1319

ESA CryoVEx/KAREN and EU ICE-ARC 2017

Arctic field campaign with combined airborne Ku/Ka-band radar and laser altimeters, together with extensive in situ measurements over sea- and land ice

H. Skourup, A. V. Olesen, L. Sandberg Sørensen, S. Simonsen, S. M. Hvidegaard, N. Hansen, A. F. Olesen, A. Coccia, K. Macedo, V. Helm, R. S. Ladkin, R. Forsberg, A. E. Hogg, I. Otosaka, A. Shepherd, C. Haas and J. Wilkinson

DTU Space
National Space Institute
Technical University of Denmark

Technical Report
August 2019

EUROPEAN SPACE AGENCY CONTRACT REPORT

ESA Contract No. 4000120131/17/NL/FF/mg (CCN1)

ESA CryoVEx/KAREN and EU ICE-ARC 2017

**Arctic field campaign with combined airborne Ku/Ka-band radar and laser altimeters,
together with extensive in situ measurements over sea- and land ice**

Authors:

H. Skourup¹, A. V. Olesen¹, L. Sandberg Sørensen¹, S. Simonsen¹, S. M. Hvidegaard¹, N. Hansen¹, A. F. Olesen¹, A. Coccia², K. Macedo², V. Helm³, R. S. Ladkin⁴, R. Forsberg¹, A. E. Hogg⁵, I. Otosaka⁵, A. Shepherd⁵, C. Haas^{3,6} and J. Wilkinson⁴

¹ National Space Institute, DTU Space, Denmark

² MetaSensing BV, The Netherlands

³ Alfred Wegener Institute for Polar and Marine Research, Germany

⁴ British Antarctic Survey, Cambridge, UK

⁵ University of Leeds, UK

⁶ York University, Canada

DTU Space
National Space Institute
Danish Technical University

Technical Report, 2019
ISBN-978-87-91694-45-5

Front page: BAS Twin Otter (VP-FAZ) in CFS Alert. Credits: H. Skourup.

ESA contract report
Version: 1.3

ESA STUDY CONTRACT REPORT			
ESA CONTRACT NO 4000120131/17/NL/FF/mg (CCN1)	SUBJECT Technical Support for CryoVEx/KAREN 2017 Arctic airborne campaign with combined Ku/Ka-band radar and coincident in situ measurements over land and sea ice		CONTRACTOR National Space Institute (DTU Space)
ESA CR No	STAR CODE	No of volumes 1 This is Volume No 1	CONTRACTORS REFERENCE CryoVEx/KAREN 2017
<p>ABSTRACT</p> <p>The ESA CryoVEx/KAREN 2017 Arctic campaign is a very ambitious airborne and in situ campaign using combined Ka- and Ku-band airborne sensors (KAREN and ASIRAS) to validate CryoSat-2, Sentinel-3 and SARAL/AltiKa altimeter missions and to exploit the dual-frequency concept for future polar satellite missions. The concept builds upon the experience gained during ESA CryoVEx/KAREN 2016 fall campaign, which were the first ESA campaign to explore the dual-frequency airborne setup.</p> <p>The collected data is unique and includes datasets along a total of five CryoSat-2, two Sentinel-3 and two dedicated SARAL/AltiKa ground tracks over sea ice in different locations representing different sea ice types and settings. The flights were coordinated with extensive large scale in situ work both over sea ice along a CryoSat-2 track from CFS Alert to 87°N and along the EGIG line on the Greenland Ice Sheet from 47-38°W covering different glacial zones. Crossings of the Greenland ice sheet includes multiple crossovers of all altimeter missions including CryoSat-2, Sentinel-3A and SARAL/AltiKa. For the first time four aircrafts with a variety of instruments were coordinated to measure along a CryoSat-2 ground track over the sea ice out of CFS Alert. This also included the first successful dedicated underflight of SARAL/AltiKa coordinated with Cambridge Bay in situ snow experiment (CamBay SnowExp), despite challenges due to the satellite being in a drifting orbit.</p>			
<p>The work described in this report was done under ESA Contract. Responsibility for the contents resides in the author or organisation that prepared it.</p>			
<p>Names of authors: H. Skourup, A. V. Olesen, L. Sandberg Sørensen, S. Simonsen, S. M. Hvidegaard, N. Hansen, A. F. Olesen, A. Coccia, K. Macedo, V. Helm, R. S. Ladkin, R. Forsberg, A. E. Hogg, I. Otosaka, A. Shepherd, C. Haas and J. Wilkinson</p>			
<p>NAME OF ESA STUDY MANAGER Tânia Casal Mission Science Division Validation Campaigns - ESTEC</p>		<p>ESA BUDGET HEADING</p>	

DOCUMENT CHANGE LOG

Version	Date	Modified pages	Modification
	01/11 2017	all	Document created, H. Skourup
1.0	23/06 2018	All	Draft delivered to ESA based on KAREN "levb" processing (Section 6.2.1 based on "hamh")
1.1	30/07 2019	All	Updates according to feedback from ESA 26/07 2019
1.2	22/08 2019	Section 6.2.1 text + Figure 41	Updated study of EGIG-line to be based on "levb" and corrected for appropriate radar offsets
1.3	07/04 2020	Sect. 5.5.1 text Sect. 5.6 text + Tables 15-16 and Figures 22-23 Appendices 21 and 24	Feedback to version 1.2 from ESA 26/8 2019 replied in mail from Sine M. Hvidegaard 27/8 2019 Includes the final version of processed KAREN data "levc"

Contents

1	Introduction.....	9
2	Summary of operation	10
2.1	Day to day.....	14
2.1.1	Phase 1	14
2.1.2	Phase 2	15
3	Hardware installation.....	17
3.1	Phase 1	17
3.2	Phase 2	22
4	Overview of acquired data	25
5	Processing.....	29
5.1	GPS data processing	29
5.2	Inertial Navigation System	30
5.3	Airborne Laser Scanner (ALS)	33
5.3.1	Calibration	33
5.3.2	Laser scanner outlier detection and removal.....	34
5.3.3	Cross-over Statistics	34
5.3.4	Final processed data.....	35
5.4	ASIRAS	38
5.4.1	Processing.....	38
5.4.2	Final processed data.....	38
5.5	KAREN.....	39
5.5.1	Processing.....	39
5.5.2	Final packed data.....	40
5.6	Calibration and absolute heights of ASIRAS and KAREN	43
5.7	Horizontal alignment between ASIRAS and KAREN	47
5.8	Camera	49
6	Calibration and Validation sites.....	51
6.1	Sea Ice.....	51
6.1.1	Sea ice flights Lincoln Sea	53

6.1.2	In situ work Lincoln Sea	55
6.1.3	First results of dual-frequency snow depth from KAREN and ASIRAS	56
6.1.4	SARAL/AltiKa underflights	57
6.1.5	Sentinel-3A under flights.....	60
6.1.6	Supporting sea ice flights	61
6.2	Land ice.....	63
6.2.1	EGIG line	64
6.2.2	Austfonna	70
6.2.3	Devon	70
6.3	Land	71
7	Conclusion	73
8	References.....	75
9	Appendix Airport codes.....	76
10	APPENDIX Operator logs	77
11	APPENDIX Coordinates of GPS base stations	108
12	APPENDIX Overview of acquired ALS data – phase 1.....	109
13	APPENDIX Overview of acquired ALS data – phase 2.....	110
14	APPENDIX Overview of acquired ASIRAS data – phase 1	113
15	APPENDIX Overview of acquired data from Ka-band radar	114
16	APPENDIX File name convention.....	124
17	APPENDIX Processed GPS data in ESA format.....	125
18	APPENDIX Processed INS data in ESA format.....	126
19	APPENDIX Processed ALS data	127
20	APPENDIX Time-tagged and geo-located images.....	129
21	APPENDIX Processed KAREN data	131
22	APPENDIX Processed ASIRAS data.....	137
23	APPENDIX Final ASIRAS profiles	138
24	APPENDIX KAREN processing documentation	139

1 Introduction

The 2017 airborne campaign was an ESA CryoSat-2 Validation Experiment (CryoVEx) primarily for CryoSat-2 validation, but also Sentinel-3 and SARAL/AltiKA, to monitor sea ice and land ice in the Arctic. The CryoVex/KAREN campaign also built upon the existing EU FP7 project ICE-ARC campaign. The airborne campaign was coordinated by National Space Institute, Technical University of Denmark (DTU Space), in cooperation with York University (YU) and Environment Canada (EC), and took place in spring 2017.

The campaign was divided in two separate campaigns referred to as phase 1 and phase 2. This was done first of all to ease the load on CFS Alert, but also to secure coordinated laser and radar flights with PanArcMIP EC/AWI Polar-5 and NASA Operation IceBridge.

Phase 1 took place March 20-31 and involved operations with ESA's Ku-band radar (ASIRAS), Dutch Company MetaSensing's Ka-band radar (KAREN) and laser scanner using chartered Twin Otter (reg. no.: TF-POF) from Norlandair, Iceland. The campaign covered sea ice flights in the Arctic Ocean and Baffin Bay, together with land ice flights over Devon icecap and the Greenland Ice Sheet. This part included a coordinated sea ice flight involving for the first time four aircrafts; ESA CryoVEx Twin Otter, PanArcMIP EC/AWI Polar-5, NASA Operation IceBridge and NASA wide-swath topographic mapper (GLISTN), carrying a suite of instruments to monitor the snow and sea ice along a CryoSat-2 ground track. In addition, flights were coordinated with large scale *in situ* work along the EGIG line of the Greenland Ice Sheet lead by University of Leeds.

Phase 2 took place April 5-23 and involved flights over sea ice and land ice from Cambridge Bay, CFS Alert, and Svalbard/Station Nord, as well as an intensive large scale sea ice *in situ* program with multiple landings between 82-86°N on sea ice along CryoSat-2 tracks north of CFS Alert. Two aircrafts were used during this phase. A Twin Otter from Kenn Borek Air, Calgary, was chartered for sea ice landings, and a British Antarctic Survey Twin Otter (VP-FAZ) was used to collect combined Ka-band radar (MetaSensing KAREN), laser and radiometer measurements, but also acting as safety back-up for the sea ice landings. This phase also included coordinated flights with Cambridge Bay Snow Experiment (CamBay SnowExp) and Austfonna ice cap in Svalbard.

This report is the final report of the experiments and summarizes the airborne and in situ field operations, instrument description and data processing together with first results. The report is an ESA CryoVEx contract report and part of EU ICE-ARC deliverable. Dedicated ICE-ARC flights are marked with green throughout the report.

The primary objectives achieved during the campaign were:

- To fly dual frequency (Ka/Ku-band) radar altimeters together with laser to study penetration depths in support of future satellite missions
- Coordinated sea ice underflights of CryoSat-2, Sentinel-3 and SARAL/AltiKa in different locations
- Coincident flights with PanArcMIP EC/AWI, NASA Operation IceBridge and GLISTN
- Large-scale in situ work on sea ice (Lincoln Sea and Cambridge Bay) and land ice (EGIG-line)

Figure 1: Overview of the flight tracks from the CryoVEx/ICE-ARC 2017 airborne campaign, phase 1 (red) and phase 2 (yellow). Satellite underflights and in situ sites have been marked.

2 Summary of operation

The CryoVEx/ICE-ARC 2017 airborne campaign was split into two operational periods. The first part, referred to as phase 1, basically circumnavigated Greenland north of 70°N, see red flight lines in Figure 1. The second part, referred to as phase 2, started out in Cambridge Bay, Nunavut, Canada and proceeded via CFS Alert to Svalbard, Norway, see yellow flight lines in Figure 1. A total of scientific flight hours were about 60 hours for each phase of the campaign.

Phase 1, took place March 19 – April 1, 2017 and included four underflights of CryoSat-2, one Sentinel-3 and two AltiKa over sea ice (Section 6.1), and was coordinated with large scale in situ work on the old traverse, the EGIG line, on the Greenland Ice Sheet (Section 6.2.1). The Norlandair Twin Otter (reg: TF-POF), which is the same aircraft as used throughout previous CryoVEx campaigns, was chartered for phase 1. The instrument installation and test flights took place in Akureyri, Iceland, March 15-18, following the general instrument certification for the aircraft obtained in 2006 (Hvidegaard and Stenseng, 2006). The exceptional setup was that for the first time four aircrafts were jointly underflying a Cryosat-2 ground track, carrying a variety of instruments to compliment the dual-frequency setup. This was done in the Lincoln Sea on March 24, and included Norlandair Twin Otter with Ka-band radar (KAREN), Ku-band (ASIRAS) and Airborne Laser Scanner (ALS), AWI Polar-5 towing an electromagnetic sensor to measure the sea ice thickness, Operation IceBridge P3 with ATM and snow radar, and NASA wide-swath topographic mapper (GLISTN). A more detailed description of the science flights can be found in Chapter 6. The flight program was very tight, leaving

no space for delays. Luckily, the weather was favorable and all planned flights were achieved within the estimated time.

The primary aim of phase 2 was to support the in situ work out of CFS Alert, both by taking coincident measurements, but also to act as safety backup for the in situ team aircraft (Ken Borek Twin Otter) which was used for multiple landings on the drifting sea ice to transport the in situ group to the different sites (see Section 6.1.2). Phase 2 was supported by the British Antarctic Survey Twin Otter (VP-FAZ), which was used for similar measurements in spring 2015 (Hvidegaard et al., 2017). The instrument installation took place March 27-April 3 in Springbanks airport, Calgary, Canada. April 4-5 the aircraft was transferred to Cambridge Bay, Nunavut, Canada, where a large *in situ* program “CamBay SnowExp” to measure the snow and ice properties along a SARAL/AltiKa ground track was setup with UK, US and Canadian scientists (Section 6.1.4). During phase 2 a total of four CryoSat-2, one SARAL/AltiKa and one Sentinel-3 underflight over sea ice was measured. In addition, a pattern of parallel lines, with a similar angle as ascending CryoSat-2 tracks were flown over Austfonna similar to CryoVEx 2016 spring campaign (Skourup et al., 2016). In addition, about 5 flight hours were dedicated to make a tight grid over land in Cambridge Bay area to validate a high-resolution DEM from NASA (Section 6.3). In general, the weather was favorable. However, some delays were introduced due to waiting for weather and de-mounting of wheel-skies, which only could be performed in Resolute Bay. The second phase of the campaign was followed by an airborne ESA campaign to test a novel “cold atom” gravimeter in an aircraft in Iceland in cooperation with ONERA, France (campaign described in a separate report).

The flight altitude during survey is typically 300 m agl, limited by the range of the laser scanner, and the nominal ground speed is 135 knots. The aircraft is equipped with an extra ferry tank permitting longer flights (5-6 hrs), and an autopilot for better navigation accuracy. In good conditions the across-track accuracy is down to a few meters using a custom-made navigation system connected to geodetic GPS receivers. Calibration flights of the instruments over buildings and runways were performed whenever possible. For a more detailed description see Section 5.3 and 5.4.

The airborne science team during phase 1 consisted of Arne V. Olesen, Louise Sandberg Sørensen from DTU Space, Alex Coccia from MetaSensing, and ESA technical officer Malcolm Davidson. In phase 2 the science team consisted of Henriette Skourup (Cambridge Bay to Svalbard) and Sebastian B. Simonsen (Svalbard) from DTU Space. Arne V. Olesen (DTU Space), Alex Coccia (MetaSensing) and Russell Ladkin (British Antarctic Survey) assisted with the instrument installation in Calgary in the aircraft prior to the campaign.

The sea ice in situ team working out of CFS Alert (April 11-18) was led by Christian Haas (Alfred Wegener Institute/York University) and supported by Ken Borek Twin Otter equipped with skies. The team consisted of Christian Haas, Justin Beckers (University of Alberta), Josh King and Arvids Silis (both from Environment Canada), Julianne Stroeve (University College London), and Jeremy Wilkinson (British Antarctic Survey).

Based on experience from CryoVEx/KAREN 2016 campaign, the in situ team working on the EGIG line used a ski-equipped Twin Otter from Norlandair, which is more flexible with respect to weather and range, when compared to helicopter as used in 2016. The team consisted of Sebastian Simonsen (DTU Space), Anna Hogg (University of Leeds), Andy Shepard (University of Leeds) and Alessandro Di Bella (DTU Space).

Cambridge Bay SnowExp 2017 (Section 6.1.4) was led by Jeremy Wilkinson (British Antarctic Survey). The experiment was based out of the recently established research facility Canadian High Arctic Research Station (CHARS), in Cambridge Bay, Nunavut, Canada. Beside Jeremy Wilkinson the ground team consisted of: Woosok Moon (British Antarctic Survey), Andrew Barrett (NSIDC), Francois Guerraz (Orographic Lift Ltd), Dwayne Beattie (POLAR), Donald McLennan (POLAR), Daniel Kramer (POLAR), Angulalik Pedersen (POLAR), Julianne Stroeve (University College London), Isobel Lawrence (University College London), Vishnu Nandan (University of Calgary) and Randy Scharien (University of Victoria).

An overview of the flights is found in Table 1 and 2 along with a detailed “day-to-day”-report in Section 2.1. Operator logs and detailed plots of flight tracks are provided in Appendix 9.2.

Table 1: Overview of CryoVEx/KAREN 2017 flights, phase 1. Initials of survey operators are Arne V. Olesen (AVO), Louise Sandberg Sørensen (SLSS) and Alex Coccia (AC).

Date	DOY	Flight	Track	Take off UTC	Landing UTC	Airborne	Airborne accumulated [dd:hh:mm]	Survey operator
18-03-2017	77		Test Flight AEY ?			00:00	00:00:00	AVO/SLSS/AC
19-03-2017	78	A	AEY-CNP	09:07	11:38	02:31	00:02:31	AVO/SLSS/AC
19-03-2017	78	B	CNP-DMH	12:04	15:34	03:30	00:06:01	AVO/SLSS/AC
20-03 2017	79	A	DMH-ULS-TobiasØ-STN	10:55	16:03	05:08	00:07:39	AVO/SLSS/AC
20-03 2017	79	B	STN-ALTIKA-STN	16:06	18:36	02:30	00:10:09	AVO/SLSS/AC
21-03 2017	80	A	STN-CS2-STN	10:25	15:21	04:56	00:15:05	AVO/SLSS/AC
21-03 2017	80	B	STN-TRIANGLE-STN	16:01	21:08	05:07	00:20:12	AVO/SLSS/AC
22-03 2017	81		NRD-GrIS-YLT	14:23	18:12	03:49	01:00:01	AVO/SLSS/AC
24-03 2017	83		YLT-CS2-YLT	14:22	20:12	05:50	01:05:51	AVO/SLSS/AC
27-03 2017	86		YLT-CS2-inSitu-YLT	13:54	18:18	04:24	01:10:15	AVO/SLSS/AC
28-03 2017	87		YLT-Peterman-GrIS-TAB	13:56	17:53	03:57	01:14:12	AVO/SLSS/AC
29-03 2017	88		TAB-S3A-DEVON-TAB	13:22	18:38	05:16	01:19:28	AVO/SLSS/AC
30-03 2017	89	A	TAB-BaffinBay-DISKO-JAV	11:49	16:18	04:29	01:23:57	AVO/SLSS/AC
30-03 2017	89	B	JAV-JQA	16:45	17:29	00:44	02:00:41	No Survey
31-03 2017	90	A	JQA-ALTIKA-JQA	08:00	12:08	04:08	02:04:49	AVO/SLSS/AC
31-03 2017	90	B	JQA-EGIG-JQA	13:52	17:20	03:28	02:08:17	AVO/SLSS/AC
01-04 2017	91	A	JQA-EGIG-CNP	09:25	13:47	04:22	02:12:39	AVO/SLSS/AC
01-04 2017	91	B	CNP-AEY	14:11	16:21	02:10	02:14:49	No Survey
Total							60h 18m	

Table 2: Overview of CryoVEx/KAREN 2017 flights, phase 2. Initials of survey operators are Henriette Skourup (HSK), Sebastian B. Simonsen (SSIM), Alex Coccia (AC) and Russell Ladkin (RL).

Date	DOY	Flight	Track	Take off UTC	Landing UTC	Airborne	Airborne accumulated [dd:hh:mm]	Survey operator
05-04-2017	95	b	YCB-AltiKa-YCB	21:25	23:45	02:20	00:02:20	RL/AC
07-04-2017	97	a	YCB-TER-YCB	19:18	19:51	00:33	00:02:53	HSK/RL
07-04-2017	97	b	YCB-TER-SI-YCB	23:32	02:04	02:32	00:05:25	HSK/RL
08-04-2017	98		YCB-TER-YCB	23:31	01:45	02:14	00:07:39	HSK
11-04-2017	101		YCB-McClintock-YRB	15:40	19:40	04:00	00:11:39	HSK
12-04-2017	102	a	YRB-YEU	13:58	17:01	03:03	00:14:42	HSK
12-04-2017	102	b	YEU-YLT	18:03	20:08	02:05	00:16:47	HSK
13-04-2017	103		YLT-inSitu-YLT	13:58	19:36	05:38	00:22:25	HSK
16-04-2017	106		YLT-CS37255MOW-YLT	13:10	18:19	05:09	01:03:34	HSK
18-04-2017	108		YLT-ShearZone-IceBridge-YLT	13:37	17:14	03:37	01:07:11	HSK
19-04-2017	109	a	YLT-YEU	12:57	15:20	02:23	01:09:34	No Survey
19-04-2017	109	b	YEU-YRB	15:58	18:32	02:34	01:12:08	No Survey
20-04-2017	110	a	YRB-YGZ	13:37	15:40	02:03	01:14:11	HSK
20-04-2017	110	b	YGZ-NAQ	16:31	18:13	01:42	01:15:53	HSK
21-04-2017	111		NAQ-A3-XX-NAQ	11:56	16:54	04:58	01:20:51	HSK
24-04-2017	114	a	NAQ-H-STN	11:21	15:32	04:11	02:01:02	HSK
24-04-2017	114	b	STN-S3-LYR	16:22	19:21	02:59	02:04:01	HSK
25-04-2017	115		LYR-Austfonna-LYR	09:43	12:14	02:31	02:06:32	SSIM/HSK
26-04-2017	116		LYR-Austfonna-LYR	07:55	12:39	04:44	02:11:16	SSIM
Total							60h 23min	

2.1 Day to day

The airborne part of CryoVEx/KAREN 2017 campaign progressed as follows:

2.1.1 Phase 1

March 14	Scientists Copenhagen - Reykjavik
March 15	Scientists Reykjavik – Akureyri. Start installation in POF
March 16-18	Instrument installation in POF, and test flight near Akureyri
March 19	Transit flight to Constable Point. Survey flight Constable Point – Danmarkshavn.
March 20	Survey flight Danmarkshavn – Station Nord.
March 21	Two survey flights out of Station Nord. One sea ice flight. One CS2 underflight.
March 22	Ice sheet survey flight Station Nord – Alert.

March 23	No flights due to poor weather
March 24	Survey flight out of Alert. CS2 underflight coordinated with AWI and NASA.
March 25-26	No flights (weekend)
March 27	Survey flight out of Alert. CS2 underflight
March 28	Survey flight Alert – Thule Air Base
March 29	Survey flight over Devon ice cap, combined with AltiKa track.
March 30	Survey flights Thule Air Base – Ilulissat - Qaarsut
March 31	Two survey flights out of Qaarsut: one AltiKa track and one coordinated with KAREN ground team on the EGIG line.
April 01	Survey flight Qaarsut – Constable Point. Coordinated with KAREN ground team on EGIG line. Transit flight Constable Point – Akureyri. Un-mount instruments.
April 02	Scientists Akureyri – Copenhagen/Canada

2.1.2 Phase 2

March 27 - April 3	Installation Springbanks airport, Calgary, Canada
April 4	Flight Calgary to Yellowknife
April 5	Flight Yellowknife to Cambridge Bay, followed by underflight of AltiKa track coincident with snow measurements on the ground over both land and sea ice. Reflectors placed perpendicular to flight lines. GPS not logging.
April 6	HSK arrive Cambridge Bay, Poor visibility, no flights
April 7	Poor visibility, tried a noon flight, but too low clouds, no ALS signal from the ground. Late flight to cover terrestrial flight + sea ice flight, the planned corner reflectors were not in place
April 8	late flight to cover the last parts of terrestrial flight + 1 runway overflight
April 9-10	Weather days. Blizzard. Drifting snow and high winds gusting 60 km/h
April 11	Excellent weather YCB. Flight YCB via waypoints in McClintock channel to Resolute
April 12	Resolute to Eureka, survey on the way, old CS2-track. Eureka to CFS Alert, problems with scanner software. The scanner did not synchronize automatically, but managed to circumvent by using RiTerm.
April 13	In situ line to 87.5N both ways. Problems with Camera PC, could see nothing on the screen. Used HSK personal laptop. In situ team at site 5
April 14	No flying due to Easter. Alert closed
April 15	No flying due to poor visibility and light snow in Alert
April 16	CryoSat-2 track 37225 to the NE. Survey area 50kmx1.5km consisting of 5 parallel tracks 350m apart on the drifting ice at about N84.5°-85.0° W40°-45°. Perfect timing of CS2 and airborne measurements in the survey area. En route follow CS2 NE track also flown in phase 1 on March 24 th , together with Icebridge formed in NE Nares Strait. Nice area with open leads. In situ work sites 1 and 4
April 17	Day off, no flying with BAS. In situ work at NE-line
April 18	Flight to shear zone MOW, and icebridge. Windy N/NW
April 19	Alert transit to Resolute Bay via Eureka. No surveying

April 20	Resolute Bay to Qaanaaq via Grise Fjord. Measuring in Jones Strait. Parts too cloudy including Hells Gate. Snowing in Qaanaaq
April 21	Returned half-way to Station Nord due to bad weather at Station Nord. Excellent weather in Qaanaaq. No weather improvements expected at Station Nord within the next 24 hrs
April 22-23	No flying due to bad weather at STN
April 24	SSIM arrive Longyearbyen the night between 23 rd and 24 th . Flight Qaanaaq to station Nord, measuring the remaining part of the ice sheet and Independence Fjord. Excellent weather at Station Nord. Continue Station Nord to Longyearbyen following Sentinel-3 track 20170424T180900
April 25	Flight to Austfonna, the survey only managed to measure on the west-ridge towards Etonbreen, before the survey had to be aborted due to clouds-
April 26	Flight to Austfonna. Cloudy condition, but survey of most of the CryoSat track in basin 3. HSK returned to CPH
April 27	Weather in LYR made surveying impossible. The crew on VP-FAZ went to Tromsø, to start the return to Cambridge, UK
April 28	SSIM return to CPH

3 Hardware installation

3.1 Phase 1

The hardware installation in the Norlandair Twin Otter (TF-POF) consisted of the following instruments:

- MetaSensing Ka-band radar altimeter KAREN
- ESA Ku-band interferometric radar ASIRAS
- DTU Space Airborne Laser Scanner (ALS) of the type Riegl LMS Q-240i-60
- Four geodetic dual-frequency GPS receivers of type Javad Delta (AIR1-4), where AIR4 was used to support ASIRAS time tagging
- An Inertial navigation system (INS) of the type Honeywell H-764G
- An Inertial navigation system (INS) of the type iMAR RQH (backup)
- A NovaTel integrated GPS-INS system of type SPAN-CPT to support KAREN (backup)
- Slant looking DSLR camera (Canon 60D)

The KAREN sensor was for the first time successfully tested during CryoVEx/KAREN 2016 fall campaign (Skourup et al., 2017a). Since then, the horn antennas have been replaced with new Microstrip patch array antennas, see Figure 2, which reduces the across-track resolution from 20 m to 12 m (see Section 5.5).

