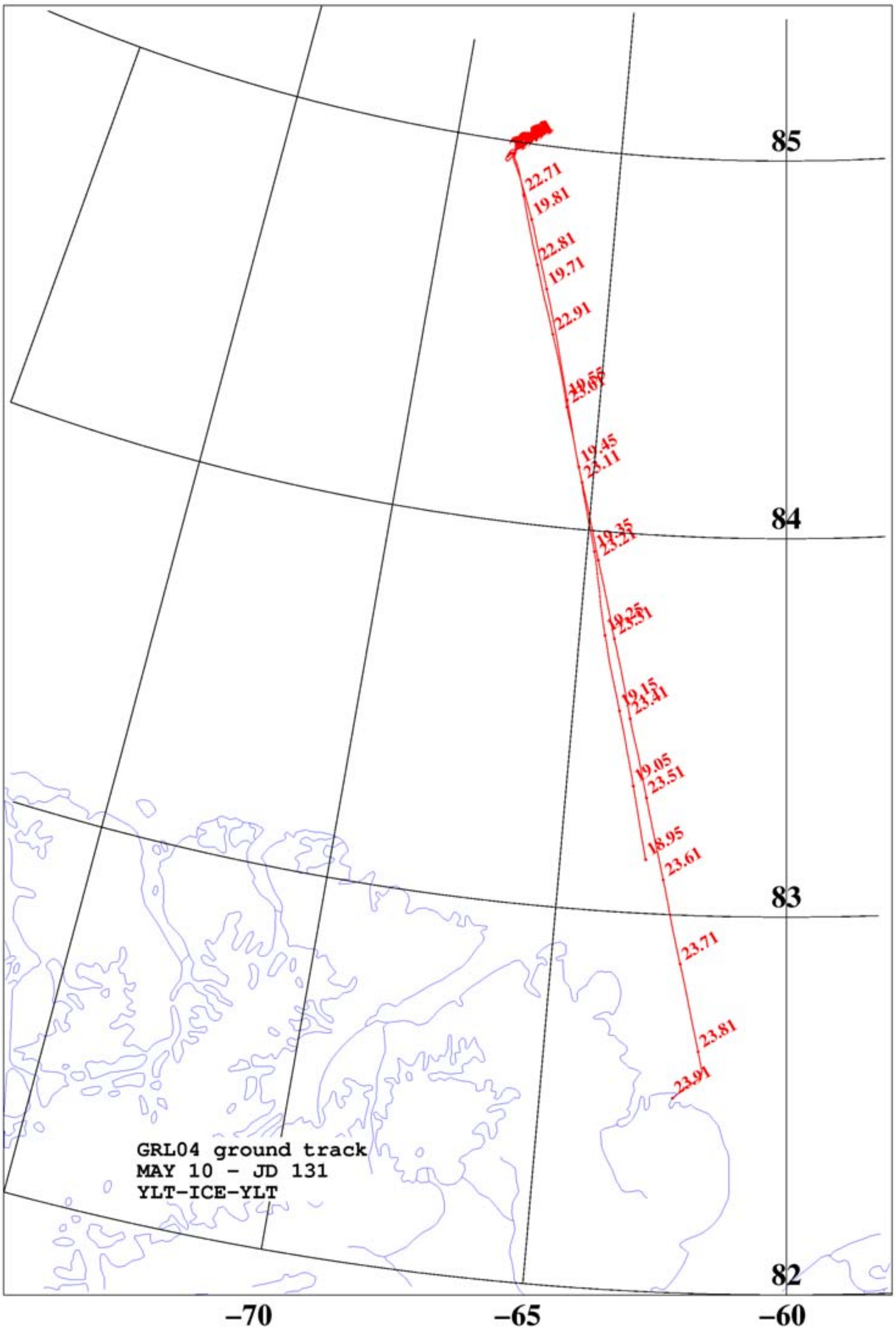
Flight track from April 23, JD 114, JAV – N4 – N-line – JAV – S-line - SFJ.