Figure 2: KAREN Radio Frequency (RF) enclosure with updated microstrip patch antennas.

To accommodate the updated KAREN sensor, it was not necessary to raise the mounting plate, as was the case during CryoVEx/KAREN 2016 fall campaign. This results in a more stable instrument setup. The horizontal position of the mounting plate, and thus the ALS, was similar to CryoVEx/KAREN 2016 fall campaign (Skourup et al., 2017). To avoid shadow effects from the hull of the aircraft the ALS was tilted slightly backwards. The KAREN control unit was fitted into the rear ASIRAS rack, see Figure 3 and 5.

The installation of the ASIRAS system was identical to the setup used throughout the previous CryoVEx campaigns (e.g. Skourup et al., 2013). A Javad Delta receiver AIR4 was used to support ASIRAS time-tagging. The bottom view of the aircraft is shown in Figure 4, with the external ASIRAS antenna, and the KAREN sensor in the hatch.

The four geodetic dual-frequency GPS receivers (AIR1, AIR2, AIR3 and AIR4), operated to log precise aircraft positioning, were connected to two separate GPS antennas (“front” and “rear”) through antenna beam splitters. The GPS antennas are permanently installed on TF-POF. Information about the antenna constellation is provided below:

Front antenna:

- AIR1
- AIR2
- AIR3 from 23-03-2017

Rear antenna:

- AIR3 until 22-03-2017
- AIR4

The logging rates of the AIR2 and AIR3 were 1 Hz, whereas AIR1 and AIR4 was logging at 2 Hz. The higher logging rate for AIR1 was chosen to obtain a higher precision for the on-board navigation system. AIR4 was also used to support ASIRAS time tagging. Offsets between GPS antennas and KAREN, ASIRAS and ALS reference points are given in Table 3.

To record the attitude (pitch, roll and heading) of the aircraft, three inertial navigation systems (INS) were used. The primary unit is a medium grade INS of type Honeywell H-764G mounted in the baggage compartment on the mounting plate together with the ALS (Figure 6). This unit collects data both in a free-inertial and a GPS-aided mode at 50 Hz. Specified accuracy levels in roll and pitch are better than 0.1° , and usual accuracy is higher than this. A super-precise INS strap-down unit of type iMAR RQH, which has the potential to measure the gravity field (Jensen et al., 2017), was installed in the cabin next to the front operator seat, see Figure 3 and 5. Finally, a light-weight (2.28 kg) integrated GPS-INS of type NovaTel SPAN-CPT with a nominal accuracy similar to the H-764G, was installed in the rear rack together with the KAREN control unit. The Honeywell INS was connected to the front antenna until 22-03-2017, after which it was changed to the rear antenna. The iMAR was connected to the rear GPS antenna during the entire phase 1.

The setup of the instruments in the aircraft is shown in Figure 3 and pictures of the various instruments are shown in Figure 4-7.

Table 3: The dx, dy and dz offsets for the lever arm from the GPS antennas to the origin of the laser scanner, the back centre of the ASIRAS antenna (see arrow Figure 3), and the KAREN reference point.

To laser scanner	dx (m)	dy (m)	dz (m)
from front GPS antenna	- 3.60	+ 0.49	+ 1.58
from rear GPS antenna	+ 0.10	- 0.38	+ 1.42
to ASIRAS antenna	dx (m)	dy (m)	dz (m)
from front GPS antenna	-3.37	+0.47	+2.005
from rear GPS antenna	+0.33	-0.40	+1.845

Figure 3: Overview of instrument setup in the TF-POF Twin Otter aircraft

Figure 4: Bottom view of the Norlandair Twin-Otter TF-POF showing KAREN and ASIRAS antennas.

Figure 5: View of cabin in aircraft; Left picture: Rack with Ka-band altimeter (front right), rack for ALS, GPS and INS (rear left). Right picture: iMAR strap-down INS, grey box attached to the floor (lower right).

Figure 6: The mount-plate seen from above. The ALS is seen in the lower part of the image just below the Ka-band RF module. The EGI is seen in the upper left corner.

Figure 7: Detail of the KAREN sensor: the new patch antennas allow for a compact installation. Part of the ALS is seen below the KAREN sensor as a bluish window.

3.2 Phase 2

The hardware installation in the BAS Twin Otter (VP-FAZ) consisted of the following instruments:

- MetaSensing Ka-band radar altimeter KAREN
- BAS Airborne Laser Scanner (ALS) of the type Riegl LMS Q-240i-80
- 1-2 geodetic dual-frequency GPS receivers of type Javad delta (AIR1-2)
- An Inertial navigation system (INS) of the type Honeywell H-764G
- An Inertial navigation system (INS) of the type OxTS xNav 550 (backup)
- A NovaTel integrated GPS-INS system of type SPAN-CPT to support KAREN (backup)
- BAS Radiometer. Eppley PIR and PSP sensors fitted to the roof and underside of the aircraft
- BAS infra-red thermometer. Heimann model KT19.82 mounted in the floor hatch panel
- BAS Nadir looking DSLR Camera (Canon EOS 7D)

The ALS setup is similar to the setup in the same aircraft during EU ICE-ARC/ESA FinExp campaign in 2015 (Hvidegaard et al., 2017). All instruments were mounted in the camera hatch located below the floor in the cabin (Figure 8-10), except for the Honeywell INS, which were mounted on the floor below the operator seat in the cabin (Figure 8).

Camera Hatch Antenna (F):

- AIR1 Javad Delta
- AIR3 Javad Delta, mounted before flight 13-04-2017

The instruments were mounted in the aircraft and tested in Calgary before the departure for the phase 2 campaign. The lever arms from GPS antenna to KAREN and ALS reference points are given in Table 4, and the hardware installation can be seen in Figure 8-11.

Table 4: The dx, dy and dz offsets for the lever arm from the GPS antenna to the origin of the laser scanner and the KAREN reference point.

To laser scanner	dx (m)	dy (m)	dz (m)
from Camera Bay GPS antenna (F)	+ 0.27	+ 0.05	+ 1.55
To KAREN reference point	dx (m)	dy (m)	dz (m)
From Camera Bay GPS antenna (F)	+0.16	+0.12	+1.68

ICE-ARC 2017 Layout VP-FAZ

Figure 8: Overview of instrument setup in the VP-FAZ Twin Otter aircraft

Figure 9: Instrument installation in the camera bay below the floor in the Twin Otter cabin; ALS (left), OxTS INS (middle right) and Trimble GPS receiver (lower right). Note ALS and OxTS INS axis are mounted along aircraft centre line. Installation: Forward to left. Aircraft right is at the top.

Figure 10: Bottom view of the BAS Twin-Otter VP-FAZ showing KAREN, ALS together with radiometers and camera.

Figure 11: Rack setup in BAS Twin Otter VP-FAZ. All instruments are fitted in one rack see image on the left from below; KAREN altimeter, power unit, rack PC to support Honeywell INS, and another power unit. Control PC's are shown in right image from below; ALS (left), camera (right), KAREN, Honeywell INS.

4 Overview of acquired data

Data from the various instruments were acquired where feasible, considering the limited range of the ALS system and the weather. An overview of all acquired data is listed in Table 5 and 6.

The sampling frequency of the KAREN sensor was set to 25 MHz corresponding to one sampling each ~30cm on the ground. The high sampling frequency results in a large amount of 360 GB of raw data per hour, plus a few MB of navigation data (dedicated GPS/IMU module). Acquisitions have been manually started and stopped by the operator according to the area which was flown; data sets of typically ~10 minutes or ~20 minutes duration have been logged. At the end of the campaign the raw data amount is ~11.4 TB (7 TB phase 1 and 4.4 TB phase 2). Due to the large amount of data, and limited backup possibilities during phase 2, some less prioritized flights have not been logged. During the flight and at the end of each acquisition day a quick data look was performed on randomly selected dataset to assess the quality and eventually adjusting the Pulse Repetition Frequency (PRF) according to the flight altitude.

Due to mal-function of PC2, all ASIRAS data were acquired in Low Altitude Mode (LAM) with low along-track resolution (LAMa). This allows flight at an altitude of 300 m, which is within the operational range of the ALS system and a relative low data volume of about 28 GB per hour. A total of 1.19 TB raw ASIRAS data were collected during phase 1 of the CryoVEx/ICE-ARC 2017 campaign. The data were stored on hard discs as ASIRAS level 0 raw data in the modified compressed format (Cullen, 2010).

In general, the ALS worked well. A total inspection of the instrument was performed at Riegl prior to the campaign, including dry out, re-flush of nitrogen, and re-ceiling to try to minimize the problems with moisture on the instrument window, which have been a problem in recent CryoVEx campaigns in cold conditions (-25°C and below). This seems to have improved the instruments capabilities, and no loss of data was observed during phase 1 due to moisture on the instrument window. During all flights in phase 1 the last pulse option was used, to avoid internal reflections of the aircraft fuselage due to the limited space. During phase 2, the more protected setup of the instrument in the camera bay never caused any problems with moisture at cold temperatures. The data volume obtained by the ALS is about 250-300 MB per hour, which is a relative small amount, when compared to the ASIRAS data volume. During the campaign a total of 32.8 GB (18.3 GB phase 1 and 14.5 GB phase 2) ALS data was acquired.

The airborne GPS units logged data internally in the receivers during flight, which were downloaded upon landing on laptop PCs. The GPS reference stations listed in Tables 5 and 6 are described in further detail in Section 5.1. During phase 1 some problems occurred with the Honeywell INS during the first part of the campaign (until 23-03-2017), which was solved by changing the antenna constellation, see Section 3.1. However, coincident data were obtained with the iMAR system leaving no gaps in the data set. The Honeywell performed well during phase 2, except the flight on April 18 (DOY 108), where the PC froze, and new files had to be started twice during the survey, leaving few minute gaps in the data set.

Due to limited space in the instrument bay, during phase 1, it was not an option to add a camera. As an alternative a camera was mounted on a rear window in the cabin using a Fat Gecko camera mount, to take slant looking images out of the window. These images were only acquired for sea ice flights. In phase 2 a high-resolution nadir-looking DSLR camera was installed. This camera took pictures during all sea ice flights, however, during the flights on April 13 and 16, the screen on the laptop supporting the camera did not work. A personal laptop was used to store the images, but due to the large amount of data, the images had to be transferred to an external HDD leaving some gaps in the data. For a more detailed description of images, see Section 5.8.

Table 5: Data acquisition overview, phase 1

Date	DOY	AIR1	AIR2	AIR3	AIR4	EGI	IMAR	ALS	ASIRAS	KAREN	GPS REF	Canon	Comments
18-03-2017	077	X	X	X	X	X	X	X	-	-	-	-	Test flight Problems with ASIRAS PC2
19-03-2017	078a	X	X ¹	X ¹	X	X	X ¹	X	LAMa ²	-	-	-	
19-03-2017	078b	X	X	X	X	X	X ³	X	LAMa	X	-	-	
20-03-2017	079a	X	X	X	X	X	X	X	LAMa	-	STN	X ⁴	
20-03-2017	079b	X	X	X	X	X	X ¹	X	LAMa	-	STN	X ⁴	
21-03-2017	080a	X	X	X	X	X	X	X	LAMa	X	STN	X ⁴	
21-03-2017	080b	X	X	X	X	X	X	X	LAMa	X	STN	X ⁴	
22-03-2017	081	X	-	-	X	X ⁵	-	X	LAMa	X	-	X	
24-03-2017	083	X	X	X	X	X	X ⁶	X	LAMa	X	YLT	X	
27-03-2017	086	X	X	X	X	X	X	X	LAMa	X	YLT	X	
28-03-2017	087	X	X	X	X	X	X	X	LAMa	X	-	X	
29-03-2017	088	X	X	X	X	X	X	X ⁷	LAMa	X	-	X ⁸	
30-03-2017	089A	X	X	X	X	X	X	X	X	X	-	X	
30-03-2017	089B	X	X	X	X	X	X	X	X		-	X	
31-03-2017	090A	X	X	X	X	X	X ⁹	X	X	X	JQA	X	
31-03-2017	090B	X	X	X	X	X	X ⁹	X	X	X	JQA	X	
01-04-2017	091A	X	X	X	X	X	X	X	X	X	-	-	

1) Started late

2) ASIRAS data only for calibration over runway CNP

3) Stopped 2.5 hours before landing

4) Partly coverage

5) Problems with GPS antenna cable. File size correct but no GPS signal so position not ok

6) Likely only small data gap

7) Not logging 15:54-16:35

8) Gap due to low battery 14:02-14:20

9) Not logging, full memory?

Table 6: Data acquisition overview, phase 2

Date	DOY	AIR1	AIR3	EGI H-764G	INS OxTS	ALS	KAREN	GPS REF	DSLR	Up	Down	SNIR	Log	Remarks
05-04-2017	95	-	-	-	X ⁶	X	X	-	X	X	X			
07-04-2017	97A		-	X	X ⁶	X	X	YCB	X	X	X		X	
07-04-2017	97B	X	-	X ¹⁺²	X	X	X	YCB	X	X	X		X	
08-04-2017	98	X	-	X ¹	X ⁶	X	X	YCB	X	X	X		X	
11-04-2017	101	X	-	X	X	X	X	-	X	X	X		X	
12-04-2017	102A	X	-	X	X	X	X	-	X	X	X		X	
12-04-2017	102B	X	-	X	X	-	-	-	X	X	X		X	
13-04-2017	103	X	X	X	X ⁶	X ³	X	YLT	X ⁴	X	X		X	
16-04-2017	106	X	X	X	X ⁶	X	X	YLT	X ⁴	X	X		X	
18-04-2017	108		X	X ⁵	X	X	X	YLT	X	X	X		X	
19-04-2017	109	-	-	-	-	-	-	-	-	X	X	-	X	
20-04-2017	110A	X	X	X	X	X	-	-	-	X	X	-	X	
20-04-2017	110B	X	X	X	X	X	-	-	X	X	X		X	
21-04-2017	111	X	X	X	X ⁶	X	-	-	-	X	X		X	
24-04-2017	114A	X	X	X	X	X	-	-	-	X	X		X	
24-04-2017	114B	X	X	X	X	X	X	-	X	X	X		X	
25-04-2017	115	X	X	X	X	X	X	LYR	-	X	X		X	Austfonna
26-04-2017	116	-	X	X	X	X	X	LYR	-	X	X		X	Austfonna

- 1) Not writing data after midnight to readegi.coo, but looks ok. PC dating issue 2003
- 2) In DASIN(dx) or ASIN(dx) or DACOS(dx) or ACOS(dx), DABS(dx).gt.1.0 (dx=-0.1683593620398824d+01). Error occurs at or near line 239 of _MAIN__
- 3) Wrong header format
- 4) Run on HSK personal laptop, some gaps due to data download
- 5) Four different files with various gaps in between. Main survey site only one gap
- 6) Something wrong with the OxTS xNav INS data. File size OK, but states in software it was not initialized properly

5 Processing

The data processing is shared between MetaSensing (MS), the Alfred Wegener Institute (AWI) and DTU Space. Both KAREN and ASIRAS data are processed using GPS and INS data supplied by DTU Space to ensure a consistent baseline, which is possible as all the instruments are flown on the same platform. GPS differential positioning and combined INS-GPS integration is performed at DTU Space followed by processing of laser distance measurement into elevation above a reference ellipsoid. The KAREN data is primarily processed by MS with input and expert knowledge from AWI. The ASIRAS data was processed by AWI using standard procedures.

The final data files are divided between the ESA CryoVEx and EU ICE-ARC projects. Links to the data is as follows:

- **CryoVEx flights (March 18-April 1 and April 12-26) can be requested at the ESA portal:**
<https://earth.esa.int/web/guest/campaigns>
- **ICE-ARC flights (April 5-11) can be downloaded through:**
<https://www.ice-arc.eu/data/>

5.1 GPS data processing

The exact position of the aircraft is found from kinematic solutions of the GPS data obtained by the GPS receivers installed in the aircraft, see Chapter 3. Two methods can be used for post-processing of GPS data, differential (DIF) processing and precise point positioning (PPP). Whereas the first method uses information from reference stations in the processing procedure, the PPP method is only based on precise information of satellite clock and orbit errors.

A Javad Maxor Receiver (REF1) with internal antenna and logging rate 1 Hz were used as temporary base station. The base station was mounted on DTU Space small tripods (vertical height 12 cm). However, the reference points were generally not marked, and thus the reference stations were not placed at the exact same position for the different flights, and a reference point has to be calculated for each flight. Permanent GPS reference stations have been used at some occasions where the base station is close to the flight route. This is the case for Scoresby Sund, Danmarkshavn, Station Nord, Thule AB, and Kelyville (Kangerlussuaq).

The positions of the temporary base stations are determined using the online GPS processing services AUSPOS (<http://www.ga.gov.au/earth-monitoring/geodesy/auspos-online-gps-processing-service.html>) offered by Geoscience Australia. The service calculates the position of the reference stations in the ITRF 2008 reference system using data from the closest permanent GPS stations with a position accuracy of about 2 cm. This accuracy is available even in the Arctic with long distances to the closest permanent stations. The coordinates of all the reference stations used during CryoVEx/ICE-ARC 2017 are found in Appendix 11.

The GPS processing was performed with Waypoint GrafNav (version 8.30 or 8.45) by use of precise IGS orbit and clock files and correction for ionospheric and tropospheric errors. For each flight several solutions are made using different combinations of GPS reference stations and aircraft receivers. The best solution for each flight is selected according to Table 7 and 8 and used in the further processing.

5.2 Inertial Navigation System

The position and attitude information (pitch, roll and heading) recovered from the INS instrument at 10 Hz, are merged with the GPS solutions by draping the INS derived positions onto the GPS solutions. The draping is done by modeling the function, found in the equation below, by a low pass smoothed correction curve, which is added to the INS.

$$\varepsilon(t) = P_{\text{GPS}}(t) - P_{\text{INS}}(t)$$

This way a smooth GPS-INS solution is obtained, which can be used for geolocation of laser and camera observations.

The selected INS solutions are listed in Table 7 and 8. As seen, most solutions are based on the primary Honeywell (H-764G) INS unit. Attitude information from the iMAR was used on flights March 19-21 during phase 1, due to issues with the GPS antenna setup supporting the Honeywell INS (see Section 4). The NovaTel was used as input for both GPS and INS solutions for flight on April 5, as this was the only instrument recording properly on this particular flight. Finally, attitudes obtained from OxTS Nav 550 were used in the processing of short sub-sections of the flight on April 18, due to gaps in the Honeywell data.

A comparison of the Honeywell and iMAR attitudes and scatterplots color-scaled according to time from flight March 28 is plotted in Figure 12 left and right, respectively. The Honeywell and iMAR aligns well, and show consistent high precision accuracy in all attitude components throughout the flight. This is consistent with a similar comparison during CryoVEx/KAREN 2016 presented in Skourup et al. (2018), supporting the conclusion that the iMAR solution is providing accuracy and precision similar to the Honeywell instrument.

A similar comparison of Honeywell and NovaTel attitudes in Skourup et al. (2018) showed that Honeywell and NovaTel roll angles compares well, except for a small off-set caused by the different installation configurations. However, both pitch and heading/yaw deviates by several degrees even at straight sections when compared to the Honeywell INS. Due to lack of data from Honeywell/OxTS and GPS units the flight on April 5 uses the NovaTel integrated GPS/INS solution as input. Only straight sections were used, corrected for offsets between solutions due to poor GPS absolute accuracy, see Section 5.3.

A prior version the OxTS Nav 550, the Inertial+2, has degraded accuracy during acceleration, which includes turns and rapid changes of altitude (Skourup et al., 2012). This could be the case also for the

OxTS Nav 550, however, as this unit was only used to patch in very short straight sub-sections of the flight on April 18, it is not expected to decrease the accuracy of this particular flight.

The best solutions of both GPS and INS data based on Table 7 and 8, is packed as binary files in the special ESA file format, see Cullen (2010). An overview of the final GPS and INS files is listed in Appendix 17 and 18 with file name convention according to Appendix 16.

Figure 12: Inter-comparison of attitudes obtained by the Honewell (H-764G) and iMAR (RQH) INS. Flight out of CFS Alert April 28, 2017.

Table 7 List of best combination of GPS and INS data, phase 1

Date	DOY	GPS rover	Reference GPS	GPS processing	INS
18-03-2017	77	AIR2	-	PPP	H-764G
					H-764G
					H-764G
19-03-2017	78A + 78B	AIR4	SCOR	DIF	iMAR
20-03-2017	79A	AIR4	DMH	DIF	iMAR
20-03-2017	79B	AIR4	STN	DIF	iMAR
21-03-2017	80A	AIR4	REF1	DIF	iMAR
21-03-2017	80B	AIR4	REF1	DIF	iMAR
22-03-2017	81	AIR1	-	PPP	H-764G
					H-764G
					H-764G
24-03-2017	83	AIR4	REF1	DIF	H-764G
27-03-2017	86	AIR4	REF1	DIF	H-764G
28-03-2017	87	AIR4	THU2	DIF	H-764G
29-03-2017	88	AIR4	THU2	DIF	H-764G
30-03-2017	89A	AIR4	THU2	DIF	H-764G
30-03-2017	89B	No measurements			No measurements
31-03-2017	90A	AIR4	KELY	DIF	H-764G
31-03-2017	90B	AIR4	KELY	DIF	H-764G
					H-764G
01-04-2017	91A	AIR4	KELY	DIF	H-764G
					H-764G

Table 8 List of best combination of GPS and INS data, phase 2

Date	DOY	GPS rover	REF GPS	GPS pro.	INS
05-04-2017	95	NovaTel	-	PPP	NovaTel
07-04-2017	97A	AIR1	YCB1	DIF	H-764G
07-04-2017	97B	AIR1	YCB1	DIF	H-764G
08-04-2017	98	AIR1	YCB1	DIF	H-764G
11-04-2017	101	AIR1	-	PPP	H-764G
12-04-2017	102a	AIR1	-	PPP	H-764G
12-04-2017	102b	AIR1	-	PPP	H-764G
13-04-2017	103	AIR1	-	PPP	H-764G
16-04-2017	106	AIR3	YLT1	DIF	H-764G
18-04-2017	108	AIR3	YLT1	DIF	H-764G
		AIR3	YLT1	DIF	H-764G/OxTS
		AIR3	YLT1	DIF	H-764G
19-04-2017	109a	AIR1	-	PPP	H-764G
19-04-2017	109b	AIR1	-	PPP	No measurements
20-04-2017	110a	AIR3	-	PPP	H-764G
20-04-2017	110b	AIR1	-	PPP	H-764G
21-04-2017	111	AIR3	-	PPP	H-764G
24-04-2017	114a	AIR3	-	PPP	H-764G
24-04-2017	114b	AIR3	-	PPP	H-764G
25-04-2017	115	AIR1	LYR1	DIF	H-764G
26-04-2017	116	AIR3	LYR1	DIF	H-764G

5.3 Airborne Laser Scanner (ALS)

Both laser scanners are basically of the same type, using rotating mirrors, which results in parallel scan lines on the surface. The basic difference is that the LMS Q-240i-60 has 4 rotating mirrors each with a maximum scan-angle of 60°, where the LMS Q-240i-80 has only 3 mirrors each with a scan-angle of 80°. This results in a larger swath width with a lower resolution for the 3 mirror ALS. Both scanners operate with wavelength 904 nm, which is expected to reflect on the air-snow surface. The vertical accuracy is in the order of 10 cm depending primarily on uncertainties in the kinematic GPS-solutions. Further specifications of the two laser scanners are provided in Table 9. The raw logged files with start /stop times are listed in Appendix 12 and 13.

Table 9: Specifications of the two types of Riegl laser scanners

Scanner	Operating wavelength (nm)	Max scan angle	Resolution (m)	Swath-width (m)	PRF (Hz)	Number of measurements per scan-line
Riegl LMS-Q240i-60	904	60°	0.7x0.7	300m	10,000	251
Riegl LMS-Q240i-80	904	80°	1.0x1.0	400m	10,000	250

5.3.1 Calibration

Calibration of ALS misalignment angles between ALS and INS can be estimated from successive overflights from different directions of the same building, where the position of the corners is known with high precision from GPS measurements. For this purpose, building overflights were performed in:

Phase 1:

- 20-03-2017 DOY 79 Station Nord
- 28-03-2017 DOY 87 CFS Alert

Phase 2:

- 13-04-2017 DOY 103 CFS Alert
- 25-04-2017 DOY 115 Longyearbyen

The ALS data has been routinely processed and the calibration angles for each flight based on the calibration flights together with inspection of cross-overs and overflights of relative flat surfaces can be found in Appendix 12-13 and Sections 5.3.3. An example of ALS elevations from overflight of the calibration building at Station Nord is given in Figure 13.

Figure 13: ALS elevations (w.r.t. WGS-84) of the calibration building (Ebbes Koldhal) at Station Nord.

5.3.2 Laser scanner outlier detection and removal

After an extensive service of the DTU Riegl ALS by the manufacturer (see Section 4) no issues were encountered with the neither the DTU nor the BAS instrument. Due to the tight installation of the instruments during Phase 1 multiple reflections from aircraft fuselage showed up as outliers in the ALS data. These outliers were filtered out in the final data set. The removal of outliers and clouds were done for both campaign phases by manual inspection of all data files using a python program (SkyFilt.py) with an option to automatically remove data points closer than a selected range (typically 50m) to the aircraft, by using input from processed GPS-heights and/or removal of a selected range window about the vertical elevation.

5.3.3 Cross-over Statistics

As a part of the processing routine, crossover statistics are derived for all repeated overflight within an hour of the first overflight. The quality of these crossover statistics varies depending on surface type, incidence angle and level of processing. In general statistics over sea ice is poor due to the drift of sea ice between inter-sections. The statistics based on raw scanner data after outlier editing are summarized in Table 10 and 11, and examples of cross-over differences over Devon ice cap and terrestrial flight near Cambridge Bay are given in Figure 14 and 15, respectively. The mean elevation differences in the cross-over points are less than 6 cm, and typically represent errors in the GPS solutions. The standard deviation of the cross-over differences is 6-10 cm over flat surfaces. These values are within the expected ranges and reflect data of high quality.

Table 10: Cross-over statistics, phase 1. Highlighted cross-overs are example provided in Figure 14.

Date	DOY	X-over	# points	Mean (m)	Std. Dev. (m)	Min. (m)	Max (m)	Notes
20170320		X0	24920	0.05	0.49	-0.54	0.23	Sea ice Fram Strait
		X1	40280	0.02	0.66	-3.72	4.16	Sea ice Fram Strait
20170321		X0	27688	0.04	0.24	-1.25	1.72	Sea ice, triangle
		X1	33683	0.02	0.39	-4.1	3.75	Sea ice, triangle
20170327		X0	10328	-0.05	0.35	-2.39	2.65	Sea ice, north of Alert
20170328		X0	28866	-0.02	0.06	-0.36	0.37	Greenland Ice Sheet
20170329		X0	26121	-0.04	0.06	-0.43	0.37	Devon
20170331		X0	34494	-0.01	0.10	-1.1	0.83	Baffin Bay sea ice
		X1	30268	0.04	0.10	-0.39	1.68	Greenland Ice Sheet
20170401		X0	31084	0.00	0.10	-3.19	3.3	Greenland Ice Sheet
		X1	28562	-0.06	0.09	-3.41	3.13	Greenland Ice Sheet

Table 11: Cross-over statistics, phase 2. Highlighted cross-overs are example provided in Figure 15.

Date	DOY	X-over	# points	Mean (m)	Std. Dev. (m)	Min. (m)	Max (m)	Notes
20170405	095	X0		0.01	0.10	-0.53	0.55	Landfast sea ice
20170407	097	X7	54002	-0.06	0.09	-0.49	0.38	Land
		X12	57602	-0.04	0.09	-0.63	0.42	Land
		X27	59421	-0.01	0.07	-0.37	0.43	Land
		X66	62441	0.03	0.07	-0.33	0.37	Land
		X87	66523	0.06	0.07	-0.31	0.38	Land
20170408	098	X21	52153	0.02	0.06	-0.43	0.37	Land
		X43	51235	-0.06	0.07	-0.36	0.33	Land
		X82	54207	0.00	0.07	-0.39	0.29	Land
		X90	81803	-0.03	0.06	-0.38	0.30	Land
		X101	52010	0.05	0.06	-0.35	0.35	Land
		X141	82381	0.03	0.06	-0.30	0.44	Land
20170413		X8	52676	-0.01	0.70	-8.09	7.51	Building CFS Alert
20170416		X1	16193	-0.01	0.36	-2.91	3.0	Sea ice
		X6	18131	-0.01	0.28	-2.33	2.59	Sea ice
20170418		X0	14534	0.01	0.24	-1.97	1.88	Sea ice
		X3	16078	-0.02	0.19	-1.21	1.73	Sea ice
		X15	16589	0.01	0.28	-2.56	2.13	Sea ice
20170426	116	X0	35633	0.03	0.09	-0.42	0.42	Austfonna

5.3.4 Final processed data

Processed ALS data comes as geo-located point clouds, in lines of width 200-300m at full resolution (1mx1m), in format time, latitude, longitude, heights given with respect to WGS-84 reference ellipsoid, amplitude and sequential number of data point per scan line (1-251). The dedicated

CryoVEx flights are packed in netcdf4 format, whereas the dedicated ICE-ARC flights are packed in DTU Space binary data format. An overview of the processed data is given in Figure 16 together with Appendix 19.

First flight in Cambridge Bay (April 5) was processed using the NovaTel GPS/INS solution (Table 8). As solutions using this unit (Section 5.2) are drifting during turns each of the 7 parallel lines have different roll offsets and different elevation offsets for each line as provided in Table 12. The elevation offsets have been estimated at 69.18°N in an area with level ice and the different lines have been adjusted to match line 3, hereafter referred to as “the reference ground track”. The elevation offsets are within 9 cm of the reference ground track. Cross-over statistics of this flight is within the expected accuracy. Only straight sections (lines 1 to 7) are delivered with the elevation offsets applied, thus it is important to add similar elevation biases to KAREN elevation when compared to ALS data.

Table 12: Offsets applied to sub-tracks taken with respect to reference ground track (line 3) on flight April 5, 2017

Sub-track ID	Start time (UTC)	End time (UTC)	Roll offset	Elevation offset
1	21.561604	21.844099	-0.12	0.09
2	21.919705	22.149399	-0.12	0.01
3	22.180901	22.432500	-0.14	0.00
4	22.494907	22.714000	-0.16	-0.09
5	22.822203	23.027102	-0.16	-0.06
6	23.097902	23.318799	-0.14	0.02
7	23.374002	23.576295	-0.14	-0.08

Figure 14: Location of cross-over point at Devon ice cap (left), ALS cross-over elevation differences (middle and right) from flight March 29, 2017.

Figure 15: Location of cross-over point over land near Cambridge Bay (left), ALS cross-over elevation differences (middle and right) from flight April 8, 2017.

Figure 16: Mission overview of the processed ALS data. All recorded heights are given as geo-located point-clouds with respect to the WGS-84 reference ellipsoid.

5.4 ASIRAS

The ASIRAS radar operates at 13.5 GHz with footprint size 10 m across-track and 3 m along-track at a standard flight height of 300 m. The range resolution for ASIRAS is 0.1098m. ASIRAS specifications are provided in Table 13. An overview of the acquired ASIRAS log-files together with start/stop times, range window and number of pulses are listed in Appendix 14.

5.4.1 Processing

The ASIRAS processing of the raw (level 0) data files is analogous to the concepts already presented in Helm et al. (2006), using ESA's processor version ASIRAS_04_03. The processed ASIRAS data is delivered as a level-1b product in the ESA binary format as described in Cullen (2010). The product includes full waveform information, and an estimate of the retracked height w.r.t. WGS-84 reference ellipsoid using a simple Offset Center of Gravity (OCOG) retracker, together with information about aircraft attitude.

The OCOG retracker was developed to give a quick and rough estimate of surface elevation and not to be as precise as possible. It may not be the optimal retracker in areas with several layers in the snow/firn, e.g. the percolation zone on ice sheets, see e.g. Helm et al. (2006) and Stenseng et al. (2007), and it is up to the user of the data to apply different retracker algorithms depending on the application. Roll angles are given as part of the attitude information, as it is common to remove roll angles above/below a certain threshold ($\pm 1.5^\circ$) due to waveform blurring.

To get absolute heights, it is crucial for the user to perform a runway calibration to estimate an off-set due to internal loss in the radar system and to apply the off-set to all retracked data. As the off-set is dependent on the choice of retracker the runway calibration shall be performed using the same retracker as used for the scientific application. To validate the ASIRAS data quality an example of the runway calibration using a simple OCOG retracker is given in Section 5.6.

5.4.2 Final processed data

The final processed ASIRAS level-1b data is delivered in the special ESA format as defined in Cullen (2010). A list of final level-1b files is available in Appendix 22 and a summary of the processing is given in Appendix 23 together with plots of each profile.

Table 13: Specifications of ASIRAS and KAREN at 300m flight altitude above the surface

Instrument	Frequency (GHz)	Footprint size		Range resolution (m)
		Along-track (m)	Across-track (m)	
ASIRAS	13.5	3	10	0.1098
KAREN	34.525	5	12	0.1650

5.5 KAREN

The KAREN airborne instrument is an interferometric frequency modulated continuous wave (FMCW) SAR altimeter working at the Ka-band with central frequency of 34.525 GHz. The sensor operates with FMCW radar modulation in interferometric mode (SARIn), with one transmitting antenna and two receiving antennas. These are patch antennas, as opposed to the CryoVEx/KAREN 2016 fall campaign where horn antennas were used. Radiation characteristics of the new patch antennas include a gain of 22 dB and a 3dB aperture of 15° x 4.6° (along track and cross track). The processed multi-looked data corresponds to an along- and across-track footprint size of 5 m (100 looks) and 12 m, respectively. The vertical resolution is 0.1650 m. KAREN specifics are provided in Table 13. An overview of the acquired data is provided in Appendix 15. The name of each file represents the date and starting time of the acquisition. For each acquisition the file size and some additional notes are given, such as duration of acquisition, altitude of the aircraft during the acquisition and area of interest.

5.5.1 Processing

There have been several iterations of the processing, as described below:

vvvv	First version with hann window combining both channels (June 2018)
hamh	Changed the Hann by the Hamming window ($\alpha=0.54$) (August 2018)
leva	The RF antenna position has been corrected, measured lever arms have been introduced w.r.t. IMU reference point (November 2018)
levb	A bug in the processing has been corrected, which was causing sudden jumps in longitude values in the “leva” version (December 2018)
levc	Doppler filtering improvement preventing high side-lobes contribution in the slant-range direction (December 2019)

The final version “levc” processing chain is similar to ASIRAS in High Altitude Mode (HAM) and introduces several steps going from the raw data format (level-0) to the final delivered data format (level 1B), including range compression (FFT and Hamming filtering), zero-Doppler filtering, ground-back projection (GBP), and multi-looking. For a more detailed description see the “KAREN altimeter - Processing chain and file format” documentation (MS-DTU-KAR-03-PFF-032). During the processing chain each KAREN data point is geo-located using input from best solutions of GPS and INS data provided by DTU units according to Table 7 and 8, and corrected for lever-arms between GPS antenna and KAREN reference points provided in Table 3 and 4 for respective campaign phases. All examples in this report are based on version “levc”, unless otherwise stated.

Several plots generated in-flight during acquisitions for quick-data analysis purposes are shown in Figure 17-21. A detailed example of Range Doppler map is shown in Figure 17, processed from data acquired during the 1st of April 2017 with in situ Twin Otter aircraft visible in Range Doppler map about (360m, -40km/h), Figure 18 and 19. In Figure 20 an iceberg is shown in the Range-Doppler maps of the two channels, and relative interferometric phase. The corresponding range compressed image is shown in Figure 21.

To get absolute heights, as in the case for ASIRAS (see Section 5.4.1) it is crucial for the user to perform a runway calibration to estimate an off-set due to internal loss in the radar system and to apply the estimated off-set to all retracked data. As the offset is dependent on the choice of retracker the runway calibration shall be performed using the same retracker as used for the specific scientific application. To validate the performance and quality of the KAREN data an example of the runway calibration using a simple OCOG retracker is given in Section 5.6. The user should also be aware of waveform blurring for large roll-angles. For ASIRAS data with roll angles below -1.5° and above a $+1.5^\circ$ is discarded. These thresholds are used for KAREN runway calibration in Section 5.6, but another threshold might apply to KAREN.

5.5.2 Final packed data

The final data is packed in netcdf format and includes position and attitude of each measurement, full waveform information, as well as phase and coherence from the use of dual antennas in the interferometric mode. The retracking is left to the user, as the choice of retracker depends on user requirements. An overview of the final data is provided in Appendix 21.

Figure 17: Plots generated during flight for quick check: data acquired on the 2nd of March 2017.

Figure 18: Example of Range-Doppler map from data acquired on April 1, 2017.

Figure 19: Picture of validation team at the EGIG-line acquired during flight on April 1, 2017.

Figure 20: RD maps for the 2 channels and interferometric phase of data acquired on March 30, 2017.

Figure 21: Example of a Range compressed image acquired on March 30, 2017, see Figure 20.

5.6 Calibration and absolute heights of ASIRAS and KAREN

To obtain absolute surface heights from ASIRAS and KAREN an offset need to be applied to account for internal delays in cables and electronics, see Sections 5.4.1 and 5.5.1. As the offset is dependent on the choice of retracker it has not been applied in the final Level 1b processing. The offset is estimated by comparing ASIRAS and KAREN surface heights to surface heights obtained by ALS over a surface, where both the radar and the laser are known to reflect at the same surface. Such measurements are typically obtained by overflights of runways. Different biases apply for the different aircraft installations, see Section 3.

The runway overflights performed during CryoVEx/ICE-ARC 2017 campaign is listed below:

Phase 1:

- 19-03-2017 DOY 78 Constable Point
- 28-03-2017 DOY 87 CFS Alert
- 31-03-2017 DOY 90 Qaarsut

Phase 2:

- 08-04-2017 DOY 98 Cambridge Bay
- 13-04-2017 DOY 103 CFS Alert
- 25-04-2017 DOY 115 Longyearbyen

The data from the runway overflights are available in the delivered data set.

In the following we compare ALS surface elevations with OCOG retracked elevations from ASIRAS and KAREN. All radar elevations with roll angles below/above $-1.5/1.5$, has been discarded due to waveform blurring. For each ASIRAS and KAREN elevation we use a search radius of 3m and 5m, for ASIRAS and KAREN, respectively, corresponding to 4-5 ALS elevations to account for the extent of the footprint size of the radar systems. The ALS elevations within the search radii are averaged and subtracted from the radar elevation. A total mean is given for each runway overflight representing the off-set provided in Tables 14-16. In addition, standard deviation and percentage of accepted points due to the limits on roll are also provided.

In phase 1 runway overflights in Qaarsut (JQA) and CFS Alert (YLT) have offsets within 3 cm for ASIRAS and 1 cm for KAREN, both with low standard deviation within the range of 5-9 cm. The best estimate of offsets during phase 1 is from March 31 first overflight in Qaarsut (JQA) using the OCOG (TRMFA 50%) retracker is 3.64 m (3.83 m) for ASIRAS and 0.04 m (0.05 m) for KAREN (marked by red in Table 14 and 15). This overflight was selected as the best runway overflight as both radar and ALS elevations are coincident in time. In phase 2 the variations between different runway overflights are much larger, when compared to phase 1. The best estimated offset for OCOG (TRMFA 50%) retracked KAREN is -0.03 m (-0.03 m) both with standard deviation 0.05 m based on first runway overflight in CFS Alert (YLT) on April 13 (marked by red in Table 16). These off-sets have to be applied to all OCOG (TRMFA 50%) retracked ASIRAS and KAREN elevations prior to any analysis using absolute heights.

The first runway overflight on March 31 is visualized in Figure 22 and 23. The along-track comparison of the ALS surface elevations (blue) and the ASIRAS OCOG retracked elevations (red) is shown in Figure 22 top left, together with aircraft roll-angles (black) and pitch (gray) in lower left. The statistical distribution of the differences between the ALS elevations and KAREN and ASIRAS are shown in the histogram (top right). As seen in Tables 14-16, the offsets depend on the chosen retracker, however, less dependent for KAREN.

In this section, the offset between the ASIRAS and ALS surface heights are found, using the OCOG and TRMFA 50% retracked surface elevations. Similar procedures have to be applied by the user of the ASIRAS and KAREN data when using other retrackers.

Table 14: ASIRAS offsets (ALS-ASIRAS) over runways, phase 1

Profile	Site	Overflight ASIRAS/ALS	Start time UTC	End time UTC	# points	OCOG		TRMFA 50%		Roll (%)
						Off- set (m)	Std (m)	Off-set (m)	Std (m)	
A20170319_01	CNP	1/comp	41141	41153	370	4.49	0.96	4.55	1.02	81
A20170328_00	YLT	2/2	-	-	-	-	-	-	-	0
A20170328_00	YLT	3/2	51109	51119	303	3.65	0.09	3.85	0.09	61
A20170331_02	JQA	1/1	61489	61495	218	3.64	0.06	3.83	0.05	47
A20170331_02	JQA	2/1	61721	61731	281	3.62	0.05	3.83	0.05	64

Table 15: KAREN levcoffsets (ALS-KAREN) over runways, phase 1

Profile	Site	Overflight KAREN/ALS	Start time	End time	# points	OCOG		TRMFA 50%		Roll (%)
						Off- set (m)	Std (m)	Off-set (m)	Std (m)	
KA20170319_112530	CNP	1/comp	41141	41153	165	0.46	0.80	0.46	1.06	81
KA20170328_140607	YLT	2/2	-	-	-	-	-	-	-	0
KA20170328_141101	YLT	3/2	51109	51120	131	0.05	0.08	0.05	0.08	61
KA20170331_170431	JQA	1/1	61489	61496	95	0.04	0.07	0.05	0.07	46
KA20170331_170802	JQA	2/1	61721	61731	128	0.04	0.06	0.05	0.06	64

Table 16: KAREN levcoffsets (ALS-KAREN) over runways, phase 2

Profile	Site	Overflight KAREN/ALS	Start time	End time	# points	OCOG		TRMFA 50%		Roll (%)
						Off- set (m)	Std (m)	Off-set (m)	Std (m)	
KA20170409_013236	YCB	1/1	5963	5987	258	-0.04	0.09	-0.03	0.09	80
KA20170413_190833	YLT	1/1	69167	69187	264	-0.03	0.05	-0.03	0.05	100
KA20170413_192741	YLT	2/1	70250	70277	200	0.01	0.03	0.02	0.03	59
KA20170425_115656	LYR	1/2	43170	43207	187	0.05	0.07	0.05	0.07	39
KA20170425_115656	LYR	2/2	43415	43450	309	-0.08	0.07	-0.07	0.07	70

Figure 22: ALS elevations model (w.r.t WGS-84) of runway in Qaarsut, March 31, overlaid with ASIRAS ground track (red) and ASIRAS ground track with roll angles below/above -1.5/1.5

Figure 23: Comparison of ALS, KAREN and ASIRAS elevations over runway in Qaarsut, March 31, 2017 (1st overflight). ALS (blue), KAREN (red) and ASIRAS (green) elevations (top left). Differences between ALS-KAREN (red) and ALS-ASIRAS (green) are shown with related histograms of ALS-ASIRAS (top right) and ALS-KAREN (bottom right). The gray areas mark parts of the flight where data has been discarded due to large roll.

5.7 Horizontal alignment between ASIRAS and KAREN

In order to compare results from ASIRAS and KAREN it is important that the two systems are aligned. The locations of the ASIRAS and the KAREN data are referred to their own reference points. ASIRAS reference point is centered at the aft of the ASIRAS antenna, whereas KAREN reference point is located at the center point between the receiving (aft) antennas. The differences between the ASIRAS and KAREN reference points for the different phases are:

Phase 1 (OY-POF): $dx=+0.34\text{m}$, $dy=+0.00\text{m}$, $dz=+0.185\text{m}$

Phase 2 (VP-FAZ): $dx=+0.98\text{m}$, $dy=+0.07\text{m}$, $dz=+0.240\text{m}$

taken with respect to the aircraft coordinate system as outlined in Figure 3.

In previous CryoVEx campaigns corner reflectors have acted as point targets. If the exact positions of these are known, the radar data can be time-tagged and thus aligned in the along-track direction. Small metal plates placed directly on the snow are in general difficult to locate in the radar waveforms and the locations are not known. The location of the corner reflectors located at Devon ice cap was known with high precision (see Table 17), but these were covered in snow (see Figure 24), and by first look, it has been impossible to identify reflections from these in the processed radar data.

Figure 24: Photo of corner reflector at Devon ice cap covered in snow by courtesy: D. Burgess, Natural Resources Canada

Table 17: Location of corner reflectors at Devon ice cap (Courtesy: D. Burgess, Natural Resources Canada)

<u>CR</u>	<u>Lat</u>	<u>Lon</u>	<u>Ell Ant Height(m)</u>	<u>AntH eight Error(m)</u>	<u>Ant Vert Offset (Ant- TopEdge m)</u>	<u>TopEdgeRe fl</u>	<u>BottApex OffsetfromTopEd ge</u>	<u>BottApex</u>	<u>BottApexToSnowSurf ace</u>	<u>Snow Surface (m)</u>
East	75° 20' 16.82268''	-82° 40' 39.55078''	1796.875	0.002	0.56	1796.315	0.72	1795.595	-0.44	1796.035
Mid	75° 20' 17.5192''	-82° 40' 41.5086''	1796.949	0.012	0.21	1796.739	0.64	1796.099	-0.34	1796.439
West	75° 20' 18.3772''	-82° 40' 43.91433''	1797.048	0.002	0.27	1796.778	0.69	1796.088	-0.47	1796.558

5.8 Camera

To complement the analysis of KAREN, ASIRAS and ALS data over sea ice high resolution images are collected along the flights. During phase 1 slant looking images were obtained using a camera of type Canon 60D. The camera was mounted in the rear window in the cabin using a Fat Gecko camera mount. To optimize the contrast of the images, the camera was mounted either in starboard or port side of the aircraft depending on the sun angle. During phase 2 a nadir-looking high resolution DSLR camera was used. An overview of the properties of the cameras is given in Table 18 and examples are shown in Figure 25-26. Both cameras were remotely controlled and time tagged using the internal camera clock. By combining the time tag of the images with GPS data the images have been geo-located along the flight lines. Positions of each image are given in a position file, and the raw images are packed in zip-files of about 2 MB (see overview Appendix 20).

Table 18: Overview of camera types and settings.

Camera type	View	Interval (sec)	Resolution (pixels)	Image size (MB)	Software program	Format
Canon 60D	Slant-looking	12	2592x1728	~0.5	DSLR Remote Pro 232	JPEG
Canon EOS 7D	Nadir-looking	5	5184x3456	~27	EOS Utility	RAW

Figure 25: Examples of slant-looking image (0031) taking during phase 1 on flight March 24, 2017.

Figure 26: Examples of nadir-looking camera during phase 2. It is mounted with the wide image dimension in the along-track direction permitting overlapping images even at a relative low acquisition rate of 0.2 Hz

6 Calibration and Validation sites

During the CryoVEx/KAREN 2017 campaign, several radar altimeter ground tracks were flown, including several CryoSat-2 orbits, Sentinel-3A and for the first time SARAL/AltiKa. Some of these were coordinated with in situ work. All airborne and coordinated in situ data acquisitions along CryoSat-2, Sentinel-3 and SARAL/AltiKa ground tracks are listed in Table 19, together with information of orbit numbers and passage times. Table 19 includes primarily sea ice flights, where timing is crucial due to the drift of the ice. No land ice flights were following near-real time satellite ground tracks, but crosses several CS-2, Sentinel-3 and SARAL/AltiKa ground tracks. In the following Sections the main calibration and validation sites are provided, together with first results, over sea ice (section 6.1), land ice (section 6.2) and land (section 6.3).

6.1 Sea Ice

In total, five CryoSat-2, two SARAL/AltiKa and two Sentinel-3 underflights were performed over sea ice (Figure 1 and Table 19) in different regions representing different sea ice types and conditions.

For satellite underflights timing is crucial especially over drifting sea ice. This was challenging due to limited opening hours of the airports. To account for the ice drift between data acquisition of flights and CryoSat-2 passages, most of the tracks were measured twice. In addition, information of the sea ice conditions and drift was kindly prepared during the field campaign from repeated SAR images from Sentinel 1a and 1b and distributed to the involved field teams by R. Saldo (DTU Space). An example of a Sentinel-1 SAR image covering the Fram Strait, together with drift information and satellite orbit ground tracks from SARAL/AltiKa kindly provided by A. Guillot (CNES) can be seen in Figure 27. Such information provides invaluable information to the field team. None or the less, most flights are flown within few hours of satellite passage time see Table 19.