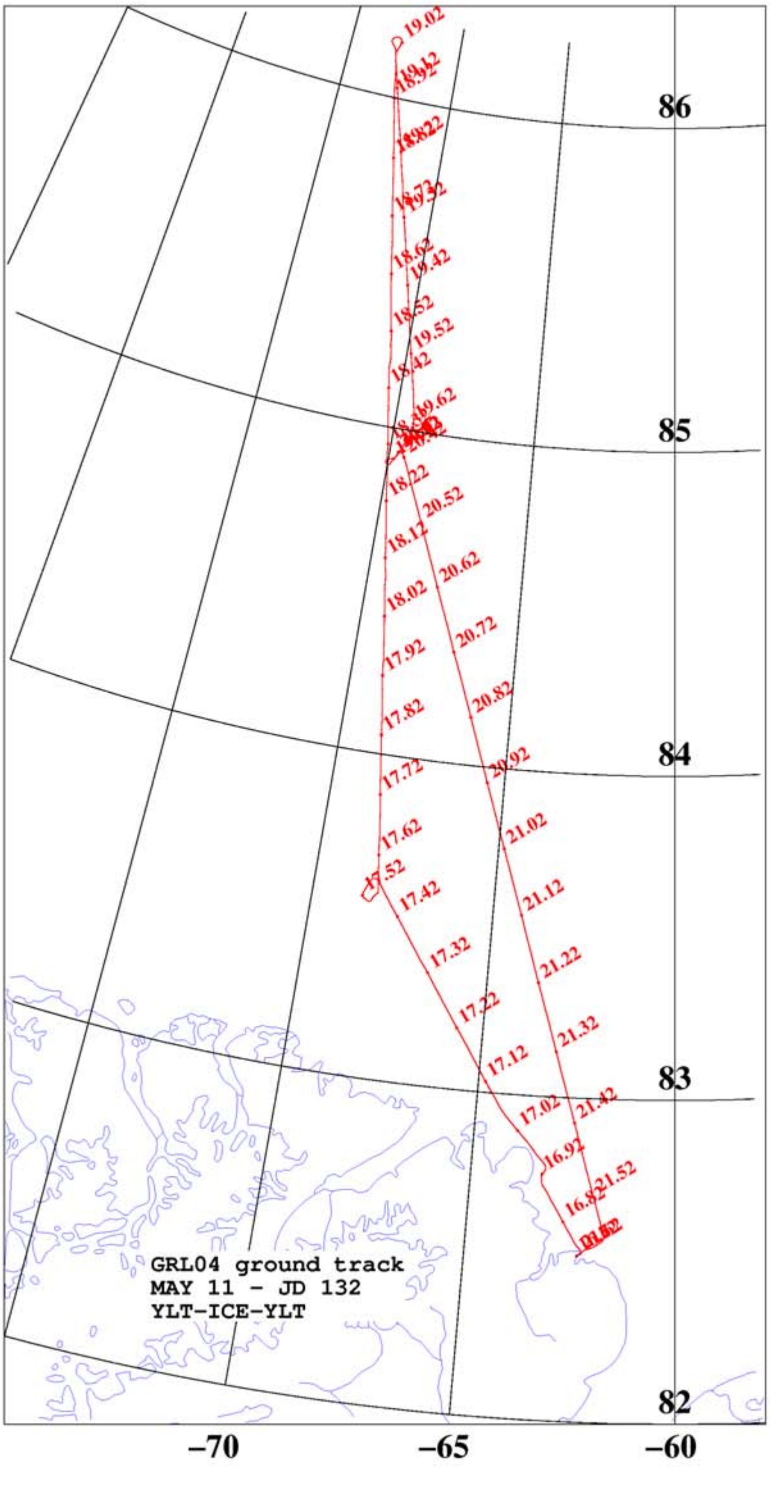
Flight track from May 4, JD 125, test flight around SFJ, followed by flight to TAB.