In the following Subsections the flights are described in more details. This yields in particular the work made out of CFS Alert (Section 6.1.1) with focus on the comparison of airborne measurements and in situ observations (Section 6.1.2 and 6.1.3). An overview of the first underflights of SARAL/AltiKa and description of coincident in situ work out of CamBay SnowExp 2017 (Section 6.1.4), and Sentinel-3A (Section 6.1.5). Additional work, including CryoSat-2 ALS swath-flight, overflight of shear zone, and additional data sources is provided in Section 6.1.6.

Table 19: Overview of airborne data acquisitions along CryoSat-2, Sentinel-3 and SARAL/AltiKa ground tracks, together with information of orbit numbers, passage time, and data acquisition.

Sea ice	Land ice	Location	Airborne Activity	Satellite	Orbit #	passage Date and time (Time given as hh:mm UTC)	ASIRAS	KAREN	ALS	AWI-AEM	NASA OIB	NASA GLISTIN	In Situ
X		Fram Strait	20-03-2017	SARAL/AltiKa ¹	387 cycle 107	20-03-2017 02:25	X	X	X				
X		Wandel Sea	21-03-2017	CryoSat-2	36847	21-03-2017 14:15	X	X	X				
X		Lincoln Sea	24-03-2017	CryoSat-2	36892	24-03-2017 16:40	X	X	X				
X		Lincoln Sea	27-03-2017	CryoSat-2	36936	27-03-2017 17:27	X	X	X	X	X	X	X ²
X		Lincoln Sea	27-03-2017	CryoSat-2	37159	12-04-2017 02:11	X	X	X				X ²
X		Baffin Bay	29-03-2017	Sentinel-3A		29-03-2017 17:47	X	X	X				
X		Baffin Bay	31-03-2017	SARAL/AltiKa	709 cycle 107	31-03-2017 08:21	X	X	X				
X ³		Dease Strait	05-04-2017	SARAL/AltiKa	846 cycle 107	05-04-2017 02:33		X	X				X
X		Lincoln Sea	13-04-2017	CryoSat-2	37159	12-04-2017 02:11		X	X		X ⁴		X
X		Lincoln Sea (MOW)	16-04-2017	CryoSat-2	37225	16-04-2017 15:23		X	X				
X		Lincoln Sea	16-04-2017	CryoSat-2	36892	24-03-2017 16:40		X	X				X
X		Fram Strait	24-04-2017	Sentinel-3A		24-04-2017 18:09		X	X				

1) Not following the exact SARAL/AltiKa track, but covering a large easy to re-track sea ice floe ...

2) In situ work in phase 2

3) Partly sea ice and partly snow on land

4) Flown on April 11, 2017

Figure 27: Example of Sentinel-1 SAR image and drift vectors (yellow and cyan) in Fram Strait together with SARAL/AltiKa ground tracks (March 20-22).

6.1.1 Sea ice flights Lincoln Sea

An overview of the flights in the Lincoln Sea using CFS Alert as base is provided in Figure 28, and details of the flights along the NE and NW lines are provided in Table 20 and 21.

As part of the CryoVEx campaign, the Alfred Wegener Institute (AWI) Bassler aircraft (Polar-5) towing an electromagnetic sounder (AEM), was based in CFS Alert for the March 24th flight (NE-line in Figure 28) and NASA's Operation IceBridge P-3 aircraft equipped with multiple sensors for sea ice and snow retrievals was located in Thule AB. Thus, coincident flights along CryoSat-2 ground track #36892 in the Lincoln Sea were coordinated to supplement the CryoVEx airborne sensors (KAREN, ASIRAS and ALS) with a variety of sea ice measurements. As the AWI AEM measures the draft of the sea ice, a comparison to KAREN, ASIRAS and the ALS is very important for the freeboard to thickness conversion. The snow radar (2 to 8 GHz) onboard NASA P-3 is valuable for snow depth estimates to support the potential of measuring snow depth directly with the dual-frequency setup, i.e. KAREN - ASIRAS. As an opportunity a fourth aircraft (DFRC Gulfstream (G-III)) carrying NASA JPL wide-swath topographic mapper (GLISTN) joined the team, and for the first time in CryoVEx campaigns four aircrafts were coordinated along the same flight track.

Coincident flights with AWI Polar-5 and DTU Space Twin Otter are straightforward as the aircrafts fly at the same survey speed of approx. 110 knots at different elevations, e.g. 50m and 300m agl. Thus, the aircrafts are able to align on the same track at the same speed only a few minutes apart, which ensures overlapping data acquisition in areas of drifting sea ice. Such formation flights were performed for the first time during CryoVEx 2011, and have been repeated in 2012, 2014 and now 2017. Due to the higher speeds of the P-3 and G-III, they were on top of the Twin Otter and DC-3 at two interception points, one on the outbound and one on the inbound tracks. Part of the line was surveyed during Phase 2 on April 16, together with observations made by the in situ team at two sites.

Figure 28: Overview of flights out of CFS Alert (left). Blue flight tracks were flown in phase 1 and red flight tracks in phase 2. Green wide tracks represent relevant CryoSat-2 ground orbits, and yellow stars all the sites visited by the in situ team. Modal thickness from the in situ sites (right) from Haas et al. (2017).

Table 20: Overview of campaign activities following the NW-line in the Lincoln Sea

NW-line

March 27	CryoVEx phase 1 (ALS, ASIRAS, KAREN)
April 11-18	In situ measurements
April 11	NASA Operation IceBridge (ATM, snow depth radar)
April 12	CryoSat-2 orbit # 37159 02:11 UTC
April 13	CryoVEx Phase 2 flight (ALS, KAREN)

Table 21: Overview of campaign activities following the NW-line in the Lincoln Sea

NE-line

March 24	CS2 orbit # 36892 CryoVEx phase 1 (ALS, ASIRAS, KAREN) AWI Polar-5 (EM sounder) NASA OIB (ATM, snow depth radar) NASA JPL GLISTIN (Topographic interferometer (ka))
April 11-18	In situ measurements
April 16	CryoVEx phase 2 (ALS, KAREN)

6.1.2 In situ work Lincoln Sea

To get large scale in situ measurements the ground team landed approximately 30 nm apart along selected CS2 orbits between Ellesmere Island and 87.1°N. The in situ team managed to visit in total 12 sites (10 on the NW line CS-2 orbit #37159 and 2 on the NE line CS2 orbit #36892) marked by stars in Figure 28 between April 11-18.

Unfortunately, the BAS Twin Otter was delayed out of Cambridge Bay due to weather, and did not arrive in CFS Alert until the evening of April 12, thus missing the opportunity for a coincident flight with OIB and match of CS2 orbit #37159. The NW-line was surveyed by OIB on April 11th and by the BAS Twin Otter with the KAREN radar and ALS on April 13. The blue line was partly surveyed by the Twin Otter (ASIRAS, KAREN and ALS) in phase 1 on March 27. The NE-line following CS2 orbit #36892 was surveyed during phase 1 by 4 aircrafts on March 24th (blue line) and partly re-flown in phase 2 by the BAS Twin Otter on April 16 (red line).

Detailed description of the in situ work, together with summaries of the data gathered (supplementary material Table S1) has been reported in Haas et al. (2018). Below is given a short summary and first results comparing in situ and airborne measurements of snow depth.

As reported in Haas et al. (2018) the in situ team measured the sea ice thickness from ground EM providing the total sea ice thickness (snow depth + sea ice thickness) along 1.7-5.0 km transects. Coincident observations of snow depth using magnaprobe were measured along the same transects, however, the length of these were usually shorter (0.1-2.5 km) due to the slower progress and limited time on ground (1-2hrs) at each in situ site. Snow pits were also obtained at each site, but are not reported here.

The in situ measurements of modal sea ice thickness are shown in Figure 28 (right). The thickest and roughest ice types are found in the south with mean varying between 2.5-3.8 and the thinnest ice types of mean <2 m in the north. The shear zone is the transition zone between the stationary ice (ice bridge) to the south and the drifting sea ice to the north. The in situ measurements of snow depth show no trend, but some variability between measurements with mean ranging between 30-47 cm (see next Section and Figure 29).

6.1.3 First results of dual-frequency snow depth from KAREN and ASIRAS

First results of inter-comparison of airborne and in situ measurements of snow depth were presented at Polar2018 DAVOS, AGU fall meeting 2018 Washington DC and most recent at ESA LPS19 in Milan. Mean (●) and mode (▲) of the in situ snow depth along the transect at each in situ site are provided in Haas et al. (2017), and plotted in Figure 29, where error bars represent the standard deviation of measurements along each transect.

Figure 29: Overview of flights out of CFS Alert (left). Blue flight tracks were flown in phase 1 and red flight tracks in phase 2. Green

Airborne data has been averaged along a 10 km section centered at the location of the in situ site provided in Haas et al. (2017). The mean snow depth obtained by OIB snow radar on April 11 (● Figure 29) tends to underestimate the snow depth when compared to the in situ observations at these scales (10km). However, the OIB data is obtained from the quicklook product, which tends to underestimate the snow depth when compared to the final product, which at the time of writing is not yet available.

In case of a perfect scenario elevation differences of KAREN-ASIRAS should potentially provide information about the snow depth. To see whether this is the case, airborne ASIRAS and KAREN “levb” data from flight March 27 (phase 1) has been retracked using a simple 50% threshold first-maximum retracker algorithm (TFMRA) first described by Helm et al. (2014) with suppression of

noise on the leading edge of the waveform. Plotted elevation differences (○) in Figure 29 between KAREN and ASIRAS result in about half of the mean snow depth obtained by the in situ observations. The elevation differences between KAREN and ASIRAS were obtained on March 27 during phase 1, which is 15 to 22 days before the in situ and OIB measurements of snow depth, thus new snow fall and/or redistribution of snow in an occurrence of a storm between measurements will affect the results. Unfortunately, it is not possible for to use the flight in phase 2, which was much better timed with the in situ measurements (-2 to 5 days), for dual-frequency snow depth measurements, as ASIRAS was not carried along during phase 2 due to logistic challenges between campaign phases. However, the combined KAREN and ALS for both phase 1 and 2 can be used to test penetration and optimization of re-trackers, as ALS both provides reference for the snow surface and also provide estimate of roughness for the scales provided here.

For comparison the most used Arctic wide snow depth climatology provided by Warren et al. (1999) has been plotted in Figure 29 from March (◇) and April (◆). These, show good agreement with the in situ data for this location and year, as also concluded in Haas et al. (2017). The variation of snow depth from Warren et al. (1999) between March and April is only few cm and not half of the snow depth as found by the dual-frequency elevations. However, one should bear in mind that there can be local and inter-annual variations from the snow depth climatology provided by Warren et al. (1999), see also Section 6.1.6.

Thus, there is still much more to learn using these combined data sets. First of all, the reduced propagation speed of light through the snow cover on sea ice floes needs to be applied to the ASIRAS retracked elevations. To a first approximation the corrected freeboard is given by $f_c = f_i + 0.25 * h_{\text{snow}}$, the correction is 9 cm which would reduce the dual-frequency snow depth even further. In addition, optimization of retrackers for KAREN and ASIRAS is crucial to learn more about penetration depths, and retrackers dependencies on roughness.

6.1.4 SARAL/AltiKa underflights

During the CryoVEx campaign SARAL/AltiKa was underflown for the first time over sea ice. Due to the lower orbit turn-around latitudes (81.5°N) compared to CryoSat-2 (88.0°N) the flights were located in Baffin Bay on March 31 (Figure 30) and Cambridge Bay on April 5 (Figure 31) following SARAL/AltiKa ground orbit #709 and #846, respectively. A planned underflight of SARAL/AltiKa ground track orbit #387 on March 20 in Fram Strait (Figure 1) was not possible to underfly real time due to time constraints. Due to the large drift rates in Fram Strait 13-18 km/day (see Figure 27) it is not favorable to follow the satellite ground track more than 12 hours after the satellite passage time, which was the case. Thus, an alternative track was selected to overfly a large ice floe south of the satellite ground track, identified in the SAR-images provided to the field team prior to flight. This was large ice floe should be easy to be identified in both the airborne and satellite observations during the post-processing.

All the SARAL/AltiKa flight tracks were from cycle 107. A successful alignment of airborne flight tracks and satellite ground track were not possible without collaboration with CNES providing orbit information directly to the field team few days prior to the flight, as SARAL/AltiKa has been in a drifting orbit since July 4, 2016.

Figure 30: Flight tracks (left) and along-track elevations (right) of first direct underflight of SARAL/AltiKa on March 31. ALS is marked with blue and SARAL/AltiKa with green. The elevations of SARAL/AltiKa have not been corrected for any geophysical corrections, explaining the about 1m difference between SARAL/AltiKa and ALS elevations. Passage time of SARAL/AltiKa during underflight is marked with red star.

Cambridge Bay SnowExp

The CamBay SnowExp 2017 took place in the vicinity of Cambridge Bay, Canadian Arctic, in the period March 31 – April 8 as part of the EU project ICE-ARC. Cambridge Bay provides easy access to the fast ice and the in situ measurements give information of snow penetration both over sea ice and land. The flight on April 5, 2017, was carried out coincident to SARAL/AltiKa satellite pass, and followed up on the overpass with a ground campaign and an under-flight on the same day.

The sea ice in Dease Strait outside Cambridge Bay consists primarily of stationary fast-ice. The airborne and satellite measurements do not provide measurements of sea ice thickness over fast ice due to the lack of open water leads acting as reference for the local sea surface height, but has the advantages of zero net sea ice drift. The combined airborne (KAREN and ALS), satellite (SARAL/AltiKa) and in situ observations of snow conditions, provide information of Ka-band penetration in different snow conditions.

The flight plan for the underflight consisted of 5 parallel flight lines spanning Dease Strait (~40km each), and a 6th calibration line diagonal across the 5 parallel lines. The parallel flight lines were spaced 200m apart, and thus should all be within SARAL/AltiKa ground track which has been suggested as being 1.4 km wide (across track). The middle line (line 3) was directly coincident to the estimated AltiKa ground track. Given the importance of line 3 it was flown twice. The flight lines (red lines) and SARAL/AltiKa ground track (green dots) can be seen in Figure 31. The northern extent of the under-flight lines contained land, to coincide with terrestrial snow sampling activities, whereas the southern extent contained sea ice to coincide with snow sampling activities over sea ice. The respective land and sea ice in situ sites along SARAL/AltiKa are marked with stars in Figure 31.

To investigate the penetration of the airborne Ka-band, radar reflectors (aluminium plates) were placed on the top of the snow pack. The sea ice team laid out four radar reflector lines perpendicular to the AltiKa ground track (flight line 3), and each radar reflector line was separated by 100 m. Analysis of the snow thickness data (over sea ice) obtained by this team revealed that the horizontal

length scale associated with the snow depth was about 75 m, and therefore by placing the radar reflectors 100 m apart we ensured that each site was statistically different. Each line was 40 m in length (across track), with reflectors spaced approximately 4 m apart along each line. Bin liners were used as markers for the airborne team and placed at each end of the lines. A similar setup, but with only 3 reflector lines, were laid out at the land in situ site. Given the potential difference in snow conductivity between sea ice snow and land snow this should give some interesting results.

The sea ice ground team laid out a ground survey line parallel to flight line 3 but off-set in the across-track direction by 20 m. The 20 m offset was to minimize contamination of the snow seem by the airborne Ka band radar as it flew down line 3. The area sampled was smooth first-year sea ice characteristic of the area and very likely the entire extent of Dease Strait covered by AltiKa and the aircraft. It was situated about 4 km off shore in Dease Strait, accessible by snowmobile from Cambridge Bay. Snow pits were conducted every 100 m along the ground survey line. Snow temperature, density, conductivity, was measured at 2 cm intervals. Snow structure, hardness, and grain size was recorded by layer. Ice thickness and freeboard adjacent to the snow pit was measured twice. In addition, a 20 by 20 m snow thickness grid was set-up around each snow pit. Snow thickness and GPS coordinate was measured at 1m spacing in the grid using a snow magnaprobe. A total of 5 snow pits and 20 by 20 snow depth grids were obtained on the survey day April 5. The terrestrial team preformed a similar snow survey.

The site was revisited the following days. On April 6 a snow depth transect 1.5 km long with 1 m spacing was done along the in situ line, beginning at the first radar reflector line and extending appx. northward towards shore. Two more snow pits, ice thickness measurements, and 20 by 20 snow depth grids (this time 5m spacing) were done. On April 7 the two deep snow pits were excavated since the team felt that, after looking at the snow depth distribution data, the deeper snow cover hadn't been properly sampled. Two, 2 km long, snow thickness transects with 100 m sampling intervals were taken along the AltiKa line, beginning at the first radar reflector line and extending approx. 2.75 km northward to the shore. The two lines were spaced 100 m apart in the a-long track direction.

Figure 31: Overview of sea ice flight April 5 out of CFS Alert (top left), elevations of SARAL/AltiKa (bottom left), and final processed ALS elevations (right).

6.1.5 Sentinel-3A under flights

First underflights of Sentinel-3A were performed during ESA CryoVEx 2016 spring campaign in the Fram Strait. Preliminary results were presented by Skourup et al. (2017). This was followed by two direct underflights during CryoVEx 2017 one on March 29, 2017, in Nares Strait and Hells gate on the route to Devon ice cap and one additional flight on April 24, 2017, in Fram Strait on April 24, 2017. An overview of Sentinel-3A underflights of both CryoVEx 2017 and CryoVEx 2016 spring campaign is provided in Figure 32.

Figure 32: Sentinel-3A flights in Nares Strait (left) and Fram Strait (right). Flight track March 29 2017 (Light blue), April 24 2017 (dark blue), April 6 2016 (red) and April 10 2016 (orange). Sentinel-3 satellites mark passage points of the satellite during the flight.

6.1.6 Supporting sea ice flights

CryoSat-2 airborne array

As part of the ESA CryoVal Sea Ice project, it was concluded that direct comparison of CryoSat-2 and airborne data averaged to the CryoSat-2 SAR footprint size ($\sim 300\text{m} \times 1,600\text{m}$) did not have any or very low correlation, most likely due to the limited across-track coverage of the airborne data. Thus, direct comparison is not possible. However, as shown by Haas et al. (2016) the correlation improved by averaging both data sets along 50 km sections.

As a proof of concept a swath approach similar to CryoVEx 2016 spring campaign over Austfonna ice cap was flown over sea ice along CS-2 orbit #37225 on April 16. Five parallel lines along 50 km sections were flown to map 167 along-track CS-2 footprints covering the full width of the CS2 across-track footprint size to test whether it is possible to better resemble the area average of each CryoSat-2 footprint, e.g. represented by single waveforms (see Figure 34). The area was correlated in space and time with CS-2 passage (Table 19) in an area with open leads.

Figure 33: Illustration of resampling of airborne data onto CryoSat footprints (left) Figure 4 in Baker et al. (2016). All airborne data (red dots) within a CryoSat footprint (red rectangle) are averaged and projected onto the CryoSat nadir location in the center of the footprint shown by a black dot. ALS elevations w.r.t. WGS84 of full swath of parallel lines from flight on April 16.

Shearzone and icebridge

The flight on April 18 included crossing of the transition zone between the stationary ice and the drifting sea ice also known as the shear zone (Figure 35). This was combined with overflight of the polynya formed next to the ice bridge in the north-eastern part of the Nares Strait outside CFS Alert (Figure 35). The polynya was partly covered by open water with low fog and areas with new ice. The measurements were assisted by airborne radiometer and infrared thermometer, which has the potential to provide new information of polynyas. The ice bridge finally collapsed mid-May.

Figure 34: SAR image from the Nares Strait area (left) with photos of shear zone (top right) and polynya next to the icebridge (bottom right).

Triangle flight and transit flights

The triangle flight flown out of Station Nord (Figure 1) on March 21, has been monitored routinely since 1998, and comprises a unique time-series in an area feeding into the largest sea ice freshwater outflow of the Arctic, the Fram Strait, see also Skourup et al. (2018b). Whenever possible transit flights were used to acquire additional data, e.g. the Canadian channels where the distribution of sea ice types is of interest.

L-band SAR

The Japanese Aerospace Exploration Agency (JAXA) kindly acquired L-band SAR images in the areas surveyed, which provide different information in e.g. sea ice classification as compared to, commonly used C-band SAR from Sentinel-1A/B, see e.g. Singha et al. (2018).

6.2 Land ice

The primary flights during CryoVEx/ICE-ARC 2017 airborne campaign were the flights over the EGIG line with coincident in situ measurements. An overview and first comparisons of the airborne and in situ observations are provided in Section 6.2.1. Over the land ice no direct underflights along satellite ground tracks are provided, however, crossings of the ice sheet e.g. the EGIG-line and north

Greenland, provides cross-overs of all altimeter missions including CryoSat-2, Sentinel-3 and SARAL/AltiKa. Dedicated flights at Austfonna and Devon, are described in Section 6.2.2 and 6.2.3, respectively.

6.2.1 EGIG line

The CryoVEx 2017 airborne campaign was aimed at the EGIG-line to document the different glacial facies along this well studied line of way-points. Six sites (T5, T9, T12, T19, T30 and T41) were visited by the in situ team see Figure 36 and Table 23 during the field campaign supported by ski-equipped Twin Otter from Norlandair.

Figure 35: Overflight of the ground team. The metal plates placed on the ground above the tail of the helicopter is acting as surface indicators in the radar return signal.

The information listed below provides a general schedule for the land ice field campaign:

Wednesday, March 29	ADB and SSIM CPH to AEY
Thursday, March 30	Flight AEY-CNP-T41-T5-JAV Visit the sites T41, where snow core was drilled along with density measurements in pit. At T5 only a snow core was drilled.
Friday, March 31	Flight JAV-T19-T12-T9-JAV
Saturday, April 1	Flight JAV-T30-JAV
Sunday, April 2	ADB and SSIM return to CPH.

Five in situ measurements were collected during the land ice campaign. This consisted of GPS measurements of the site location, a shallow firn core, a snow pit of the top 30 cm of snow that could not be cored, pRES radar measurements, and metal reflectors for the airborne overflight.

Table 22: Overview of CryoVEx 2017 EGIG site locations.

Site	Base station start (UTC)	Base Station stop (UTC)	Processing	Latitude [deg. N]	Longitude [deg. W]	Altitude above ellipsoid [m]	Orthometric elevation ¹ [m]
T5	18:18	19:05	Maxtor	69 51.13787	47 15.32759	1937.09	1902.20
T9	17:13	17:50	Maxtor	70 01.19598	46 18.37317	2145.39	2108.47
T12	15:12	16:00	Maxtor	70 10.56013	45 20.65050	2346.93	2308.32
T19	12:44	??:??	Maxtor	70 28.20306	43 33.80099	2659.24	2618.93
T30	10:39	??:??	Maxtor	70 51.00095	40 30.00328	3014.08	2970.15
T41	14:49	15:59	Maxtor	71 04.72094	37 55.18671	3014.08	3153.61

Due to time constraints at each site, and the necessity of each measurement, not all experiments were conducted at each site. For example, at some sites the ice core could be collected directly from the surface of the snow due to the presence of a wind crust, therefore negating the need for a snow pit. Equally if the airborne team were not scheduled to overfly the site while the ground team was at a site they did not put out the metal surface reflectors. Table 24 below provides an overview of which measurements collected at each site.

Table 23: Overview of acquired data at the T-sites

Date	Site	GPS	Core	Radar	Pit	Overflight reflectors
March 30th	T41	X	X	-	X	-
March 30th	T5	X	X	-	-	-
March 31st	T19	X	X	X	X	X
March 31st	T12	X	X	X	-	-
March 31st	T9	X	X	X	-	-
April 1st	T30	X	X	X	-	X

The pRES in situ radar data was collected using an agilent network analyzer operated from a thermally insulated box, with antennas that can acquire data in the Ku-Band part of the electromagnetic spectrum. The kinematic pRES equipment set up inside the twin otter plane, with the antenna boom pointing out of the side door, mounted 1 m above the snow surface, over fresh snow that was not disturbed by the twin otters ski footprint. 10 static measurements were collected over the same patch of clean snow, and these 10 shots were then averaged to form one mean profile, dampening out any noise in the data. A second set of 10 shots were collected after a metal plate was placed on the snow surface in order to create a highly reflective surface that could be used to calibrate the snow surface. These 10 shots were also averaged into one mean profile.

¹ Geoid16

We extracted measurements acquired by the ASIRAS airborne sensor at each of the three radar sites examined, T9, T12 and T19. In addition to the measurement acquired closest to the ground campaign sites, we took five measurements from either side of this point to create a mean profile for the field site. Both the airborne and in situ radar profiles were converted to depth using the speed of light (c) and the bandwidth of the sensor (1 GHz for ASIRAS, 15.9GHz for the pRES). The resulting vertical resolution of each sensor is 7.965 cm for ASIRAS and 0.68 cm for the pRES. The following plots (Figures 37, 38, and 39) show the depth vs power profiles for each field site for both the pRES and ASIRAS radars, where higher power returns indicate the presence of an expected layer in the snow pack.

Figure 36: pRES (left) and ASIRAS (right) mean power to depth profiles for site T9 on the EGIG line, Greenland.

Figure 37: pRES (left) and ASIRAS (right) mean power to depth profiles for site T12 on the EGIG line, Greenland.

Figure 38: pRES (left) and ASIRAS (right) mean power to depth profiles for site T19 on the EGIG line, Greenland.

Figure 37 shows the pRES and ASIRAS depth to power profile from site T9 on the EGIG line on the Greenland ice sheet. The snow surface is clearly picked out by a high power return in the pRES data when a metal plate is placed on the snow surface (red line). In the profile obtained on clean snow, without a metal plate on the snow surface (blue line) we can see that the highest power return comes from approximately 1 meter below the snow surface, with no obvious peaks (layers) in the snowpack below it. This result is similar to the one we obtained from the mean depth to power profile in ASIRAS data acquired at the same site, where a single broad return is seen in the depth profile, with the peak at approximately 0.5 to 1 meter below the surface. At site T12 (Figure 38), we again see the strongest returns from two layers located within the top 1 to 2 meters of the snow pack. These peaks are present in both ASIRAS and pRES data. In the pRES data from site T12 we also see a broad high power peak approximately 6 meters below the snow surface, however this snow layer is not visible in the ASIRAS data. This may suggest that at site T12 on the EGIG line that ASIRAS data does not penetrate this deep into the snowpack. In the dry snow zone at site T19 on the EGIG line (Figure 39), we see multiple layers in both the ASIRAS and pRES data. There are two very strong peaks seen at the snow surface and then at 1 meter depth in both the ASIRAS and pRES data, followed by three lower power peaks located between 2 and 4 meters depth. An extremely strong power return, almost equivalent in amplitude to the first two surface and sub-surface peaks, at approximately 5 meters depth. It is likely that this peak is the same one seen at 6 meters depth in the pRES data from site T12, which may suggest that at site T19 on the EGIG line volume scattering from up to 6 meters depth should be expected. This is in line with theory that suggests more volume scattering should be expected in the dry snow zone.

When we show the ASIRAS data along the whole EGIG line in a depth vs distance plot, with the power of each waveform indicated by the colour scale, we can see how the stratigraphic layers seen in the ASIRAS power to depth profiles vary across the Greenland Ice Sheet (Figure 40 top). The layers are not so clearly visible at low elevation sites at the margin of the Greenland Ice Sheet, as in the ablation zone ice cores show that there is now layering, only solid ice present (Figure 40 bottom). From site T12 onwards, by looking at the waveforms along the EGIG line, layers in the snowpack can be identified as the radar signal penetrates in the snowpack and is backscattered when a change in

density is encountered. The strongest return comes from the surface but several weaker reflections below the surface can also be seen in the dry snow zone. The stratigraphy of the snowpack is varying across the profile. Near the margins of the ice sheet, barely any layer can be distinguished whereas further inland, several highly reflective layers can be identified with these different layers corresponding to annual accumulation periods (Hawley et al., 2006; de la Peña et al, 2010). Assuming that the different internal layers each corresponds to an annual accumulation layer, we can clearly identify at T41 the different accumulation layers until 2012. Furthermore, it can be noted that the 2012 layer is highly reflective compared to the following, more recent layers and could correspond to the extreme melt event of 2012.

Figure 39: ASIRAS waveforms over the EGIG line (top) and Firn cores collected during the CryoVEx campaign and density profile from the RACMO model (bottom).

We compared a density profile from RACMO (Regional Atmospheric Climate Model) with the 9 firn cores collected during the CryoVEX campaign (Figure 40 bottom). There is a good agreement between the firn cores and the modelled densities. The density decreases along the profile as we move further from the margins where the surface density is almost at the density of ice. At T12, a very dense layer can be seen in the firn core at a depth of 1.5 m and at a similar depth of 1.7 m a dense layer is also found in the modelled density.

To investigate how these snow properties affects the elevations measured by the Ka- and Ku-band sensors, KAREN and ASIRAS respectively, we looked at the difference between KAREN “levb” and ASIRAS airborne data over a section of the EGIG line of 2 km located between T19 and T30 in central Greenland (Figure 41). We retrack the waveforms using a TFMRA (Threshold First-Maximum Retracking Algorithm) using a 50 % threshold and calculate the corresponding calibration offsets to get the absolute heights. Across this section of the EGIG line, the difference between KAREN “levb” and ASIRAS data is stable with a mean difference of -0.84 cm and an associated standard deviation of 7.9 cm.

Figure 41: Re-tracked surface elevations along a section of the EGIG line from Ka (blue line) and Ku-band (pink line) airborne data. Calibration offsets from runway overflights have been applied (3.63 m for ASIRAS and 0.16 m for KAREN). Also shown is the surface elevation measured by the ALS laser altimeter (green line) also onboard the same flight. Right shows the elevation difference between the Ka and Ku-band sensors. The gap in the data is due to roll angles exceeding $\pm 1.5^\circ$.

6.2.2 Austfonna

The Austfonna ice cap (Figure 42) was flown on April 25-26. A similar approach was used as in Sørensen et al. (2018) based on flights from the CryoVEx 2016 spring campaign to form a dense grid of parallel lines centered around CryoSat-2 orbit #31971 from April 19, 2016. Spacing between parallel lines was 2 km apart. Unfortunately, the south-eastern part of the survey area was covered in low clouds and resulted in a shortening of the flight lines. On the inbound flight on April 25 the flight surveyed the ice divide, following plans of the in situ team (NPI/University of Oslo) working on the ice cap.

Figure 40: Overflight of Austfonna ice cap April 25 and 26.

6.2.3 Devon

Devon ice cap was overflown on March 29, repeating flight lines of previous CryoVEx campaigns. The flight was not coordinated with in situ work, but the flight lines were crossing corner reflectors left from 2016. These could potential act to check the time tagging of the radar data, but this was difficult to see the reflections from the corner reflectors in the waveform data, as these were covered with snow, see also Section 5.7.

6.3 Land

To support validation of a new high-resolution NASA digital elevation model (DEM), a very tight flight pattern of parallel lines was flown over land in Cambridge Bay on April 7 and 8 (Figure 43, upper plot). Statistics at ALS cross-over points are within the expected accuracy with biases less than 6 cm and standard deviation less than 9 cm (Table 11).

During the survey, GPS ground control points were collected on April 7 by the ground team along a flight track marked by yellow stars in Figure 43 (upper plot) and point A-F in Figure 43 (lower plot). Here point A and F are located at the same spot. The GPS control points have been geo-located accurately with static post-processing of the observations using NovaTel Waypoint 8.20 GrafNet software. The related statistics are found in Table 25 (column 1-8) and show sub 3 cm accuracy, except at point A due to unknown reasons.

A comparison of the ALS data and the ground control points show consistency within 10 cm (Table 25) both using nearest ALS point (column 9) and an average of the 9 nearest points (column 10). Note that point A/C show an offset of 18/19 (17/18) cm when compared to nearest neighbor (9 nearest neighbors) of ALS. As point A has the poorest solution this is expected. The increased difference in point C is currently unknown.

Table 24: GPS ground control points acquired in Cambridge Bay on April 7 and differences between statistic GPS ground control points using nearest ALS point (column 9) and an average of the 9 nearest ALS points (column 10).

Station ID	Latitude	Longitude	Height (WGS84)	Solution Type	std	rms	GPS Base-line	ALS-GPS	ALS-GPS 9
	Deg	Deg	m		mm	mm	km	m	M
A	69.1537187831	-104.898407602	-16.335	Bad	7.2	29.0	6.9	-0.18	-0.17
B	69.1524464008	-104.884377758	-13.971	Good	2.6	12.5	7.3	-0.06	-0.01
C	69.1515809089	-104.873061736	-10.813	Good	2.7	17.3	7.7	-0.19	-0.18
D	69.1505728308	-104.861349459	-10.886	Good	2.4	12.5	8.0	0.05	0.03
E	69.1497204036	-104.851798620	-4.463	Good	2.4	15.2	8.3	0.02	0.05
F	69.1537180464	-104.898412341	-16.114	Good	2.1	15.2	6.9	0.05	0.08
REF	69.1217085444	-105.046288608	-20.070	Unprocessed

Figure 41: Flight tracks over catchment basin in Cambridge Bay April 7-8. Yellow stars (upper plot) represents collected GPS ground control points. Sub-plot of ALS elevations w.r.t. WGS84 along the GPS ground control points A-E (lower plot).

7 Conclusion

The CryoVEx/KAREN 2017 campaign has collected a unique data set along a total of five CryoSat-2, two Sentinel-3 and two dedicated SARAL/AltiKa ground tracks over sea ice in different location representing different sea ice types and settings. The flights were coordinated with extensive large scale in situ work both over sea ice north of CFS Alert and along the EGIG line on the Greenland Ice Sheet. Crossings of the Greenland ice sheet includes multiple crossovers of all altimeter missions including CryoSat-2, Sentinel-3A and SARAL/AltiKa. For the first time four aircrafts with a variety of instruments were coordinated to measure along a CryoSat-2 ground track over the sea ice out of CFS Alert. This also included the first successful dedicated underflight of SARAL/AltiKa coordinated with Cambridge Bay in situ snow experiment (CamBay SnowExp), despite challenges due to the satellite being in a drifting orbit.

First part of the campaign included dual-frequency airborne measurements using ESA's Ku-band radar (ASIRAS) and MetaSensing Ka-band radar (KAREN) together with high-resolution laser scanner measurements. Due to the limited time gap between the campaign phases it was impossible to transfer the ASIRAS radar from Iceland to Canada, and thus phase 2 did not include the ASIRAS radar. For future campaigns a combination of the two instruments are preferred.

The planned schedules were tight, especially during phase 1, leaving no room for delays. However, the weather was favorable and all planned flights were acquired. In general, the instruments performed well. During test of the ASIRAS radar PC2 was not working, thus data was only acquired in Low Altitude Mode (LAMA). It was a challenge to keep up with the KAREN data backup due to the high along-track sampling rate (~30cm on the ground) resulting in a huge amount of acquired data. Another challenge was to keep the temperature of the KAREN instrument below the maximum allowed limit, especially during phase 2, where the instrument was mounted near the heater in the aircraft. In future campaigns these issues should be taking into consideration.

During the project new processing software for the KAREN data has been developed supporting routine processing. The processing chain is similar to ASIRAS SARIn acquisition in High Altitude Mode, which provides multi-looked echoes at a slightly coarser range-resolution than ASIRAS. The ASIRAS and ALS instruments worked well, and post-processed ALS data show results with mean elevation differences less than 6 cm and standard deviation within 6-10cm over flat areas at cross-over points.

First results of KAREN and ASIRAS differences over sea ice show about half the snow depth when compared to large scale in situ measurements taken in the Lincoln Sea. This is however, based on a simple TRMFA 50% for both radars, and needs further evaluation. Published results of the in situ data show overall good agreement with snow depths obtained using Warren climatology for this particular period and location. Quicklook data of snow depth obtained with NASA Operation IceBridge snow radar show results between in situ and KAREN-ASIRAS.

Over the EGIG line the in situ firn cores show good correlation with RACMO firn density model. Based on pRES and ASIRAS data the upper annual layers can be identified in the dry snow zone T19 and beyond with expected volume scattering down to 6 m at T19. Comparisons of absolute retracked KAREN and ASIRAS data needs further investigation.

With the CryoVEx/KAREN 2017 airborne campaign data the scientific community now has a unique collection of dual-frequency airborne and coordinated in situ measurements to validate the radar altimeter satellites CryoSat-2, Sentinel-3A and SARAL/AltiKa. The results of this campaign will assist on-going calibration and validation activities and support decision-making of future dual frequency satellite missions.

8 References

- Borby-Nielsen, K. M., M. Jensen and M. O. Therkelsen (2018). Sea ice thickness in Fram Strait – measured from top and bottom. 30110 Introductory project - Earth and Space Physics and Engineering, Technical University of Denmark
- Cullen, R.: CryoVEx Airborne Data Products Description, Issue 2.6.1, ESA, Ref. CS-LI-ESA-GS-0371, 2010
- Forsström, S., Gerland, S., & Pedersen, C. A. (2011). Thickness and density of snow-covered sea ice and hydrostatic equilibrium assumption from in situ measurements in Fram Strait, the Barents Sea and the Svalbard coast. *Annals of Glaciology*, 52(57), 261–269.
<https://doi.org/10.3189/172756411795931598>
- Haas, C., Beckers, J., King, J., Silis, A., Stroeve, J., Wilkinson, J., Notenboom, B., Schweiger, A., & Hendricks, S. (2017). Ice and snow thickness variability and change in the high Arctic Ocean observed by in situ measurements. *Geophysical Research Letters*, Vol. 44, pp 10,462–10,469.
<https://doi.org/10.1002/2017GL075434>
- Haas, C., Hendricks, S., Ricker, R., King, J., Beckers, J., Skourup, H., et al. (2016). CryoVal-SI: CryoSat Sea Ice Product Validation using CryoVEx and IceBridge campaign data (Tech. Note 3: Assessment of different sources of uncertainty). ESA document CVSI-TN-WP3-3001
- Baker, S., J. Gaudelli, et al. (2016): CryoVal-SI: CryoSat Sea Ice Product Validation using CryoVEx and IceBridge campaign data (Tech. Note 7: Description of the CryoVal--Sea Ice Datasets). ESA document CVSI-TN-FMT-3002
- Hvidegaard, S. M., H. Skourup, J. Wilkinson, R. Ladkin, and R. Forsberg: ICE-ARC airborne campaign 2015 - Data collection and processing report, June 2017.
- Singha, S., N. Hughes, M. Johansson, S. M. Hvidegaard, and H. Skourup (2018): Arctic Sea Ice Characterization using Spaceborne fully polarimetric L-, C- and X-Band SAR with validation by airborne measurements. *IEEE Transactions on Geoscience and Remote Sensing*. Vol 56, No. 7, doi:10.1109/TGRS.2018.2809504
- Skourup, H., S. B. Simonsen, S. L. Sandberg Sørensen, R. Forsberg, and V. Helm (2018a): ESA CryoVEx 2016 spring campaign - Airborne field campaign with ASIRAS radar, and laser scanner measurements. Technical Report, National Space Institute (DTU Space), Technical University of Denmark, ISBN-978-87-91694-41-7
- Skourup, H., S. B. Simonsen, A. Coccia, and R. Forsberg (2018b): ESA CryoVEx/KAREN 2016 fall campaign – First airborne field campaign with combined Ku/Ka-band radars over the EGIG-line with coincident in situ measurements. Technical Report, National Space Institute (DTU Space), Technical University of Denmark
- Helm, V., A. Humbert, and H. Miller (2014): Elevation and elevation change of Greenland and Antarctica derived from CryoSat-2, *The Cryosphere*, 8, 1539–1559, doi:10.5194/tc-8-1539-2014
- Warren, S. G., Rigor, I. G., Untersteiner, N., Radionov, V. F., Bryazgin, N. N., Aleksandrov, Y. I., et al. (1999). Snow depth on Arctic sea ice. *Journal of Climate*, 12, 1814–1829.
[https://doi.org/10.1175/1520-0442\(1999\)012<1814:SDOASI>2.0.CO;2](https://doi.org/10.1175/1520-0442(1999)012<1814:SDOASI>2.0.CO;2)

9 Appendix Airport codes

IATA		Location	Land	Latitude	Longitude
AEY		Akureyri	Iceland	65.659994	-18.072703
CNP		Constable Pynt	Greenland	70.7444	-22.6482
n/a	DMH	Danmarkshavn	Greenland	76.7704	-18.6581
JAV		Ilulissat	Greenland	69.217	-51.083
KUS		Kulusuk	Greenland	65.573611	-37.123611
LYR		Longyearbyen	Norway	78.2456	15.4991
NAQ		Qaanaaq	Greenland	77.50	-69.25
n/a	STN	Station Nord	Greenland	81.5971	-16.6569
SFJ		Kangerlussuaq	Greenland	67.006	-50.703
THU		Thule AB	Greenland	76.53	-68.71
YEU		Eureka	Canada	79.994444	-85.811944
YLT		CFS Alert	Canada	82.500	-62.325

10 APPENDIX Operator logs

DOY 077a, March 18, 2017: AEY-AEY, Test flight

ALS and ASIRAS:

12:21 Take off

Could not boot PC2. Several tries with different error messages, such as "No operating system found".

After several tries, the PCs were shut down and we returned to AEY

12:52 Landing

DOY 077b, March 18, 2017: AEY-AEY, Test flight

ALS and ASIRAS:

16:07 Take off

After concluding that ASIRAS was working on PC1 alone, we returned to AEY.

16:23 Landing

DOY 078a, March 19, 2017: AEY - CNP

ALS:

First flight AEY-CNP
Calibration of ASIRAS over runway in CNP

09:07 Take off

11:36 Landing CNP

ASIRAS:

09:07 Take off
Make short acquisition (*_00) to check, everything looks ok. 1 file collected
10:58 F4 LAM Calibration
11:10 start recording (*_01)

ASIRAS calibration measurements over runway in CNP:

Event 1: first overflight
Event 2: second overflight

11:27 Tried S SDS but error
11:29 stop recording (4 files collected)
11:30 F4 LAM Calibration
11:36 Landing CNP

DOY 078b, March 19, 2017: CNP - DMH

ASIRAS:

Second flight CNP-DMH
Measurements of Greenland ice sheet. Has been measured several times before. Flight ended with 10 minutes of sea ice measurements.

12:04 Take off
13:28 F4 LAM Calibration
13:35: start recording (*_02)
14:51 Stop recording (16 files collected)
15:08 Start recording (*_03)

When trying to stop recording, the asicc program froze and had to be shut down brute force. Files seem ok. Not clear what the issue was.
4 files collected

15:33 landed DMH

DOY 079a, March 20, 2017: DMH – ULS – Tobias Ø - STN

Measurements in Fram Strait over ULSs and end
with measurements over 79fjord Glacier.

Isblink

1513

restart scanner, no return over Flade

1543

new scan file

1550~

Koldhallen

1603

landed STN

ALS:

1055 take off DMH
Ka band not working
1214 new scan file
1323 -- -- --
14 Canon left side, 70 deg
1405 Tobias Ø
Ka band working again, just before

ASIRAS:

1055 Take off
1059 F4 LAM Calibration
1112 Star recording (*_00)
1443 Stop recording (43 files collected)
1445 F4 LAM Calibration
1603 Landing NRD

shoreline

1447 new scan file
1509 scanner stop, async error

DOY 079b, March 20, 2017: STN – AltiKa - STN

Canon note: Canon time is wrong, but time of logged files are OK

ALS:

1606 airborne
Canon left, 70 deg
1836 landed STN

ASIRAS:

Measurements over Sea ice close to Station Nord. Waypoints chosen based on satellite images of sea ice cover and drift and AltiKa predicted orbits. Varying sea ice conditions along line.

1645 Take off
1652 F4 LAM Calibration
1706 Start recording (*_01)
1740 Stop recording (7 files collected)
1742 F4 LAM Calibration
1836 Landing NRD

DOY 080a, March 21, 2017: STN – CS2 - STN

ALS:

1025 CS2 line
take off STN
EGI lost satellites, power failure,
IMAR ok
1230 Canon shut down, connection
problems
1254 turning at N 86 16. W 0 35.1
1255 Canon started again
1521 landed

Measurements along CS2 track, track number ??.
Measures the CS 2 track in both directions.

1026 Take off
1029 F4 LAM calibration
1031 Start recording (*_00)
~ 1254 End of line. Teardrop turn to return
via the same WPs back.
1456 Stop recording (54 files collected)
1457 F4 LAM calibration
1521 landing NRD

ASIRAS:

First flight NRD-NRD.

DOY 080b, March 21, 2017: STN – Triangle - STN

Canon note: Canon time is wrong, but time of logged files are OK
adjust Canon time for next flights

ALS:

1601 airborne F-line
1845 Canon right side 50 deg
1935 Canon left side 70 deg
1949 Canon stopped, too dark
2108 landed

ASIRAS:

Second flight NRD-NRD.
Measurements in a triangle out of NRD. Has been measured several times earlier.

1601 Take off
1603 F4 LAM Calibration
1605 start recording (*_01)
2038 Stop recording (55 files collected)
2038 F4 LAM Calibration
2108 Landing NRD

DOY 081, March 22, 2017: NRD – Independence Glacier - YLT

ALS:

1423 airborne
1455 Canon right side 50 deg, time is correct
1812 landed Alert

note:

rear antenna issues from beginning.

- 1) Ka unstable sats
 - 2) air4 no sats, replace cable
 - 3) air3 few sats, check cable
- seems air3 cable has been unplugged from splitter the day???

also issues with EGI sats, but EGI on front antenna.

ASIRAS:

NRD-Alert.
Measurement in the Independence Fjord, over the Greenland Ice sheet and to Alert.

On ground Alert: some issues occurred with the GPS signal/cables and this delayed departure.

1423 Take off
1430 F4 LAM Calibration
1440 start recording (*_00)
1718 stop recording (32 files collected)
1719 F4 LAM Calibration
1812 Landing Alert

Note ! It is not possible to collect SDSs (short data selections). Unclear what the problem is, but assume it is due to the missing PC2.

DOY 083, March 24, 2017: YLT – CS2 - YLT

CS2 track, On track during satellite pass
NASA P3 and Polar 5 on track as well
POF just behind Polar 5 until satellite pass

1812 iMAR restarted
2012 landed

ALS:

1422 airborne
1455 Canon left side 50 deg, time is correct
1600 NASA P3 overhead going south
Polar 5 <8 nm ahead of POF,
reduced to 1 nm when satellite
passes 16:41
1641 CS2 pass, POF just behind Polar5
1642 Polar5 breaks off to the west
1721 87N turn around
iMAR disconnected power, for how
long???

ASIRAS:

Alert - CS2 - Alert
Coordinated measurements along CS2 track
together with OIB and AWI. CS2 track number
36892.
1223 Take off
1426 F4 LAM Calibration
1428 Start recording (*_00)
1945 stop recording (64 files collected)
1946 F4 LAM Calibration
2011 Landing YLT

DOY 086, March 27, 2017: YLT – CS2 – in situ line - YLT

C.Haas +CS2 track, On track during satellite pass
17:26

ALS:

1354 airborne
Canon left side 50 deg, time is correct
1427 air1 start logging
1430 scanner async error
restart and synch
1525 Canon shut down, bad visibl
1548 Canon on again
1748 Canon shut down, bad visibl
1800 break line, turning towards Alert,
strong wind,
snow drift in Alert
1834 landed

ASIRAS:

Alert - NW line – CS2 track – Alert
Measured along a line going NW suggested by
Christian Haas. Returning to Alert via CS track
number 36936.

1353 Take off
1356 F4 LAM Calibration
1359 Start recording (*_00)
1726 CS2 pass
1801 Break away from line due to poor
visibility
1817 Stop recording (52 files collected)
1818 F4 LAM Calibration
1334 Landed Alert

DOY 087, March 28, 2017: YLT – Peterman – GrIS - TAB

ALS:

1356 airborne
1407 calib runway + spinaker
Canon right side 60 deg, time is correct
1427 air1 start logging
1445 climb due poor visibl
1455 stop canon due bad visibl
1500 descend to 1200 ft, canon started again
1501 off track due weather, canon shut down
1600 canon started again
1753 landed Thule

ASIRAS:

Alert – TAB

Via Greenland Ice Sheet, Petermann Glacier

1356 Take off
1357 F4 LAM Calibration
1359 Start recording (*_00)
Calibration over runway:
Event #1 : First runway overflight
Event #2 : Second runway overflight
1446 Stop recording (10 files collected)
Had to climb due to clouds
1518 Start recording (*_01)
Petermann
1718 Stop recording (25 files collected)
1719 F4 LAM calibration
1752 Landed TAB

DOY 088, March 29, 2017: TAB – Sentinel-3A – Devon - TAB

ALS:

1322 airborne
1334 canon right side 60 deg
1402 canon off, batt low
1420 canon on again
1433 climb due clouds near devon
1438 down again
devon flown 360-800 m clearance
1610 canon left side 50 deg
scanner not logging 1554-1635
1838 landed

ASIRAS:

TAB – TAB
Flight over Devon Ice Cap. Return to TAB via
Sentinel-3 track

1322 Take off
1324 F4 LAM Calibration
1325 Start recording (*_00)
Line directly to Devon

1434 Stop recording (14 files collected)
Had to climb due to clouds
1438 Start recording (*_01)
1442 Stop recording (1 file collected)
Had to break line and climb due to
strong turbulence near Devon
1448 Start recording (*_02)
1451 Stop recording (1 file collected)
1452 Start recording (*_03)
1523 Stop recording (7 files collected)
1530 Start recording (*_04)
Devon Ice Cap
1617 Stop recording (10 files collected)
Align with/descend to Sentinel-3
track from Devon Ice Cap
1620 Start recording (*_05)
On S-3 track
Event #1 S-3 overpass
1751 Stop recording (19 files collected)
1751 F4 LAM Calibration
1837 Landed TAB

DOY 089a, March 30, 2017: TAB – Baffin Bay – Disko - JAV

ALS:

1149 airborne
1220 on line
1402 canon right side 60 deg
async error closing file, scanner
restarted
1540-1555 clouds over disko, no laser
1618 landed jav

ASIRAS:

TAB – JAV
Measure over sea ice from TAB to Disko Island.
Measurements over Disko (but limited due to
clouds).