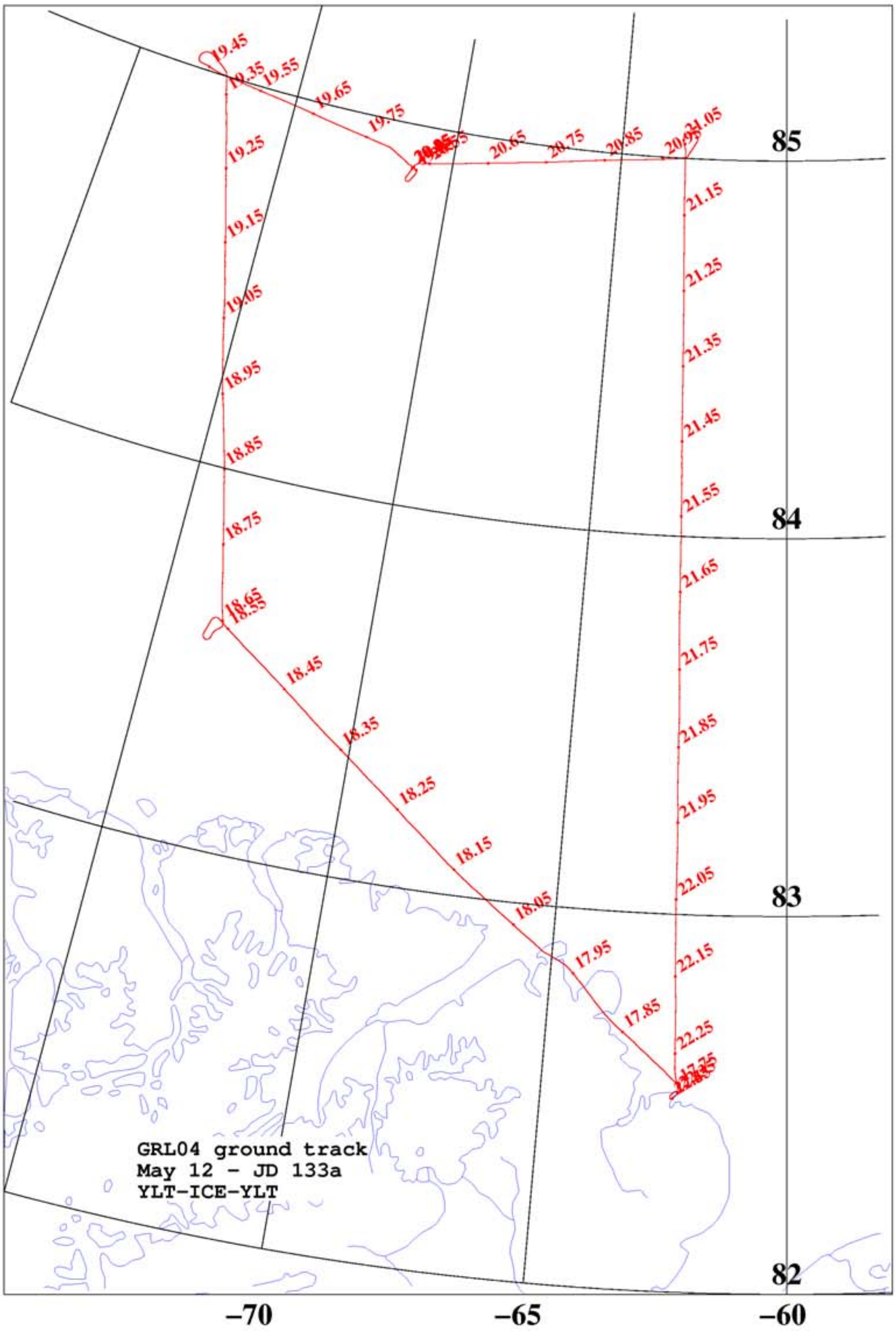
Flight track from May 5, JD 126, TAB – Peterman Glacier - YLT.



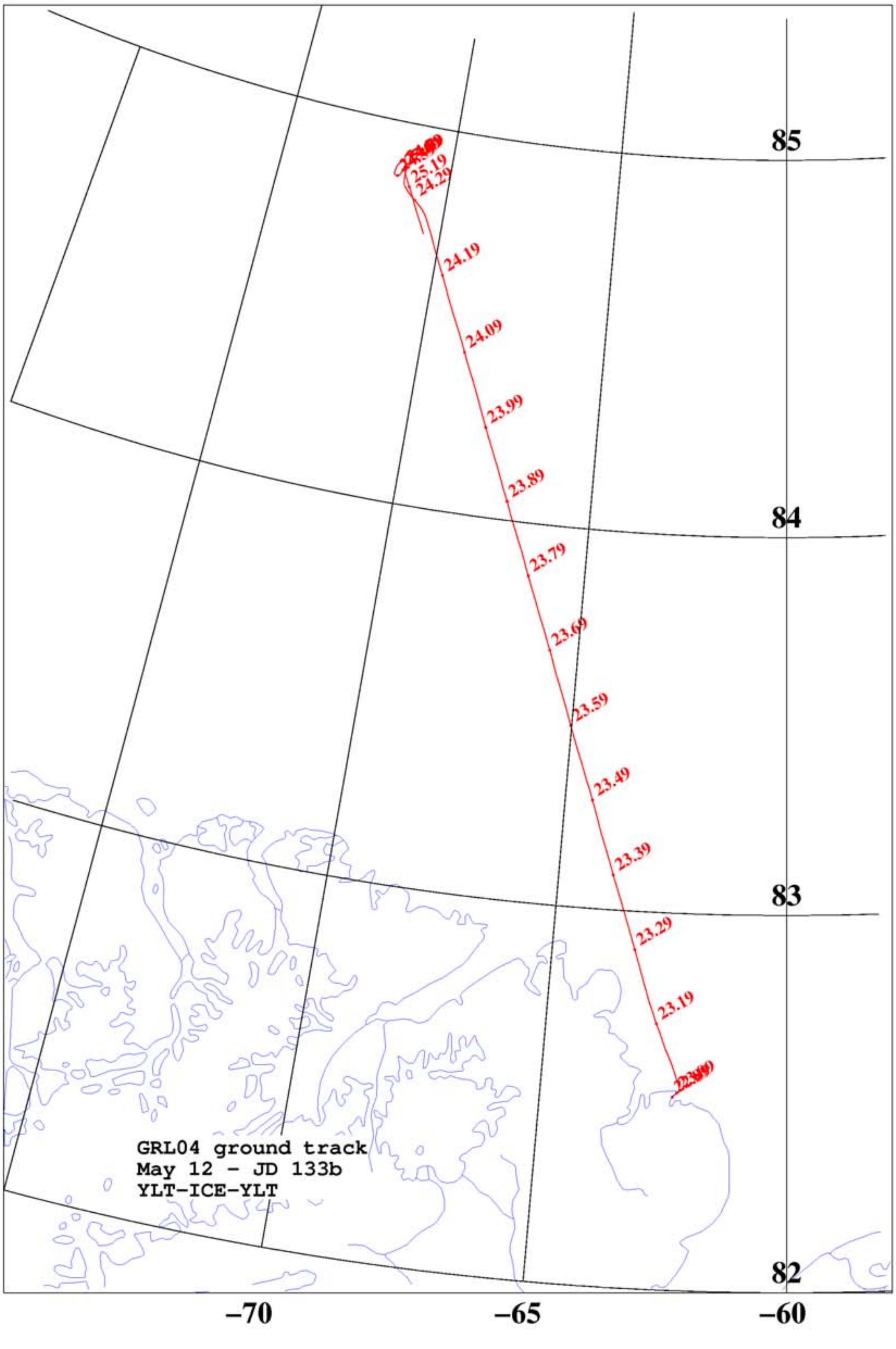
Flight track from May 10, JD 131, YLT – ICE - YLT.