1149 Take off
1154 F4 LAM Calibration
1158 Start recording (*_00)
1207 Stop recording (2 files collected)
1223 Start recording (*_01)
on line to Disko
1527 Stop recording (37 files collected)
climb for track on Disko
1550 Clouds over Disko Island.
1553 Start recording (*_02)
Disko
1559 Stop recording (2 files collected)
1601 F4 LAM Calibration
1618 Landed JAV

DOY 089b, March 30, 2017: JAV - JQA

ALS:

1645 airborne jav
1729 landed Qaarsut

DOY 090a, March 31, 2017: JQA – AltiKa -JQA

snow, low visibl, delay dep

ALS:

0800 airborne
0905 canon left 60 deg
0936 canon off, fog
0956 canon on
1057 end of line, backtrack 5 min
1103 towards Qaarsut
1208 landed

ASIRAS:

Qaarsut-Altika track - Qaarsut
Measure over Altika track (0.5 hours after satellite)

0800 Take off
0909 F4 LAM Calibration
0900 Start recording (*_00)
0907 On Altika track
1103 Stop recording (25 files collected)
Return to Qaarsut
1104 F4 LAM Calibration
1307 Landed Qaarsut

DOY 090b, March 31, 2017: JQA – EGIG in situ - JQA

ALS:

EGI not aligned, cannot wait, IMAR semi aligned

1352 take off

1415 EGI ok, fom=117

1520-1530 3 passes of T12, people on ground

imar says logging ok, but only little data, no more logging, memory full?

1706 runway+building calibration

1720 landed JQA

ASIRAS:

EGIG line T1-T19, overfly ground team on T12.

1358 Take off

1406 F4 LAM Calibration

1436 Start recording (*_01)

1555 Stop recording (16 files collected)

1700 Start recording (*_02)

Calibration flight over runway in Qaarsut. Two directions.

Event #1: first pass over runway

Event #2: second pass over runway

1709 Stop recording (2 files collected)

1709 F4 LAM Calibration

DOY 091a, April 1, 2017: JQA – EGIG - CNP

ALS:

0925 airborne
1112 overhead other TO
1347 landed CNP
1411 airborne
1621 landed AEY

ASIRAS:

Measure over EGIG line from T19 towards East. Ground team overflight at point C30 (between T21 and T41)

0924 Take off
1009 F4 LAM Calibration
1032 Start recording (*_00)
~1120-11:27 ground team overflight
1228 Stop recording (24 files collected)
head for CNP
1229 F4 LAM calibration

DOY 091b, April 1, 2017: CNP - AEY

No surveying

DOY 95, April 5, 2017: YCB-AltiKa-YCB

ALS + KAREN:

1906 Ready

DOY 97a, April 7, 2017: YCB-TER-YCB

ALS + KAREN:

1906 Ready
1914 Taxi
1918 Take-off
1925 Start camera logging, start Ka-band radar
1933 Low clouds, stop surveying
1951 On ground

DOY 97b, April 7, 2017: YCB-TER-SI-YCB

ALS + KAREN:

2329	Taxi
2332	Take-off
2334	Ka test file, OK
2338	On the line, start Ka-file + DSLR
2352	New line, new Ka-file + DSLR
235908	New line
001000	Crossing of lines
0014	Go for 3 sea ice lines, no reflectors
0020	Start logging Ka-file + DSLR
	Sea ice
003214	New line, new Ka-file + DSLR
	Some low clouds on the last sea ice line
0040	End of sea ice line
005230	New line Terrestrial survey, New Ka-file
0059	New Ka-file
010606	New Ka-file
011522	New Ka-file
012501	New Ka-file
013345	New Ka-file
014359	New Ka-file
015441	New Ka-file
0204	On ground

DOY 98, April 8, 2017: YCB-TER-YCB

Drifting snow

ALS + KAREN:

2327 Taxi
Take-off
233452 Ka test file, OK
233822 On the line, 1
On the line, 2
234709 New Ka-file, on line 3
235235 New Ka-file, on line 4
000242 New Ka-file, on line 5
001426 New Ka-file, on line 6
Tka=60C, turn down heat
002539 New Ka-file, on line 7
003055 New Ka-file, on line 8

003725 New Ka-file, on line 9
004226 New Ka-file, on line 10
004933 New Ka-file, on line 11
005356 New Ka-file, on line 12
010020 New Ka-file, on line 13
010432 New Ka-file, on line 14
011044 New Ka-file, on line 15
011502 New Ka-file, on line 16
012017 New Ka-file, on line 17
012403 New Ka-file, on line 18
013235 New Ka-file, on line 19
Crossing lines en route YCB
0139 Runway overflight
On ground

DOY 101, April 11, 2017: YCB-McClintock-YRB

ALS + KAREN:

1536 Ready
1538 Taxi
1540 Take-off
154807 Ka test file, OK
At high level until first WP in
McClintock channel
Leaving the scanner logging, out of
range
163647 Descending, start logging Ka-file, start
DSLr

WP1
Ka-radar PC went to sleep, but still
logging
165356 New Ka-file
171327 New Ka-file
1733 End of line
171327 Keep on the line, new Ka-file
1736 Over land, stop logging Ka + DSLr
1753 Stop logging ALS
On ground YRB

DOY 102a, April 12, 2017: YRB- C1-C2-C3-YEU

Old CS-2 track from 2014

ALS + KAREN:

1346	Ka-band radar + EGI, OK
	ALS + DSLR laptops too cold
1350	Taxi
	Take-off
1412	ALS and DSLR laptops up and running
141231	Test of Ka-band radar, OK
	Download EGI, missed 110
1454	Approaching C1, Start ALS logging
	Low ground speed 96kn
1508	On the line
151015	Start logging Ka-file + DSLR
152000	New Ka-file
1539	Over land, island
153937	New Ka-file
1555	Stop logging Ka-file, ALS, DSLR
~1702	On ground YEU

DOY 102b, April 12, 2017: YEU- Gline-YLT

Old track from 2012

ALS + KAREN:

Started to taxi before EGI aligned
New alignment
1800 Problems with ALS, all red
Taxi
Take-off
1845 Tka=69C, Shut down system
Got ALS synchronized using RiTerm, all OK
20... On ground YLT

DOY 103, April 13, 2017: YLT- InSitu-YLT

ALS + KAREN:

Following CS-2 track 73159 from April 12, 02 UTC.

Modified to overfly already surveyed in situ sites

(2,3,7,8)

In situ team on ground point IS05, landed when we passed first time

1355 Ready to taxi
Camera PC not working
Installed AIR2 as a spare GPS, same splitter as OXTS INS ?
1358 Take off
140145 New Ka-file
1420 No survey due to clouds
142703 New ALS + Ka-files
143800 New Ka-file, ~200m due to low clouds
144901 New Ka-file
145841 New Ka-file
150842 New Ka-file
1518 IS05E
151836 New Ka-file
1530 Camera running on my personal laptop
153342 New Ka-file
154804 New Ka-file
1553 IS06F
1555 Clouds
1608 Passing IS08H
160957 New Ka-file
New camera session, 500 pix
162910 New Ka-file

164136 IS10J
1648 At N087 15.27 W093 58.XX, turn around
165404 New ALS and Ka-file
Stop DSLR, download data
171044 New Ka-file
172748 New Ka-file
IS06F
174806 New Ka-file, ground speed 143kn
Start DSLR
175913 New Ka-file
1803 Overfly in situ site IS05
1813 IS04D
1816 Restart DSLR
182357 New Ka-file
183558 New Ka-file
1841 Clouds, stop DSLR
1855: End of line
Stop ALS and Ka
Approaching YLT
190832 Start logging ALS, Ka, DSLR
Descending
1912 Runway E-> W
Stop logging Ka-radar
1917 Building S-> N
1920 Building N-> S
1923 Building E-> W
1917 Building W-> E
192740 New Ka-file
1931 Runway W-> E
~1933 On ground

DOY 106, April 16, 2017: YLT- CS-37225-MOW-NEp1-IceBridge-YLT

ALS + KAREN:

1307	Taxi	160058	Stop DSLR, downloading
1310	Take-off	1604	New scanner file
131143	Ka-radar test file, OK	160610	Ka-radar up and running
1320	New scanner file, looks weird, parabola	1609	New Ka-file
	Reboot scanner, all OK	161727	Descending ~200m low clouds
133928	New scanner file	1620	New Ka-file
1345	CSNE2A	1624	Start DSLR
134522	New Ka-file	162932	Ascending to 300m
135817	New Ka-file	165309	New Ka-file
141501	New Ka-file	1701	New Ka-file
142406	New Ka-file	170325	Stop DSLR, Download
143222	New Ka-file, start DSLR	170325	New Ka-file
	CSNE2E, start of MOW	171326	New Ka-file
1448	EOL	1725	End of line CS2NE1
145232	MOW1AJ, New Ka-file		Going for the IceBridge, Nares Strait
	Headwind 110kn ground-speed	172607	New Ka-file, start DSLR
1509	EOL	173720	New Ka-file
151109	MOW1BL, New Ka-file	1745	Crossing ice edge, grey ice with finger rafting
1523	CS-2 satellite passage time	1748	Following the ice edge
1524	EOL	174950	Crossing ice edge
152618	MOW1AG, New Ka-file	175201	New Ka-file
	No photos on this line, downloading	1757	Crossing ice edge to open water, or nilas
1541	EOL	180843	New Ka-file
1543	MOW1BM, start DSLR	1813	Crossing ice edge
	Ka-radar frozen, Restart Ka-GUI	1815	Go for landing, Stop Ka-file, DSLR
1555	Hard switch off radar	1819	On ground YLT
1558	Crossing the lines

DOY108, April 18, 2017: YLT- ShearZone-IceBridge-YLT

Windy, drifting snow T=-21C

ALS + KAREN:

1330 Re-align EGI, Ka + ALS OK
Take-off
133735 Ka test-file, OK
Ka lost connection, no power, Green switch off
134858 New Ka test-file, OK
135016 Start new Ka-file
EGI froze
1401 Restart EGI-con, EGI OK
140233 All looks OK
Stop Ka-logging
96kn ground speed
142524 New Ka-file
1430 At the MOW area
143133 SZ01A, New Ka-file
143930 SZ02B, New Ka-file
EGI froze again
1443 Restart EGI-con, new EGI file
144404 New Ka-file
1446 End of line
144754 SZ03A, New Ka-file, DSLR
1454 End of line
145629 SZ04B, New Ka-file, DSLR
1502 End of line
150358 SZ05A, New Ka-file, DSLR
1510 End of line
151217 SZ06B, New Ka-file, DSLR

1518 End of line
152022 SZ07A, New Ka-file, DSLR
1527 End of line
152841 SZ08B, New Ka-file, DSLR
1535 End of line
153637 SZ09A, New Ka-file, DSLR
1543 End of line
155020 SZ10B, New Ka-file, DSLR
1556 End of line
Left turn
155836 Crossing lines, New Ka-file, DSLR
1605 New scanner file
160544 New Ka-file
161519 New Ka-file
162615 New Ka-file
Icebrige, Crossing ice -> water
163718 New Ka-file
1640 Water -> ice
164346 New Ka-file
1650 Ice -> water
165125 New Ka-file
1655 Water -> ice
170039 New Ka-file
1705 Ice -> water
1707 Water -> ice
170912 New Ka-file
Inbound for landing
1710 Stop Ka log-file
1713 On ground YLT

DOY 109a, April 19, 2017: YLT- YEU

No survey

ALS + KAREN:

1255 Nav not navrdy
~1257 Take-off
1520 On ground YEU

DOY 109b, April 19, 2017: YEU- YRB

No survey

ALS + KAREN:

1557 INS aligned, OK
1558 Take-off
1655 Main switch off :-(
Stop INS
1832 On ground YRB

DOY 110, April 20, 2017: YRB –CYGZ, CYGZ-NAQ

ALS + KAREN:

CYGZ Grise Fjord
Survey Hells Gate and Jones Strait
No Ka-radar, backup

1333 Ready to go
1337 Take-off
143410 Approaching Hells Gate
New scanner file
1440 Very thin layer of clouds
ALS signal on and off
Stop DSLR

1446 Stop survey too many low clouds
145006 New scanner file + DSLR
~150m altitude, nice signal
1504 Stop DSLR no contrast
1539 Stop survey
1540 On ground CYGZ

1627 Taxi
1631 Take off
1643 Polynya
1645 Low thin clouds
1813 On ground

DOY 111, April 21, 2017: NAQ-A3-H-NAQ

NAQ-STN, had to return to NAQ due to bad weather at STN
No Ka-radar, backup

ALS:

1152	Ready to go
1156	Take-off
	Stop scanner
121751	New scanner file, ~450m a.g.
131930	New scanner file
142102	New scanner file
1425	Return to NAQ
	Shut down ALS
1654	On ground NAQ

DOY 114a, April 24, 2017: NAQ-H-STN

No Ka-radar, backup

ALS:

1119	Taxi
1121	Take-off
134007	Start scanner file
	Start survey at ~N81.14, W42.10
1410	Start DSLR
1413	Circumnavigating rock
1420	Very thin layer of clouds, No ALS
1421	Stop DSLR
1428	OK, weather, clear
	A bit off the line, due to clouds
152329	New scanner file
1532	On ground STN

DOY 114b, April 24, 2017: STN-S3-LYR

ALS + KAREN:

1618	Taxi
1622	Take-off
164014	New scanner file
162937	New Ka-file
	Flade Isblink
163905	New Ka-file
1646	Glacier front
	Start camera
164853	New Ka-file
165836	New Ka-file
170733	New Ka-file, 151 knots
171628	New Ka-file
1724	Scattered clouds
172532	New Ka-file
173444	New Ka-file
173619	New scanner file
174354	New Ka-file
1749	Scattered low clouds/fog
175323	New Ka-file
180224	New Ka-file
1805	ice-edge ?
	Scattered ice floes
~1809	S3 satellite passage time ~N79 24.80 E03 52.00
1812	Open water with snow showers
1812	Open water with snow showers
1814	Persistent snow, stop logging
	Climbing
1921	On ground LYR

DOY 115, April 25, 2017: LYR-Austfonna-LYR

ALS + KAREN:

0938 Ready to go
0940 Taxi
0943 Take-off
0945 Scanner stop logging
0946 Ka test-file, OK
1025 Start scanner
1027 L1_1
1028 Start new Ka-file
1032 L1_2
1033 L1_3
1034 L1_4
1036 L1_5
1037 L1_6
1038 Clouds between LI_6 and Eton
1047 Ka start/stop

Still clouds
SV3
1047 Survey stopped, due to persistent cloud cover
1050 Stop scanner
1053 Ka-radar stopped logging
Returning to LYR for calibration flight
1149 Scanner started
1156 New Ka-file
1159 Runway overflight
1203 Runway overflight
1205 Ka-radar stop logging
1206 Building E->W
120940 Building S->N
1210 Stop scanner
1214 On ground LYR

DOY 116, April 26, 2017: LYR-Austfonna-LYR

ALS + KAREN:

0751 Taxi
0755 take-off
0813 started Ka
0814 stopped Ka, test-file ok
0825 all systems ok
0839 start scanner
0840 clouds ahead heading for cs-tracks
0847 started ka
0848 clouds, no signal
0849 return from clouds
0853 on line L13s19-L13n19, from now on
the line will be referred to as LxxCS19
0858 stop/start Ka
0905 end line L13CS19
0906 start line L21CS19 towards south
0914 stop/start Ka
0918 clouds turn, stop/start scanner
0910 on line L17CS19 towards north
0929 stop/start Ka
0933 go lines Sv2-Sv3
0934 stopped ka
0937 on line sv2-sv3, started Ka
0939 at sv3
0942 at sv4
0946 at sv5 and turn, stoppe dka
0947 clouds
0948 started ka
0950 stop ka
0953 stop/start scanner, clouds
0955 on line CS19n-CS19s
0956 starting ka surface in scn.
1003 stopped ka clouds

1006 on line L5CS19
1007 turned for L9CS19 towards north to
avoid clouds, no luck back on line
L9CS19
1014 no clouds on L9CS19
1015 Started Ka
1021 turn stopped ka
1024 on R9CS19 towards south, clouds
1025 started Ka no clouds
1031 turn, clouds, ka stop
1034 on line L5CS19 towards north, started
Ka
1040 turn, ka stop, clouds
1042 scanner stopped/start
1043 on line R13CS19 towards north, ka
started
1049 turn, ka-stop, clouds
1053 on line R17CS19 north ka-start
1059 clouds ka-stop, turn
1108 on line R21CS19 south, ka-start
1114 clouds ka-stop, turn
1117 on line R25CS19 north, ka-started
1124 clouds ka-stop, turn
1128 on line R5CS19 south
1134 clouds ka-stop, turn for the ridge exit
1138 stop/start scanner
1139 start ka
1140 at the ridge from NPI
1144 clouds ka and scanner stop, heading
for LYR
1239 on ground LYR.

11 APPENDIX Coordinates of GPS base stations

Date	DOY	Reference	Latitude (DMS)	Longitude (DMS)	Ellipsoidal Height (m)
Phase 1					
19-03-2017	79A	STN fixed	Not calculated	Not calculated	Not calculated
19-03-2017	79B	STN fixed	Not calculated	Not calculated	Not calculated
20-03-2017	80A	STN	81° 35' 46.43742''	-16° 39' 25.94093''	62.453
20-03-2017	80B	STN	81° 35' 46.43735''	-16° 39' 25.99253''	62.451
24-03-2017	83	YLT	82° 30' 43.24847''	-62° 19' 47.76181''	50.198
27-03-2017	86	YLT	82° 30' 43.24865''	-62° 19' 47.76286''	50.197
31-03-2017	90A	JQA	70° 43' 58.46009''	-52° 41' 47.90436''	113.695
31-03-2017	90B	JQA	70° 43' 58.46009''	-52° 41' 47.90436''	113.695
Phase 2					
07-04-2017	97A	YCB	69° 06' 21.07341''	-105° 07' 17.78724''	-13.005
07-04-2017	97B	YCB	69° 07' 18.15076''	-105° 02' 46.63899''	-20.070
08-04-2017	98	YCB	69° 06' 21.07316''	-105° 07' 17.78587''	-12.956
13-04-2017	103	YLT	82° 30' 41.84928''	-62° 19' 50.99325''	50.828
16-04-2017	106	YLT	82° 30' 41.84945''	-62° 19' 51.00366''	50.803
18-04-2017	108	YLT	82° 30' 41.83143''	-62° 19' 50.84157''	50.822
25-04-2017	115	LYR	78° 14' 45.44436''	15° 30' 17.42615''	54.039
26-04-2017	116	LYR	78° 14' 45.71767''	15° 30' 18.05446''	52.176

12 APPENDIX Overview of acquired ALS data – phase 1

Date	DOY	File name	Start time (dechr)	Stop time (dechr)	Angles (pitch, roll, heading)	dt (s)
18-03-2017	077	077_155330.2dd	11.8919918	12.58027		
19-03-2017	078	078_090330.2dd	09.2085185	09.37203	Only clouds	-
		078_105700.2dd	10.9498577	11.63403	-1.20 -0.11 0.0	-1
		078_120510.2dd	12.0876682	12.15967	-1.20 -0.11 0.0	-1
		078_133230.2dd	13.5415656	14.22997	No INS	-
20-03-2017	079	079_104800.2dd	Error	Error	-1.00 -0.10 0.0	0
		079_121410.2dd	Error	Error	-1.00 -0.10 0.0	0
		079_132300.2dd	Error	Error	-1.00 -0.10 0.0	0
		079_144700.2dd	Error	Error	-1.00 -0.10 0.0	0
		079_154240.2dd	15.7105326	16.01048	-1.00 -0.10 0.0	-1
		079_164110.2dd	16.6865431	17.37497	-1.00 -0.09 0.0	-1
21-03-2017	080	080_102240.2dd	10.3796138	11.06795	-1.00 -0.09 0.0	-1
		080_112100.2dd	11.3477446	12.03618	-1.00 -0.09 0.0	-1
		080_125540.2dd	12.9270748	13.61569	-1.00 -0.09 0.0	-1
		080_134915.2dd	13.8203001	14.50893	-1.00 -0.09 0.0	-1
		080_153510.2dd	15.5851462	16.27376	On ground ?	-
		080_155630.2dd	15.9412343	16.07175	-1.00 -0.10 0.0	0
		080_160540.2dd	16.3574182	17.04583	-1.00 -0.10 0.0	0
		080_172300.2dd	17.3834262	18.07186	-1.00 -0.11 0.0	0
		080_190300.2dd	19.0495518	19.73801	-1.00 -0.11 0.0	0
		080_200630.2dd	20.1066510	20.79530	-1.00 -0.11 0.0	0
22-03-2017	081	081_142130.2dd	14.3594261	15.04800	No INS	-
		081_164420.2dd	16.7390224	17.29017	No INS	-
		081_171750.2dd	17.2957590	17.80800	No INS	-
24-03-2017	083	083_142400.2dd	14.3996700	15.08799	-1.05 0.14 0.0	0
		083_153510.2dd	15.5851462	16.27376	-1.05 0.14 0.0	0
		083_172400.2dd			-1.05 0.14 0.0	0
		083_183050.2dd			-1.05 0.14 0.0	0
		083_195010.2dd	19.8365341	20.13310	-1.05 0.14 0.0	0
27-03-2017	086	086_132545.2dd	Error	Error	-1.05 0.14 0.0	-1
		086_143230.2dd	14.5424921	15.23087	-1.05 0.14 0.0	-1
		086_154710.2dd	15.7860937	16.47451	-1.05 0.14 0.0	-1
		086_165330.2dd	16.8907950	17.57921	-1.05 0.14 0.0	-1
28-03-2017	087	087_134630.2dd	13.7754655	13.95491	-1.05 0.13 0.0	0
		087_135830.2dd	13.9744724	14.66301	-1.05 0.13 0.0	0
		087_152400.2dd	15.3976734	16.08628	-1.05 0.13 0.0	0
		087_163200.2dd	16.5286776	17.21727	-1.05 0.13 0.0	0
29-03-2017	088	088_132340.2dd	13.3945796	13.40346	-1.05 0.16 0.0	-1
		088_132540.2dd	13.4279495	14.11630	-1.05 0.16 0.0	-1
		088_142210.2dd	14.3688424	15.05745	-1.05 0.16 0.0	-1
		088_155420.2dd	16.6072891	17.29570	-1.05 0.16 0.0	-1
30-03-2017	089	089_114345.2dd	11.7296312	12.41795	-1.05 0.14 0.0	-1
		089_125530.2dd	12.9248778	13.61328	-1.05 0.14 0.0	-1
		089_141040.2dd	Error	Error	-1.05 0.14 0.0	0
		089_151640.2dd	Error	Error	-1.05 0.14 0.0	0
		089_152830.2dd	Error	Error	-1.05 0.14 0.0	0
31-03-2017	090	090_080808.2dd	08.1482923	08.83682	-1.05 0.14 0.0	0
		090_085700.2dd	08.9484718	09.63688	-1.05 0.14 0.0	0
		090_102010.2dd	10.3369528	11.02535	-1.05 0.14 0.0	0
		090_142145.2dd	14.3626368	15.05135	-1.05 0.14 0.0	-1
		090_170150.2dd	17.0295635	17.30310	-1.05 0.14 0.0	-1

01-04-2017	091	091_102145.2dd 091_114120.2dd	10.3628259 11.6892823	11.05126 12.37772	-1.05 0.18 0.0 -1.05 0.18 0.0	-1 -1
------------	-----	----------------------------------	--------------------------	----------------------	----------------------------------	----------

13 APPENDIX Overview of acquired ALS data – phase 2

Date	DOY	File name	Start (dechr)	Stop (dechr)	Angles (pitch, roll, heading)	dt (s)
05-04-2017	95	170405_212827_Scanner 1.2dd	00.06879	02.84661	See Table 12 Section 5.3.4	499
07-04-2017	97A	170407_191316_Scanner 1.2dd	00.07477	00.78648	0.32 -0.455 0.10	-17
07-04-2017	97B	170407_234446_Scanner 1.2dd	00.09315	02.68990	0.32 -0.455 0.10	512
08-04-2017	98	170408_232213_Scanner 1.2dd	00.03683	00.19456	0.32 -0.46 0.10	-17
		170408_235331_Scanner 1.2dd	00.21200	02.34060	0.32 -0.46 0.10	-17
11-04-2017	101	170411_152932_Scanner 1.2dd	00.04209	02.44689	0.32 -0.46 0.10	-17
12-04-2017	102A	170412_145448_Scanner 1.2dd	00.71330	01.74579	0.32 -0.47 0.10	-18
13-04-2017	103	170413_141105_Scanner 1.2dd				-
		170413_141120_Scanner 1.2dd			0.32 -0.46 0.10	2
		170413_144740_Scanner 1.2dd			0.32 -0.455 0.10	2
		170413_171108_Scanner 1.2dd			0.32 -0.455 0.10	2
		170413_191824_Scanner 1.2dd			0.32 -0.455 0.10	2
16-04-2017	106	170416_130714_Scanner 1.2dd	13.12060	13.30134		-
		170416_132011_Scanner 1.2dd	13.33662	13.59839		-
		170416_133714_Scanner 1.2dd	-	-		-
		170416_133928_Scanner 1.2dd	00.03333	02.36138	0.32 -0.47 0.10	-17
		170416_160058_Scanner 1.2dd	02.36568	04.67762	0.32 -0.47 0.10	-17
18-04-2017	108	170418_134643_Scanner 1.2dd	13.43293	16.07767	0.32 -0.47 0.10/ 0.18 -0.15 0.40*	-17
		170418_160456_Scanner 1.2dd	16.08239	17.22149	0.32 -0.47 0.10	-17

20-04-2017	110B	170420_134213_Sca nner 1.2dd	-	-	No data	-
		170420_135410_Sca nner 1.2dd	13.55659	13.69766	?	-
		170420_143410_Sca nner 1.2dd	14.56929	14.78102	0.32 -0.47 0.10	-16
		170420_144957_Sca nner 1.2dd	-	-	No data	-
		170420_145006_Sca nner 1.2dd	14.83492	15.65192	0.32 -0.47 0.10	-16
		170420_164626_Sca nner 1.2dd	16.42812	18.23716	0.32 -0.46 0.10	-16
21-04-2017	111	170421_115206_Sca nner 1.2dd	00.03333	00.25262	0.32 -0.46 0.10	-17
		170421_121752_Sca nner 1.2dd	00.43075	01.45452	0.32 -0.46 0.10	-17
		170421_131930_Sca nner 1.2dd	01.45776	02.48028	0.32 -0.46 0.10	-17
		170421_142102_Sca nner 1.2dd	02.48334	02.60797	0.32 -0.46 0.10	-17
24-04-2017	114	170424_113834_Sca nner 1.2dd	Error	Error	0.32 -0.47 0.10	-17
		170424_114841_Sca nner 1.2dd	Error	Error	0.32 -0.47 0.10	-17
		170424_133019_Sca nner 1.2dd	Error	Error	0.32 -0.47 0.10	-17
		170424_134007_Sca nner 1.2dd	Error	Error	0.32 -0.47 0.10	-17
		170424_152329_Sca nner 1.2dd	Error	Error	0.32 -0.47 0.10	-17
		170424_164014_Sca nner 1.2dd	16.3257101	17.01641	0.32 -0.46 0.10	-18
		170424_173619_Sca nner 1.2dd	17.6057111	18.26381	0.32 -0.46 0.10	-18
25-04-2017	115	170425_093204_Sca nner 1.2dd	9.5292661	9.75131	0.32 -0.43 0.10	2
		170425_102530_Sca nner 1.2dd	10.4197904	10.85457	0.32 -0.43 0.10	2
		170425_114959_Sca nner 1.2dd	11.8278280	12.17468	0.32 -0.43 0.10	2

26-04-2017	116	170426_074829_Sca nner 1.2dd	00.0333394	00.03635	0.32 -0.43 0.10	(-17)
		170426_083840_Sca nner 1.2dd	00.8488519	01.51910	0.32 -0.43 0.10	-17
		170426_091859_Sca nner 1.2dd	01.5209211	02.10651	0.32 -0.43 0.10	-17
		170426_095414_Sca nner 1.2dd	02.1084183	02.79911	0.32 -0.43 0.10	-17
		170426_104208_Sca nner 1.2dd	02.9066552	03.59734	0.32 -0.43 0.10	-17
		170426_113909_Sca nner 1.2dd	03.8569284	03.95776	0.32 -0.43 0.10	-17

14 APPENDIX Overview of acquired ASIRAS data – phase 1

Date	File name	Start time (UTC)	End time (UTC)	Range window (m)	# Pulses
18-03-2017	A170318_00.log	16:13:52	16:17:51	90.00	597496
19-03-2017	A170319_00.log	09:11:11	09:12:15	90.00	159999
	A170319_01.log	11:10:01	11:29:51	90.00	2974981
	A170319_02.log	13:35:07	14:51:01	90.00	11384931
	A170319_03.log	15:08:12	15:23:34	90.00	2304987
20-03-2017	A170320_00.log	11:11:35	14:43:07	90.00	31729805
	A170320_01.log	17:06:11	17:40:33	90.00	5154968
21-03-2017	A170321_00.log	10:30:56	14:56:31	90.00	39837237
	A170321_01.log	16:05:29	20:38:21	90.00	40929730
22-03-2017	A170322_00.log	14:39:55	17:18:11	90.00	23739846
24-03-2017	A170324_00.log	14:28:20	19:45:16	90.00	47539698
27-03-2017	A170327_00.log	13:59:00	18:17:41	90.00	38802243
28-03-2017	A170328_00.log	13:58:37	14:46:25	90.00	7169956
	A170328_01.log	15:17:57	17:18:42	90.00	18112378
29-03-2017	A170329_00.log	13:25:51	14:34:31	90.00	10299935
	A170329_01.log	14:38:32	14:42:21	90.00	572496
	A170329_02.log	14:48:31	14:51:38	90.00	467497
	A170329_03.log	14:52:10	15:23:53	90.00	4757470
	A170329_04.log	15:30:52	16:17:46	90.00	7034954
	A170329_05.log	16:19:32	17:50:59	90.00	13717411
30-03-2017	A170330_00.log	11:58:10	12:07:28	90.00	1394992
	A170330_01.log	12:22:45	15:27:41	90.00	27739818
	A170330_02.log	15:54:49	15:59:49	90.00	749995
31-03-2017	A170331_00.log	09:00:44	11:03:29	90.00	18412378
	A170331_01.log	14:35:46	15:55:42	90.00	11989921
	A170331_02.log	17:01:32	17:09:22	90.00	1174993
01-04-2017	A170401_00.log	10:32:44	12:28:20	90.00	17339891

15 APPENDIX Overview of acquired data from Ka-band radar

Acquisition overview of the 19th of March 2017 flight.

#	Bw [MHz]	PRF [KHz]	Duration [mins]	Notes
112530	400	8.2	~1	Calibration track over Constable Point
112759			~1	
112909			~1	
134212			10	B1B2
135321			20	B1B2
141405			9	B1B2
143306			5	B2B3
151230			5	
151808			5	

Acquisition overview of the 21st of March 2017, morning flight.

Acq #	Bw [MHz]	PRF [KHz]	Duration [mins]	Notes
104909	600	6.15	20	Track C9C5
111213			30	Track C9C5
114322				Track C9C5_2
114653			30	Track C5C1
121804			20	Track C5C1
124024				Track C5C1_2
130345				Track C1C5
131054			20	
133415			10	
135109			10	
140904			20	
143027			20	
145222			5	

Acquisition overview of the 21st of March 2017, afternoon flight.

Acq #	Bw [MHz]	PRF [KHz]	Duration [mins]	Notes
160835	600	6.15	20	Track STN-F1
163008			30	
171329			30	Track F1-F2
174729			30	
182000			40	

190504				Track F2-STN
191725			30	
195101			30	
202358			9	

Acquisition overview of the 22nd of March 2017

Acq #	Bw [MHz]	PRF [KHz]	Duration [mins]	Notes
145001	400	8.2	8	Track H1H2
145841			11	Track H2H3
151119			10	Track H3H4
152229			11	Track H4H5
153426			9	Track H5H6
154942			20	Track H6H7
161058			18	
163117			30	Track H7C32
171105			7	Track C32C33

Acquisition overview of the 24th of March 2017

Acq #	Bw [MHz]	PRF [KHz]	Duration [mins]	Notes
145351	600	6.15	30	Track 1A-36892N
152401			18	Track 1A-36892N
154228			30	Track 36892N-Q
161252			15	Track 36892N-Q
162806			30	Track 36892Q-U
165817				Track 36892Q-U
173154			30	Track 36892U-Q
181335				Track 36892U-Q
182152			20	Track 36892Q-N
184142			17	Track 36892Q-N
191431			20	Track 36892N-1A

Acquisition overview of the 27th of March 2017

Acq #	Bw [MHz]	PRF [KHz]	Duration [mins]	Notes
140415	600	6.15		Track YLT-1
143543			2	Track 1-3_4
143815			10	Track 3-6
144827			12	Track 3-6_2
150206			10	Track 3-6_3
151309			5	Track 3-6_4
151759			20	Track 6-8
151819			7	Track 6-8_2
155115			20	Track 8-64
161227			20	Track 8-64_2
163256			3	Track 8-64_3
164023			20	Track 46-62
170103			6	Track 46-62_2
171944			10	Track 62-78_3
173056			2	Track 62-78_4
173415			13	Track 78-102
174719			4	Track 78-102_2
175347				Track 78-102_3

Acquisition overview of the 28th of March 2017

Acq #	Bw [MHz]	PRF [KHz]	Duration [mins]	Notes
140606	600	6.15	Cal	Calibration track over airport runway (NS)
141101			Cal	Calibration track over airport runway (SN)
141905			18	Track C20-C19
143851			8	Track C19-C18
151939			20	TrackA4-A3
154034			10	TrackA4-A3_2
155656			30	Track A3-NW7
163213			25	Track A3-NW7_2
165738			5	Track A3-NW7_3

Acquisition overview of the 29th of March 2017

Acq #	Bw [MHz]	PRF [KHz]	Duration [mins]	Notes
134011	400	6.15	20	Track TAB-450_part1
140321			20	Track TAB-450_part2
150319			11	Track 450_2-450_9
153248			1	Track May3_9- May3_1
153313			20	Track May3_9- May3_1
161324			3	Track 174802-22
162314	600		20	Track 174802-22
164321			34	Track 174802-22
172046			30	Track 174802-22

Acquisition overview of the 30th of March 2017

Acq #	Bw [MHz]	PRF [KHz]	Duration [mins]	Notes
122050	400	6.15	12	TrackTAB-D1
123918			10	TrackTAB-D1
125522			14	TrackTAB-D1
132031			10	TrackTAB-D1
133954			10	TrackTAB-D1
141029			10	TrackTAB-D1
144041			15	TrackTAB-D1
150752			5	TrackTAB-D1

Acquisition overview of the 31st of March 2017

Acq #	Bw [MHz]	PRF [KHz]	Duration [mins]	Notes
090724	500	6.15	34	TrackA01A03
094203			30	TrackA03A05
101430			32	TrackA05A07
104651			5	TrackA07A08
105715			5	TrackA08 A07
145125			6	T3T5
145709			10	T5T9
150716				T9T12 over twin otter
152259				Over twin otter
153253				Over twin otter
153622			17	T12T19
170431				Over airport runway
1170801				Over airport runway
1171220				Over hotel

Acquisition overview of the 1st of April 2017

Acq #	Bw [MHz]	PRF [KHz]	Duration [mins]	Notes
104255	500	6.15	5	trackT19-T21, begin 210.avi
104842			23	trackT21-T41
111133				trackT21-T41 over twin otter
111805				Perpendicular to trackT21-T41 over twin otter
112643				trackT21-T41 over twin otter
112820			22	trackT21-T41
115213			3	trackT41-EG5
115519			20	
121549			12	trackEG5-EG6

Acquisition overview for the 5th of April 2017.

Acq #	Dimension [Gb]	Notes
20170405213754	66	YCB- ALtiKa-YCB
20170405215525	70	
20170405221401	74	
20170405223027	70	
20170405224942	70	
20170405230626	68	
20170405232313	68	
20170405233742	5	

Acquisition overview for the 7th of April 2017.

Acq #	Dimension [Gb]	Notes
20170407153927	5	Test
20170407192535	44	YCB-TER-YCB, flight cancelled due to low clouds
20170407233847	60	
20170407235208	21	
20170407235907	51	
20170408001959	57.4	
20170408003214	43.3	
20170408005230	46.5	
20170408010606	45.5	
20170408011522	42.8	
20170408012501	43.3	
20170408013345	51	
20170408014359	51.8	
20170408015441	10.8	

Acquisition overview for the 8th of April 2017.

Acq #	Dimension [Gb]	Notes
20170408230000		
20170409000242	50.1	
20170409001426	48.9	
20170409002539	15.1	
20170409003055	23.3	
20170409003725	15.3	
20170409004226	23.5	
20170409004933	15.1	
20170409005356	23.6	
20170409010020	14	
20170409010432	21.7	

20170409011044	12.1	
20170409011502	19.7	
20170409012017	10.4	
20170409012403	36.8	
20170409013235	48.2	

Acquisition overview for the 11th of April 2017.

Acq #	Dimension [Gb]	Notes
20170411163647	92	YCB-McClintock-YRB
20170411165356	10	
20170411171327	10	
20170411173326	15.3	

Acquisition overview for the 12th of April 2017.

Acq #	Dimension [Gb]	Notes
20170412151015	88	YRB- C1-C2-C3-YEU
20170412152600	73	
20170412153937	93	

Acquisition overview for the 13th of April 2017.

Acq #	Dimension [Gb]	Notes
20170413140145	81	YLT- InSitu-YLT
20170413142703	59	
20170413143800	60	
20170413144901	53	
20170413145841	53	
20170413150842	55	
20170413151836	84	
20170413153342	80	
20170413154804	82	
20170413160957	107	
20170413162910	105	
20170413165404	93	

Acquisition overview for the 18th of April 2017.

Acq #	Dimension [Gb]	Notes
20170418135016	68	YLT- ShearZone-IceBridge-YLT
20170418140233	56	
20170418142524	17	
20170418143133	35	
20170418143930	24	
20170418144404	12	
20170418144754	32	
20170418145629	33	
20170418150358	40	
20170418151217	37	
20170418152022	36	
20170418152841	35	
20170418153637	37	
20170418155020	34	
20170418155836	39	
20170418160544	52	
20170418161519	60	
20170418162615	53	

Acquisition overview for the 24th of April 2017.

Acq #	Dimension [Gb]	Notes
20170424162937	52	STN-S3-LYR
20170424163905	50	
20170424164853	52	
20170424165836	49	
20170424170733	49	
20170424171628	50	
20170424172532	51	
20170424173444	51	
20170424174354	52	
20170424175323	50	
20170424180224	66	

Acquisition overview for the 25th of April 2017.

Acq #	Dimension [Gb]	Notes
20170425102823	107	LYR-Austfonna-LYR
20170425104737	30	
20170425115655	46	

Acquisition overview for the 26th of April 2017.

Acq #	Dimension [Gb]	Notes
20170426084726	60	LYR-Austfonna-LYR
20170426085816	90	
20170426091418	86	
20170426092950	28	
20170426093726	51	
20170426094902	10	
20170426095610	40	
20170426101543	32	
20170426102514	34	
20170426103445	33	
20170426104339	33	
20170426105358	33	
20170426110852	35	
20170426111743	41	
20170426112852	34	
20170426113928	29	

16 APPENDIX File name convention

In general, the filename contains a shortcut for the instrument and the start and stop time of the data file.

KAREN:

KAR_OPER_Level1b_ SSSSSSSSSSSSSS_ PPPPPPPPPPPPPP_XXXX.nc

SSSSSSSSSSSSSSS Start time given as YYYYMMDDTHHMMSS
PPPPPPPPPPPPPPP Stop time given as YYYYMMDDTHHMMSS
XXXX version of processing, as described in Section 5.5.1, thus XXXX could e.g. be
"hamh"

ASIRAS:

AS30AXX_ASIWL1BNNNN_ SSSSSSSSSSSSSS_ PPPPPPPPPPPPPP_0001.DBL

AS30AXX ASIRAS (AS30), AXX number of data log
ASIWL1BNNNN Level 1B data (L1B) processor version (NNNN)
SSSSSSSSSSSSSSS Start time given as YYYYMMDDTHHMMSS
PPPPPPPPPPPPPPP Stop time given as YYYYMMDDTHHMMSS

GPS

GPS_ANT_VER_ SSSSSSSSSSSSSS-PPPPPP_0001.DBL

ANT GPS antenna, e.g. R for rear, and F for front
VER Version
SSSSSSSSSSSSSSS Start time given as YYYYMMDDTHHMMSS
PPPPPP Stop time given as HHMMSS

Inertial Navigation System (INS)

INS_ SSSSSSSSSSSSSS-PPPPPP_0001.DBL

SSSSSSSSSSSSSSS Start time given as YYYYMMDDTHHMMSS
PPPPPP Stop time given as HHMMSS

Airborne laser scanner (ALS) full resolution

ALS_ SSSSSSSSSSSSSS-PPPPPP.nc

SSSSSSSSSSSSSSS Start time given as YYYYMMDDTHHMMSS
PPPPPP Stop time given as HHMMSS

17 APPENDIX Processed GPS data in ESA format

Differentially processed GPS data is delivered in binary, big endian format with each record formatted as described by Cullen (2010).

Date	DOY	File	Size [MB]
19-03-2017	78	GPS_R_20170319T085742_153614_0001.DBL	1.4
20-03-2017	79	GPS_R_20170320T104217_161214_0001.DBL	1.2
20-03-2017	79	GPS_R_20170320T163612_184154_0001.DBL	0.5
21-03-2017	80	GPS_R_20170321T102743_152438_0001.DBL	1.1
21-03-2017	80	GPS_R_20170321T155654_211134_0001.DBL	1.1
24-03-2017	83	GPS_R_20170324T141322_201658_0001.DBL	1.3
27-03-2017	86	GPS_R_20170327T132621_183802_0001.DBL	1.1
28-03-2017	87	GPS_R_20170328T133620_175559_0001.DBL	0.9
29-03-2017	88	GPS_R_20170329T131653_183826_0001.DBL	1.2
30-03-2017	89	GPS_R_20170330T112116_162143_0001.DBL	2.2
31-03-2017	90	GPS_R_20170331T074707_130849_0001.DBL	1.2
31-03-2017	90	GPS_R_20170331T134206_172142_0001.DBL	0.8
01-04-2017	91	GPS_R_20170401T091537_123202_0001.DBL	0.7

Date	DOY	File	Size [MB]
05-04-2017	95		
07-04-2017	97	GPS_BAS_20170407T184537_195448_0001.DBL	0.2
07-04-2017	97	GPS_BAS_20170407T231855_260758_0001.DBL	0.6
08-04-2017	98	GPS_BAS_20170408T232349_254848_0001.DBL	0.5
11-04-2017	101	GPS_BAS_20170411T152209_194447_0001.DBL	1.0
12-04-2017	102	GPS_BAS_20170412T133637_170330_0001.DBL	0.7
12-04-2017	102	GPS_BAS_20170412T174807_201027_0001.DBL	0.5
13-04-2017	103	GPS_BAS_20170413T134722_193915_0001.DBL	1.3
16-04-2017	106	GPS_BAS_20170416T125227_182215_0001.DBL	1.2
18-04-2017	108	GPS_BAS_20170418T131501_171553_0001.DBL	0.9
19-04-2017	109	GPS_BAS_20170419T125717_152257_0001.DBL	0.5
20-04-2017	110	GPS_BAS_20170420T132537_154338_0001.DBL	0.5
20-04-2017	110	GPS_BAS_20170420T162010_181646_0001.DBL	0.4
21-04-2017	111	GPS_BAS_20170421T114432_165810_0001.DBL	1.1
24-04-2017	114	GPS_BAS_20170424T111031_153612_0001.DBL	1.0
24-04-2017	114	GPS_BAS_20170424T160813_192516_0001.DBL	0.
25-04-2017	115	GPS_BAS_20170425T092431_120837_0001.DBL	0.6
26-04-2017	116	GPS_BAS_20170426T073852_124425_0001.DBL	1.1

18 APPENDIX Processed INS data in ESA format

Processed INS data is delivered in binary, big endian format with each record formatted as described by Cullen (2010).

Date	DOY	File	Size [MB]
19-03-2017	78	INS_20170319T110036_125554_0001.DBL	11.9
20-03-2017	79	INS_20170320T085651_161136_0001.DBL	44.9
20-03-2017	79	INS_20170320T163638_184334_0001.DBL	13.1
21-03-2017	80	INS_20170321T100834_155043_0001.DBL	35.3
21-03-2017	80	INS_20170321T155108_210919_0001.DBL	32.8
24-03-2017	83	INS_20170324T141312_201725_0001.DBL	37.6
27-03-2017	86	INS_20170327T132548_183730_0001.DBL	32.2
28-03-2017	87	INS_20170328T133600_175608_0001.DBL	26.9
28-03-2017	87	INS_20170328T133636_175608_0001.DBL	26.8
29-03-2017	88	INS_20170329T131648_183900_0001.DBL	33.2
30-03-2017	89	INS_20170330T112100_162119_0001.DBL	31.0
31-03-2017	90	INS_20170331T074648_130846_0001.DBL	33.2
31-03-2017	90	INS_20170331T135157_172147_0001.DBL	21.7
01-04-2017	91	INS_20170401T091536_123225_0001.DBL	20.3

Date	DOY	File	Size [MB]
05-04-2017	95		
07-04-2017	97	INS_20170407T184839_195333_0001.DBL	6.7
07-04-2017	97	INS_20170407T232053_260712_0001.DBL	17.2
08-04-2017	98	INS_20170408T232324_254745_0001.DBL	14.9
11-04-2017	101	INS_20170411T152534_194314_0001.DBL	26.6
12-04-2017	102	INS_20170412T134800_170234_0001.DBL	20.1
12-04-2017	102	INS_20170412T180051_200951_0001.DBL	13.3
13-04-2017	103	INS_20170413T134648_193738_0001.DBL	36.2
16-04-2017	106	INS_20170416T130600_182107_0001.DBL	32.5
18-04-2017	108	INS_20170418T132821_134646_0001.DBL	1.9
18-04-2017	108	INS_20170418T140046_143906_0001.DBL	4.0
18-04-2017	108	INS_20170418T144221_171437_0001.DBL	15.7
18-04-2017	108	INS_OXTS_20170418T131454_171546_0001.DBL	124.3
19-04-2017	109	INS_20170419T124333_152219_0001.DBL	16.4
20-04-2017	110	INS_20170420T132727_154224_0001.DBL	13.9
20-04-2017	110	INS_20170420T163122_181549_0001.DBL	10.8
21-04-2017	111	INS_20170421T114614_165727_0001.DBL	32.1
24-04-2017	114	INS_20170424T111350_153502_0001.DBL	27.0
24-04-2017	114	INS_20170424T162136_192404_0001.DBL	18.8
25-04-2017	115	INS_20170425T093824_121733_0001.DBL	16.4
26-04-2017	116	INS_20170426T075024_124306_0001.DBL	30.2

19 APPENDIX Processed ALS data

Date	DOY	File	Size [MB]
19-03-2017	78	ALS_20170319T110602_113659.nc	45.6
20-03-2017	79	ALS_20170320T105545_121334.nc	307.2
		ALS_20170320T121409_132218.nc	287.1
		ALS_20170320T132233_144633.nc	365.3
		ALS_20170320T144700_150838.nc	78.1
		ALS_20170320T154236_160036.nc	83.3
		ALS_20170320T164537_174444.nc	266.9
21-03-2017	80	ALS_20170321T102554_112024.nc	253.4
		ALS_20170321T112050_125511.nc	437.7
		ALS_20170321T125536_134736.nc	252.6
		ALS_20170321T134912_151212.nc	400.4
		ALS_20170321T160048_160418.nc	3.9
		ALS_20170321T162126_172234.nc	289.7
		ALS_20170321T172300_190209.nc	489.5
		ALS_20170321T190258_200602.nc	304.2
		ALS_20170321T200623_210631.nc	289.5
24-03-2017	83	ALS_20170324T142358_153442.nc	316.7
		ALS_20170324T153506_164704.nc	346.5
		ALS_20170324T164745_172338.nc	175.6
		ALS_20170324T172401_183019.nc	328.7
		ALS_20170324T183043_194947.nc	386.1
		ALS_20170324T195011_200759.nc	67.5
27-03-2017	86	ALS_20170327T135357_142809.nc	164.3
		ALS_20170327T143231_154640.nc	358.1
		ALS_20170327T154708_165307.nc	298.3
		ALS_20170327T165325_183321.nc	473.8
28-03-2017	87	ALS_20170328T135614_135717.nc	1.2
		ALS_20170328T135828_152332.nc	155.6
		ALS_20170328T152351_163118.nc	273.8
		ALS_20170328T163143_172233.nc	199.1
29-03-2017	88	ALS_20170329T132339_132411.nc	0.5
		ALS_20170329T132539_142148.nc	218.8
		ALS_20170329T142206_155400.nc	271.8
		ALS_20170329T163625_175559.nc	327.2
30-03-2017	89	ALS_20170330T114441_115617.nc	27.7
		ALS_20170330T125528_132930.nc	119.1
		ALS_20170330T141040_151600.nc	259.2
		ALS_20170330T151635_152433.nc	21.5
		ALS_20170330T155216_155957.nc	20.3
31-03-2017	90	ALS_20170331T080853_085616.nc	171.2
		ALS_20170331T085654_101949.nc	197.7
		ALS_20170331T102013_110651.nc	194.3

01-04-2017	91	ALS_20170331T143356_155502.nc	305.5
		ALS_20170331T170145_171810.nc	71.1
		ALS_20170401T102145_114056.nc	288.2
		ALS_20170401T114120_123148.nc	175.7

Date	DOY	Final file:	File size (MB)
05-04-2017	95		
07-04-2017	97	ALS_20170407T192157_193253.sbi	
		ALS_20170407T233303_255931.sbi	
08-04-2017	98	ALS_20170408T233055_233124.sbi	
		ALS_20170408T233227_254010.sbi	
11-04-2017	101	ALS_20170411T163311_175332.sbi	
12-04-2017	102	ALS_20170412T145430_155627.nc	307.2
13-04-2017	103	ALS_20170413T135740_141622.nc	83.1
		ALS_20170413T142643_164904.nc	785.1
		ALS_20170413T170000_185616.nc	635.7
		ALS_20170413T190000_193459.nc	122.0
16-04-2017	106	ALS_20170416T133911_160025.nc	764.8
		ALS_20170416T160041_174304.nc	585.1
18-04-2017	108	ALS_20170418T133056_134645.nc	48.2
		ALS_20170418T134646_140047.nc	74.6
		ALS_20170418T140047_143906.nc	225.4
		ALS_20170418T143906_144221.nc	18.6
		ALS_20170418T144221_160422.nc	470.1
		ALS_20170418T160439_163458.nc	172.0
20-04-2017	110	ALS_20170420T143616_144540.nc	13.1
		ALS_20170420T144949_151312.nc	112.0
		ALS_20170420T151528_153850.nc	117.8
		ALS_20170420T163154_181326.nc	373.0
21-04-2017	111	ALS_20170421T115653_120306.nc	18.8
		ALS_20170421T121735_131901.nc	195.5
		ALS_20170421T131912_142033.nc	186.4
		ALS_20170421T142045_142813.nc	28.3
24-04-2017	114	ALS_20170424T112125_112757.nc	32.5
		ALS_20170424T134017_152255.nc	490.8
		ALS_20170424T152312_153109.nc	45.6
		ALS_20170424T162307_173551.nc	338.2
		ALS_20170424T173602_181531.nc	166.9
25-04-2017	115	ALS_20170425T102513_103747.nc	49.0
		ALS_20170425T114942_121030.nc	38.6
26-04-2017	116	ALS_20170426T083822_091809.nc	167.2
		ALS_20170426T092036_094932.nc	119.5
		ALS_20170426T095506_104042.nc	149.2
		ALS_20170426T104300_113434.nc	179.1