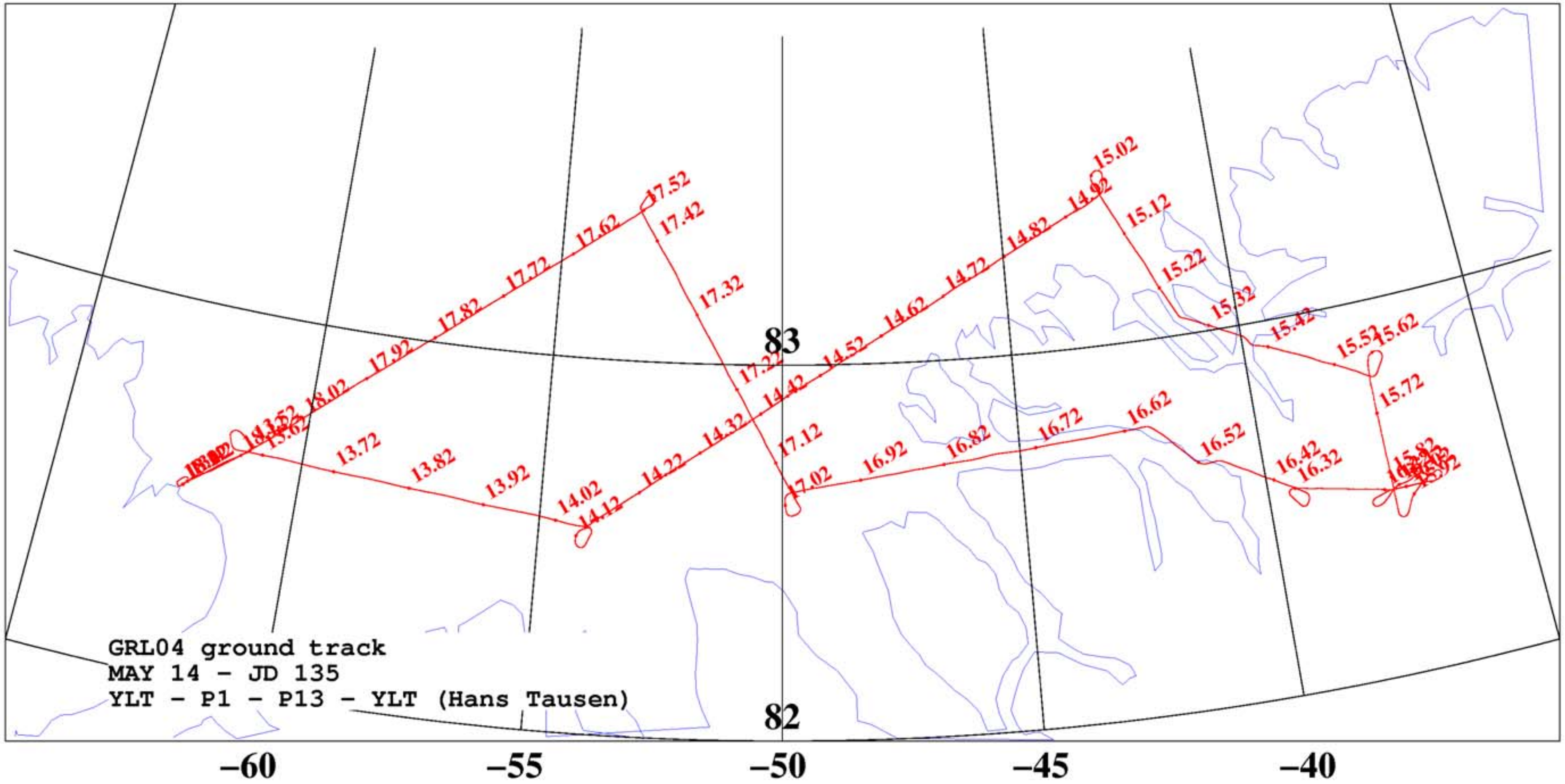
Flight track from May 11, JD 132, YLT – icecamp - YLT.



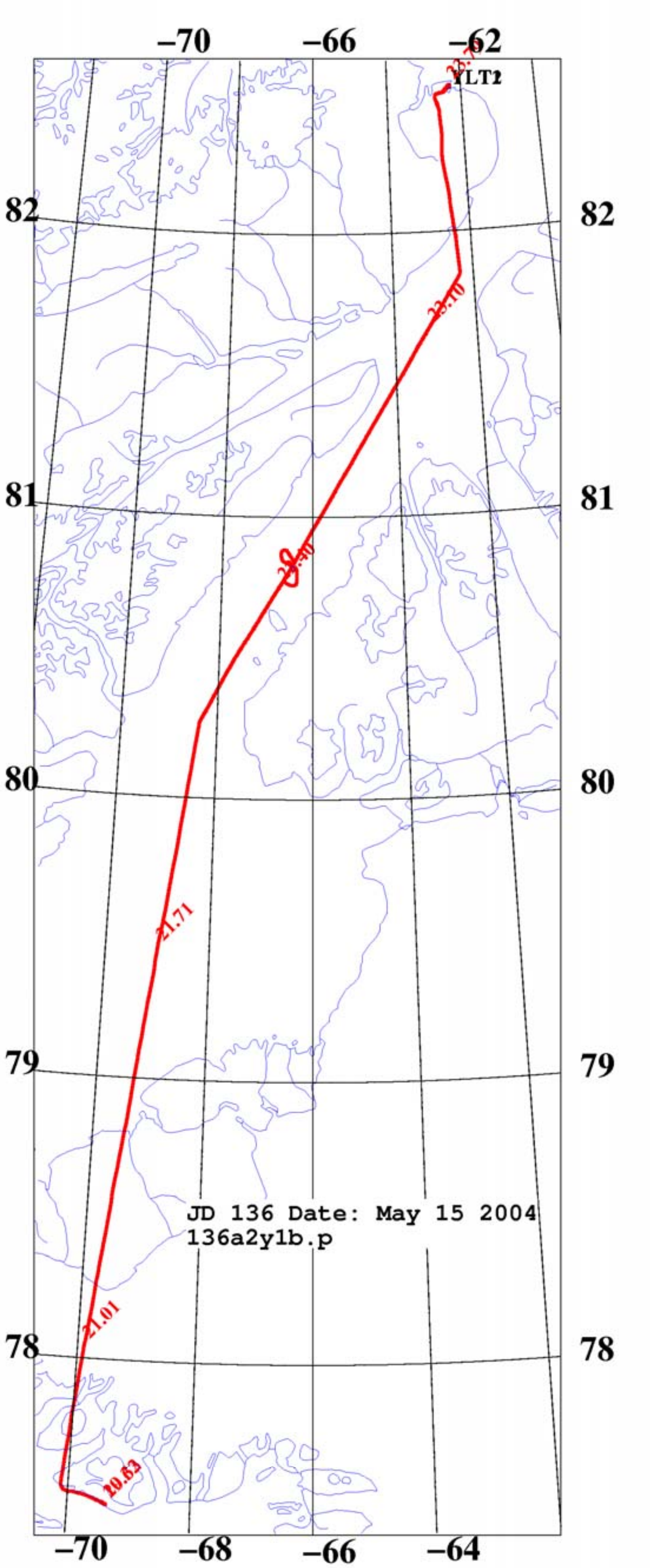
Flight track from May 12, JD 133 first flight (133a), YLT – icecamp - YLT.



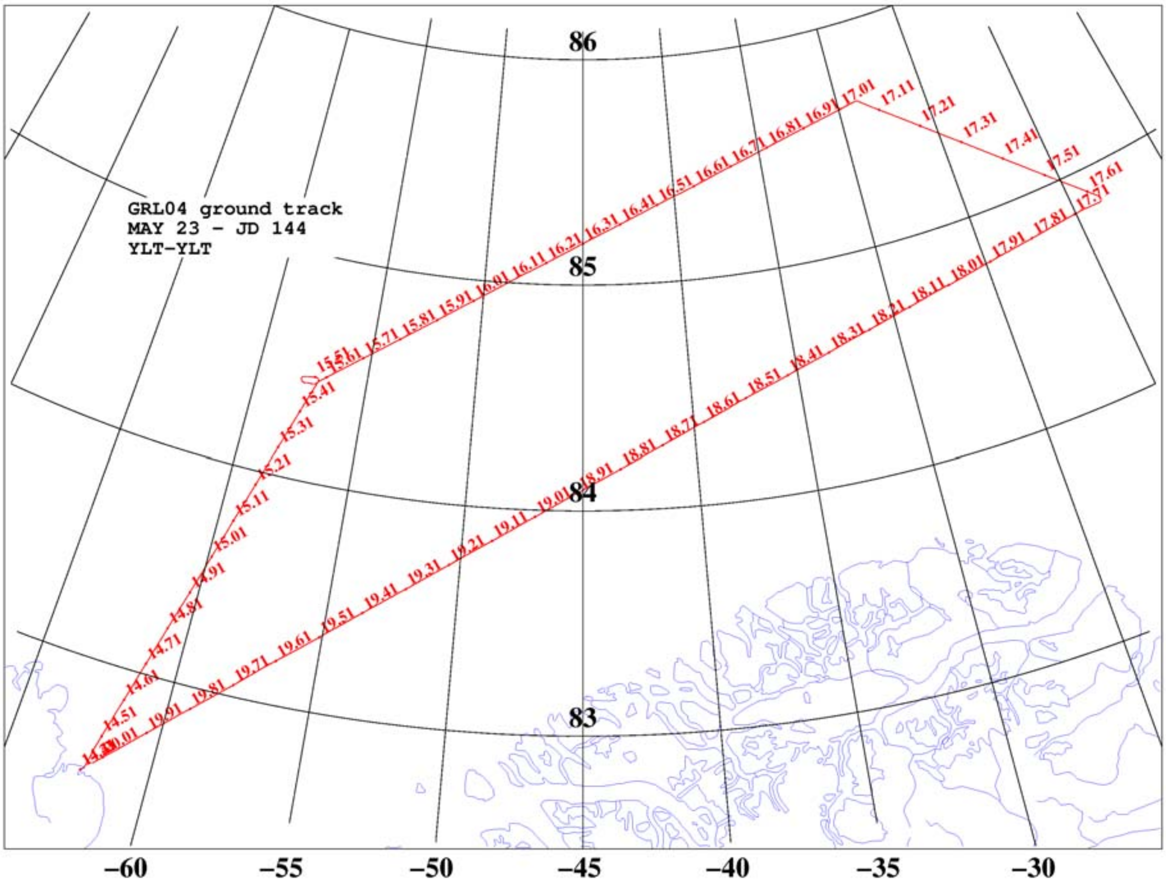
Flight track from May 12, JD 133 second flight (133b), YLT – icecamp - YLT.



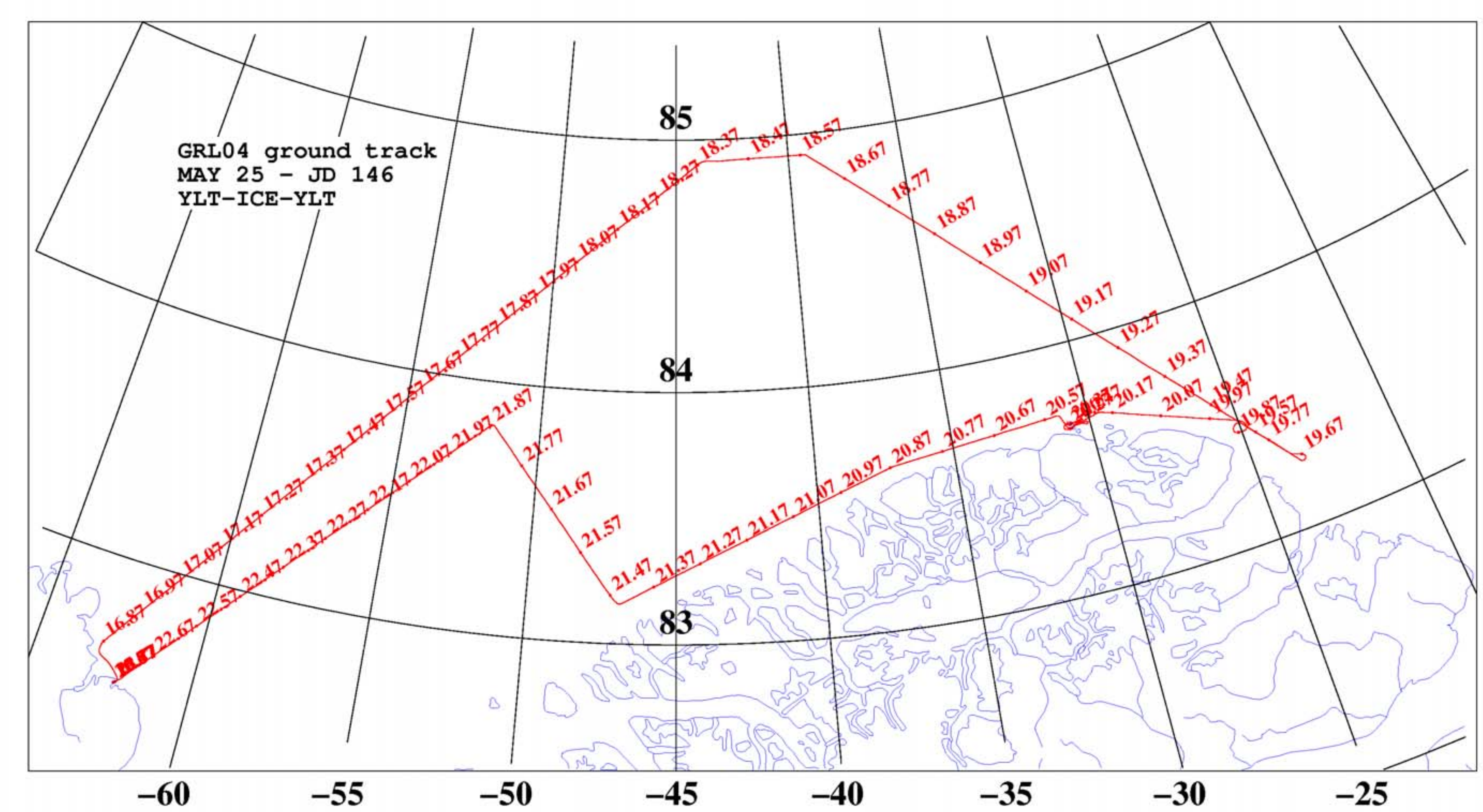
Flight track from May 14, JD 135, YLT – Hans Tausen Ice Camp - YLT.



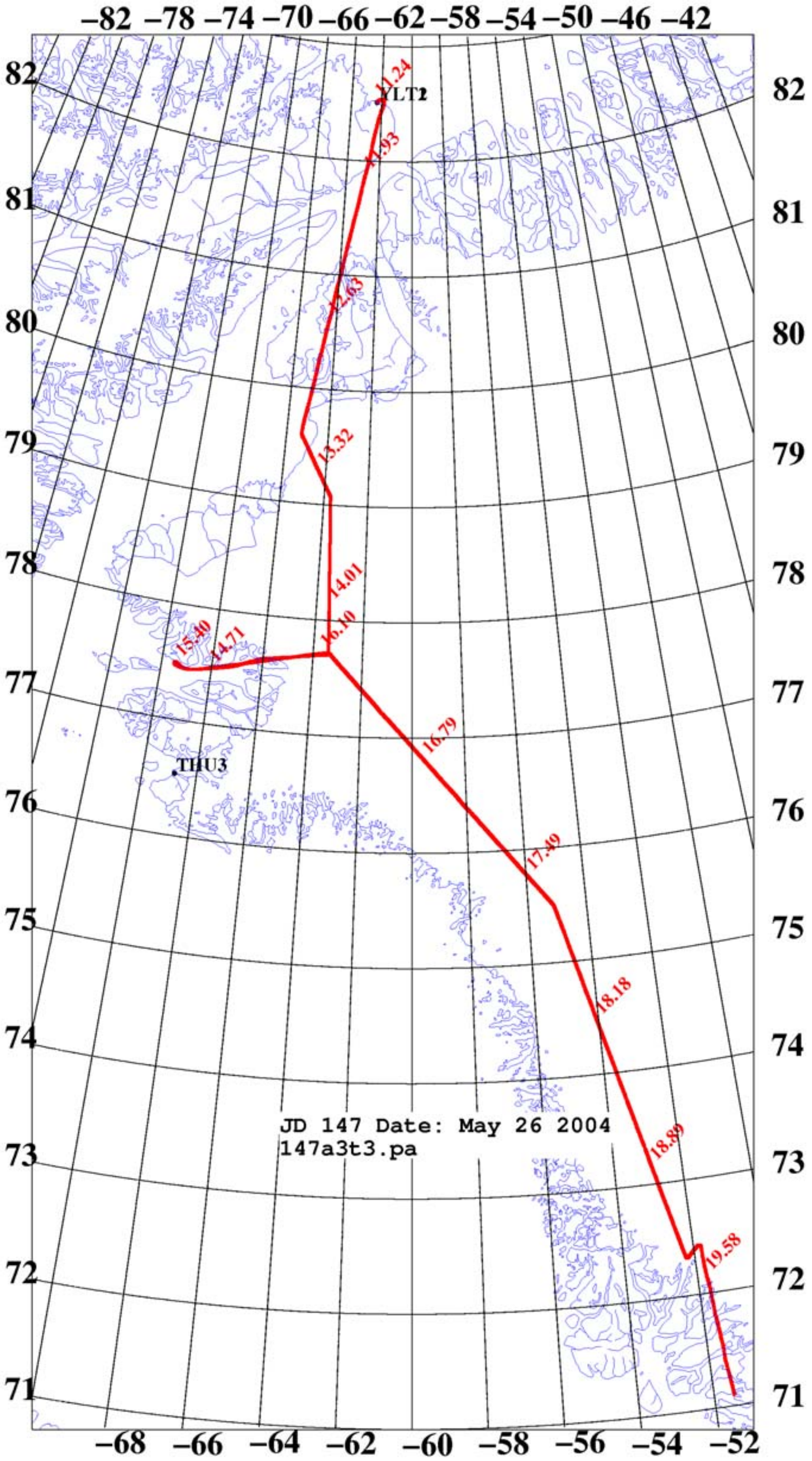
Flight track from May 15, JD 136, NAQ – Hans Ø - YLT.



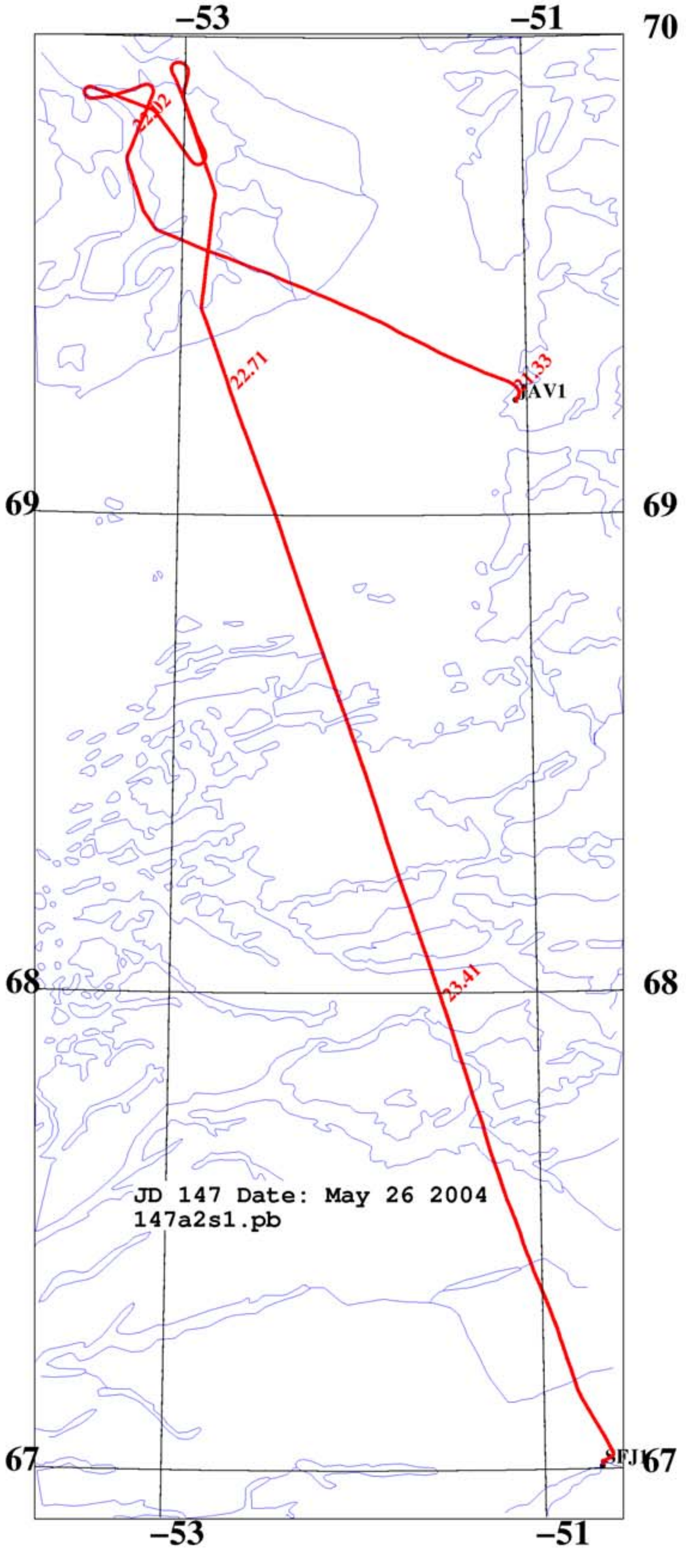
Flight track from May 23, JD 144, YLT - YLT.



Flight track from May 25, JD 146, YLT - YLT.



Flight track from May 26, JD 147, first flight (147a), YLT – NAQ, NAQ - JAV.



Flight track from May 26, JD 147, second flight (147b), JAV – Lyngmark Ice Cap – SFJ

References

1. N. S. Dalå, R. Forsberg, K. Keller, L. Stenseng, S. M. Hvidegaard: *Airborne Lidar Measurements of Sea Ice North of Greenland and Ellesmere Island 2004. GreenICE/SITHOS/CryoGreen/A76 Projects. Final Report*, 69 pp., 2005.

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