20 APPENDIX Time-tagged and geo-located images

ASCII file	Date	File name of zipped file	File Size (MB)
PIX_slant_20170320.pos	20-03-2017	PIX_slant_20170320T130929-135959.zip	720.5
		PIX_slant_20170320T140011-142733.zip	427.9
PIX_slant_20170320B.pos	20-03-2017	PIX_slant_20170320T171518-174142.zip	426.8
PIX_slant_20170321A.pos	21-03-2017	PIX_slant_20170321T105059-105959.zip	77.5
		PIX_slant_20170321T110011-115955.zip	424.9
		PIX_slant_20170321T120007-125957.zip	256.2
		PIX_slant_20170321T130007-135955.zip	33.4
		PIX_slant_20170321T140007-145527.zip	406.3
PIX_slant_20170321B.pos	21-03-2017	PIX_slant_20170321T161211-165949.zip	299.1
		PIX_slant_20170321T170001-175517.zip	218.2
		PIX_slant_20170321T180931-185953.zip	112.2
		PIX_slant_20170321T190005-194903.zip	100.1
PIX_slant_20170322.pos	22-03-2017	PIX_slant_20170322T145854-145954.zip	6.0
		PIX_slant_20170322T150006-155950.zip	166.0
		PIX_slant_20170322T160002-165952.zip	44.9
		PIX_slant_20170322T170004-175322.zip	127.4
PIX_slant_20170324.pos	24-03-2017	PIX_slant_20170324T143732-145956.zip	147.8
		PIX_slant_20170324T150008-155950.zip	313.0
		PIX_slant_20170324T160002-165956.zip	326.5
		PIX_slant_20170324T170008-175948.zip	224.4
		PIX_slant_20170324T180000-185956.zip	249.8
		PIX_slant_20170324T190008-195954.zip	344.8
		PIX_slant_20170324T200006-201314.zip	41.6
PIX_slant_20170327.pos	27-03-2017	PIX_slant_20170327T140933-145950.zip	101.3
		PIX_slant_20170327T150002-155950.zip	96.4
		PIX_slant_20170327T160002-165454.zip	159.1
		PIX_slant_20170327T170006-174926.zip	106.1
PIX_slant_20170328.pos	28-03-2017	PIX_slant_20170328T141522-145958.zip	77.4
		PIX_slant_20170328T150008-155956.zip	57.3
		PIX_slant_20170328T160006-165958.zip	133.1
		PIX_slant_20170328T170008-173342.zip	96.5
PIX_slant_20170329.pos	29-03-2017	PIX_slant_20170329T133513-135955.zip	76.6
		PIX_slant_20170329T140007-145951.zip	127.5
		PIX_slant_20170329T150003-150413.zip	13.4
		PIX_slant_20170329T161845-165951.zip	147.2
		PIX_slant_20170329T170003-175719.zip	153.3
PIX_slant_20170330.pos	30-03-2017	PIX_slant_20170330T120104-125956.zip	183.9
		PIX_slant_20170330T130008-135956.zip	157.1
		PIX_slant_20170330T140008-145954.zip	154.7
		PIX_slant_20170330T150006-155956.zip	135.4
		PIX_slant_20170330T160008-160740.zip	17.2
PIX_slant_20170331.pos	31-03-2017	PIX_slant_20170331T090820-095952.zip	61.6
		PIX_slant_20170331T100004-105956.zip	172.0

		PIX_slant_20170331T110008-110826.zip	22.4
ASCII file	Date	File name of zipped file	File Size (MB)
	05-04-2017		
PIX_BAS_20170407.pos	07-04-2017	PIX_BAS_20170407T193112-193912.zip	277.0
PIX_BAS_20170407b.pos	07-04-2017	PIX_BAS_20170407T000002-005956.zip	1,418.3
		PIX_BAS_20170407T010001-015808.zip	1,536.7
		PIX_BAS_20170407T233824-235957.zip	651.0
PIX_BAS_20170408.pos	08-04-2017	PIX_BAS_20170408T010032-014016.zip	2,353.9
		PIX_BAS_20170408T235302-005828.zip	1,237.8
PIX_BAS_20170411.pos	11-04-2017	PIX_BAS_20170411T163713-165958.zip	940.8
		PIX_BAS_20170411T170003-173638.zip	1,642.0
PIX_BAS_20170412.pos	12-04-2017	PIX_BAS_20170412T151012-155637.zip	1,775.7
PIX_BAS_20170413_A.pos	13-04-2017	PIX_BAS_20170413T152651-164802.zip	3,175.3
PIX_BAS_20170413_B.pos		PIX_BAS_20170413T175509-181228.zip	941.9
PIX_BAS_20170413_C.pos		PIX_BAS_20170413T181630-193136.zip	2,061.3
PIX_BAS_20170416.pos	16-04-2017	PIX_BAS_20170416T143357-145955.zip	818.0
		PIX_BAS_20170416T150000-155958.zip	1,052.8
		PIX_BAS_20170416T160003-165957.zip	1,556.7
		PIX_BAS_20170416T170002-175959.zip	1,238.3
		PIX_BAS_20170416T180004-181545.zip	462.2
PIX_BAS_20170418.pos	18-04-2017	PIX_BAS_20170418T134412-135957.zip	660.7
		PIX_BAS_20170418T140002-145958.zip	2,583.1
		PIX_BAS_20170418T150003-155955.zip	2,164.5
		PIX_BAS_20170418T160000-165958.zip	2,541.4
		PIX_BAS_20170418T170003-171323.zip	549.1
PIX_BAS_20170420A.pos	20-04-2017	PIX_BAS_20170420T143804-150429.zip	765.9
PIX_BAS_20170420B.pos	20-04-2017	PIX_BAS_20170420T163249-165957.zip	934.7
		PIX_BAS_20170420T170002-175732.zip	2,159.3
PIX_BAS_20170424.pos	24-04-2017	PIX_BAS_20170424T164647-165957.zip	636.7
		PIX_BAS_20170424T170002-175957.zip	2,645.6
		PIX_BAS_20170424T180002-180957.zip	387.7

21 APPENDIX Processed KAREN data

Date	DOY	File name	Size (MB)
19-03-2017	78	KAR_OPER_Level1b_20170319T112530_20170319T112734_levc.nc	24
		KAR_OPER_Level1b_20170319T112759_20170319T112856_levc.nc	10
		KAR_OPER_Level1b_20170319T112909_20170319T112944_levc.nc	6
		KAR_OPER_Level1b_20170319T134213_20170319T135126_levc.nc	719
		KAR_OPER_Level1b_20170319T135321_20170319T135911_levc.nc	447
		KAR_OPER_Level1b_20170319T140032_20170319T141319_levc.nc	940
		KAR_OPER_Level1b_20170319T141516_20170319T143217_levc.nc	1962
		KAR_OPER_Level1b_20170319T143306_20170319T144751_levc.nc	1137
		KAR_OPER_Level1b_20170319T151230_20170319T151648_levc.nc	48
		KAR_OPER_Level1b_20170319T151808_20170319T152324_levc.nc	47
20-03-2017	79	KAR_OPER_Level1b_20170320T141519_20170320T142515_levc.nc	116
		KAR_OPER_Level1b_20170320T142858_20170320T144030_levc.nc	292
		KAR_OPER_Level1b_20170320T180818_20170320T180956_levc.nc	13
		KAR_OPER_Level1b_20170320T170829_20170320T172829_levc.nc	330
		KAR_OPER_Level1b_20170320T172937_20170320T173940_levc.nc	152
		KAR_OPER_Level1b_20170320T181333_20170320T181430_levc.nc	8
21-03-2017	80	KAR_OPER_Level1b_20170321T104910_20170321T110906_levc.nc	355
		KAR_OPER_Level1b_20170321T114323_20170321T114632_levc.nc	46
		KAR_OPER_Level1b_20170321T114654_20170321T121653_levc.nc	521
		KAR_OPER_Level1b_20170321T121804_20170321T123828_levc.nc	355
		KAR_OPER_Level1b_20170321T124024_20170321T125356_levc.nc	223
		KAR_OPER_Level1b_20170321T130346_20170321T130724_levc.nc	37
		KAR_OPER_Level1b_20170321T131053_20170321T133006_levc.nc	226
		KAR_OPER_Level1b_20170321T133414_20170321T134432_levc.nc	116
		KAR_OPER_Level1b_20170321T135108_20170321T140008_levc.nc	100
		KAR_OPER_Level1b_20170321T140904_20170321T142916_levc.nc	212
		KAR_OPER_Level1b_20170321T143028_20170321T145052_levc.nc	236
		KAR_OPER_Level1b_20170321T145222_20170321T145630_levc.nc	63
		KAR_OPER_Level1b_20170321T160835_20170321T162832_levc.nc	381
		KAR_OPER_Level1b_20170321T163008_20170321T170004_levc.nc	476
		KAR_OPER_Level1b_20170321T171329_20170321T174339_levc.nc	436
		KAR_OPER_Level1b_20170321T174729_20170321T181740_levc.nc	488
		KAR_OPER_Level1b_20170321T182001_20170321T190205_levc.nc	698
		KAR_OPER_Level1b_20170321T190504_20170321T190903_levc.nc	63
		KAR_OPER_Level1b_20170321T191725_20170321T194729_levc.nc	512
		KAR_OPER_Level1b_20170321T195102_20170321T202104_levc.nc	539
		KAR_OPER_Level1b_20170321T202359_20170321T203217_levc.nc	127
22-03-2017	81	KAR_OPER_Level1b_20170322T145001_20170322T145810_levc.nc	81
		KAR_OPER_Level1b_20170322T145841_20170322T150952_levc.nc	114
		KAR_OPER_Level1b_20170322T151119_20170322T152121_levc.nc	101
		KAR_OPER_Level1b_20170322T152229_20170322T153319_levc.nc	112
		KAR_OPER_Level1b_20170322T153427_20170322T154352_levc.nc	681
		KAR_OPER_Level1b_20170322T154942_20170322T160520_levc.nc	1559
		KAR_OPER_Level1b_20170322T161058_20170322T162907_levc.nc	1246
		KAR_OPER_Level1b_20170322T163117_20170322T170140_levc.nc	2146
		KAR_OPER_Level1b_20170322T171105_20170322T171641_levc.nc	601

24-03-2017	83	KAR_OPER_Level1b_20170324T145352_20170324T152347_levc.nc	463
		KAR_OPER_Level1b_20170324T152402_20170324T154214_levc.nc	256
		KAR_OPER_Level1b_20170324T154229_20170324T161240_levc.nc	442
		KAR_OPER_Level1b_20170324T161252_20170324T162751_levc.nc	219
		KAR_OPER_Level1b_20170324T162806_20170324T165803_levc.nc	478
		KAR_OPER_Level1b_20170324T165818_20170324T172144_levc.nc	438
		KAR_OPER_Level1b_20170324T173155_20170324T180151_levc.nc	489
		KAR_OPER_Level1b_20170324T181336_20170324T181502_levc.nc	21
		KAR_OPER_Level1b_20170324T182151_20170324T184112_levc.nc	314
		KAR_OPER_Level1b_20170324T184142_20170324T185819_levc.nc	269
		KAR_OPER_Level1b_20170324T191430_20170324T193359_levc.nc	315
		KAR_OPER_Level1b_20170324T193656_20170324T194435_levc.nc	118
27-03-2017	86	KAR_OPER_Level1b_20170327T140415_20170327T141000_levc.nc	93
		KAR_OPER_Level1b_20170327T141144_20170327T142005_levc.nc	126
		KAR_OPER_Level1b_20170327T143544_20170327T143739_levc.nc	29
		KAR_OPER_Level1b_20170327T143815_20170327T144810_levc.nc	153
		KAR_OPER_Level1b_20170327T144827_20170327T150042_levc.nc	190
		KAR_OPER_Level1b_20170327T150206_20170327T151201_levc.nc	161
		KAR_OPER_Level1b_20170327T151309_20170327T151747_levc.nc	71
		KAR_OPER_Level1b_20170327T151759_20170327T153806_levc.nc	343
		KAR_OPER_Level1b_20170327T153820_20170327T154508_levc.nc	106
		KAR_OPER_Level1b_20170327T155115_20170327T161115_levc.nc	335
		KAR_OPER_Level1b_20170327T161227_20170327T163234_levc.nc	358
		KAR_OPER_Level1b_20170327T163256_20170327T163549_levc.nc	46
		KAR_OPER_Level1b_20170327T164023_20170327T170023_levc.nc	310
		KAR_OPER_Level1b_20170327T170103_20170327T170658_levc.nc	87
		KAR_OPER_Level1b_20170327T170716_20170327T171146_levc.nc	67
		KAR_OPER_Level1b_20170327T171313_20170327T171721_levc.nc	62
		KAR_OPER_Level1b_20170327T171944_20170327T172939_levc.nc	147
		KAR_OPER_Level1b_20170327T173057_20170327T173340_levc.nc	41
		KAR_OPER_Level1b_20170327T173415_20170327T174646_levc.nc	212
		KAR_OPER_Level1b_20170327T174719_20170327T175137_levc.nc	65
28-03-2017	87	KAR_OPER_Level1b_20170328T140607_20170328T140832_levc.nc	41
		KAR_OPER_Level1b_20170328T141101_20170328T141209_levc.nc	20
		KAR_OPER_Level1b_20170328T141905_20170328T143725_levc.nc	325
		KAR_OPER_Level1b_20170328T143851_20170328T144548_levc.nc	185
		KAR_OPER_Level1b_20170328T145833_20170328T145853_levc.nc	3
		KAR_OPER_Level1b_20170328T151528_20170328T151625_levc.nc	22
		KAR_OPER_Level1b_20170328T151939_20170328T153715_levc.nc	3300
		KAR_OPER_Level1b_20170328T154035_20170328T155029_levc.nc	885
		KAR_OPER_Level1b_20170328T155656_20170328T162651_levc.nc	1473
		KAR_OPER_Level1b_20170328T163213_20170328T165721_levc.nc	1397
		KAR_OPER_Level1b_20170328T165739_20170328T170235_levc.nc	263
29-03-2017	88	KAR_OPER_Level1b_20170329T134011_20170329T140003_levc.nc	249
		KAR_OPER_Level1b_20170329T140321_20170329T142315_levc.nc	221
		KAR_OPER_Level1b_20170329T150319_20170329T151332_levc.nc	923
		KAR_OPER_Level1b_20170329T153148_20170329T153234_levc.nc	15
		KAR_OPER_Level1b_20170329T153314_20170329T153921_levc.nc	645
		KAR_OPER_Level1b_20170329T154025_20170329T155342_levc.nc	1401

		KAR_OPER_Level1b_20170329T162314_20170329T164309_levc.nc	288
		KAR_OPER_Level1b_20170329T164322_20170329T171720_levc.nc	473
		KAR_OPER_Level1b_20170329T172047_20170329T175039_levc.nc	416
31-03-2017	90	KAR_OPER_Level1b_20170331T090724_20170331T094143_levc.nc	480
		KAR_OPER_Level1b_20170331T094203_20170331T101202_levc.nc	399
		KAR_OPER_Level1b_20170331T101430_20170331T104619_levc.nc	454
		KAR_OPER_Level1b_20170331T104652_20170331T105244_levc.nc	73
		KAR_OPER_Level1b_20170331T105715_20170331T110325_levc.nc	82
		KAR_OPER_Level1b_20170331T145126_20170331T145658_levc.nc	273
		KAR_OPER_Level1b_20170331T145710_20170331T150703_levc.nc	565
		KAR_OPER_Level1b_20170331T150716_20170331T151810_levc.nc	625
		KAR_OPER_Level1b_20170331T152259_20170331T152401_levc.nc	18
		KAR_OPER_Level1b_20170331T153253_20170331T153605_levc.nc	99
		KAR_OPER_Level1b_20170331T153622_20170331T155312_levc.nc	1282
		KAR_OPER_Level1b_20170331T170431_20170331T170459_levc.nc	7
		KAR_OPER_Level1b_20170331T170802_20170331T170858_levc.nc	13
		KAR_OPER_Level1b_20170331T171221_20170331T171324_levc.nc	23
01-04-2017	91	KAR_OPER_Level1b_20170401T104255_20170401T104828_levc.nc	160
		KAR_OPER_Level1b_20170401T104842_20170401T111122_levc.nc	1415
		KAR_OPER_Level1b_20170401T111134_20170401T111257_levc.nc	25
		KAR_OPER_Level1b_20170401T111805_20170401T111932_levc.nc	20
		KAR_OPER_Level1b_20170401T112643_20170401T112808_levc.nc	20
		KAR_OPER_Level1b_20170401T112820_20170401T115026_levc.nc	1107
		KAR_OPER_Level1b_20170401T115213_20170401T115504_levc.nc	50
		KAR_OPER_Level1b_20170401T115519_20170401T121527_levc.nc	967
		KAR_OPER_Level1b_20170401T121549_20170401T122744_levc.nc	527

Campaign 2017 - Phase 2

Date	DOY	File name	Size (MB)
05-04-2017	95	KAR_OPER_Level1b_20170405T213754_20170405T214949_levc.nc	200
		KAR_OPER_Level1b_20170405T215525_20170405T220823_levc.nc	285
		KAR_OPER_Level1b_20170405T221401_20170405T222543_levc.nc	216
		KAR_OPER_Level1b_20170405T223027_20170405T224224_levc.nc	210
		KAR_OPER_Level1b_20170405T224942_20170405T230125_levc.nc	211
		KAR_OPER_Level1b_20170405T230625_20170405T231834_levc.nc	209
		KAR_OPER_Level1b_20170405T232313_20170405T233413_levc.nc	193
		KAR_OPER_Level1b_20170405T233742_20170405T233846_levc.nc	13
07-04-2017	97	KAR_OPER_Level1b_20170407T192536_20170407T193316_levc.nc	208
		KAR_OPER_Level1b_20170407T233847_20170407T234924_levc.nc	214
		KAR_OPER_Level1b_20170407T235209_20170407T235548_levc.nc	64
		KAR_OPER_Level1b_20170407T235908_20170408T000809_levc.nc	139
		KAR_OPER_Level1b_20170408T001959_20170408T003308_levc.nc	332
		KAR_OPER_Level1b_20170408T003215_20170408T003955_levc.nc	107
		KAR_OPER_Level1b_20170408T005231_20170408T010046_levc.nc	221
		KAR_OPER_Level1b_20170408T010607_20170408T011403_levc.nc	224
		KAR_OPER_Level1b_20170408T011522_20170408T012248_levc.nc	155
		KAR_OPER_Level1b_20170408T012502_20170408T013236_levc.nc	164
		KAR_OPER_Level1b_20170408T013345_20170408T014247_levc.nc	190
		KAR_OPER_Level1b_20170408T014400_20170408T015302_levc.nc	196
		KAR_OPER_Level1b_20170408T015442_20170408T015840_levc.nc	82
		KAR_OPER_Level1b_20170408T233452_20170408T233543_levc.nc	28
08-04-2017	98	KAR_OPER_Level1b_20170408T233822_20170408T234546_levc.nc	261
		KAR_OPER_Level1b_20170408T234709_20170408T234954_levc.nc	36
		KAR_OPER_Level1b_20170408T235235_20170409T000053_levc.nc	241
		KAR_OPER_Level1b_20170409T000242_20170409T001118_levc.nc	190
		KAR_OPER_Level1b_20170409T001427_20170409T002253_levc.nc	229
		KAR_OPER_Level1b_20170409T002539_20170409T002820_levc.nc	52
		KAR_OPER_Level1b_20170409T003055_20170409T003501_levc.nc	51
		KAR_OPER_Level1b_20170409T003726_20170409T003947_levc.nc	46
		KAR_OPER_Level1b_20170409T004227_20170409T004635_levc.nc	44
		KAR_OPER_Level1b_20170409T004933_20170409T005213_levc.nc	49
		KAR_OPER_Level1b_20170409T005357_20170409T005806_levc.nc	54
		KAR_OPER_Level1b_20170409T010021_20170409T010249_levc.nc	45
		KAR_OPER_Level1b_20170409T010432_20170409T010818_levc.nc	52
		KAR_OPER_Level1b_20170409T011044_20170409T011252_levc.nc	39
		KAR_OPER_Level1b_20170409T011502_20170409T011830_levc.nc	42
		KAR_OPER_Level1b_20170409T012018_20170409T012208_levc.nc	37
		KAR_OPER_Level1b_20170409T012404_20170409T013034_levc.nc	127
		KAR_OPER_Level1b_20170409T013235_20170409T014059_levc.nc	267
11-04-2017	101	KAR_OPER_Level1b_20170411T163647_20170411T165308_levc.nc	202
		KAR_OPER_Level1b_20170411T165356_20170411T171314_levc.nc	237
		KAR_OPER_Level1b_20170411T171327_20170411T173310_levc.nc	244
		KAR_OPER_Level1b_20170411T173326_20170411T173608_levc.nc	32
12-04-2017	102	KAR_OPER_Level1b_20170412T151016_20170412T152548_levc.nc	280

13-04-2017	103	KAR_OPER_Level1b_20170412T152601_20170412T153853_levc.nc	174
		KAR_OPER_Level1b_20170412T153938_20170412T155610_levc.nc	334
		KAR_OPER_Level1b_20170413T140145_20170413T141608_levc.nc	232
		KAR_OPER_Level1b_20170413T142704_20170413T143733_levc.nc	166
		KAR_OPER_Level1b_20170413T143801_20170413T144847_levc.nc	190
		KAR_OPER_Level1b_20170413T144901_20170413T145828_levc.nc	149
		KAR_OPER_Level1b_20170413T145841_20170413T150811_levc.nc	124
		KAR_OPER_Level1b_20170413T150843_20170413T151823_levc.nc	142
		KAR_OPER_Level1b_20170413T151836_20170413T153329_levc.nc	194
		KAR_OPER_Level1b_20170413T153342_20170413T154752_levc.nc	247
		KAR_OPER_Level1b_20170413T154804_20170413T160945_levc.nc	360
		KAR_OPER_Level1b_20170413T160957_20170413T162858_levc.nc	289
		KAR_OPER_Level1b_20170413T162910_20170413T164756_levc.nc	418
		KAR_OPER_Level1b_20170413T165404_20170413T171030_levc.nc	385
		KAR_OPER_Level1b_20170413T171044_20170413T172736_levc.nc	340
		KAR_OPER_Level1b_20170413T172749_20170413T174751_levc.nc	399
		KAR_OPER_Level1b_20170413T174807_20170413T175900_levc.nc	196
		KAR_OPER_Level1b_20170413T175913_20170413T181203_levc.nc	197
		KAR_OPER_Level1b_20170413T181216_20170413T182345_levc.nc	180
		KAR_OPER_Level1b_20170413T182357_20170413T183540_levc.nc	220
		KAR_OPER_Level1b_20170413T183558_20170413T185318_levc.nc	337
		KAR_OPER_Level1b_20170413T190833_20170413T191422_levc.nc	434
		KAR_OPER_Level1b_20170413T192741_20170413T193128_levc.nc	139
16-04-2017	106	KAR_OPER_Level1b_20170416T134523_20170416T135805_levc.nc	204
		KAR_OPER_Level1b_20170416T135818_20170416T141449_levc.nc	290
		KAR_OPER_Level1b_20170416T141501_20170416T142330_levc.nc	124
		KAR_OPER_Level1b_20170416T142407_20170416T143201_levc.nc	152
		KAR_OPER_Level1b_20170416T143222_20170416T144852_levc.nc	296
		KAR_OPER_Level1b_20170416T145233_20170416T150931_levc.nc	370
		KAR_OPER_Level1b_20170416T151110_20170416T152413_levc.nc	294
		KAR_OPER_Level1b_20170416T152619_20170416T154145_levc.nc	225
		KAR_OPER_Level1b_20170416T160609_20170416T161714_levc.nc	165
		KAR_OPER_Level1b_20170416T161728_20170416T162918_levc.nc	223
		KAR_OPER_Level1b_20170416T162932_20170416T164226_levc.nc	156
		KAR_OPER_Level1b_20170416T164245_20170416T165256_levc.nc	130
		KAR_OPER_Level1b_20170416T165309_20170416T170312_levc.nc	130
		KAR_OPER_Level1b_20170416T170325_20170416T171314_levc.nc	153
		KAR_OPER_Level1b_20170416T171326_20170416T172552_levc.nc	178
		KAR_OPER_Level1b_20170416T172608_20170416T173708_levc.nc	137
		KAR_OPER_Level1b_20170416T173721_20170416T175016_levc.nc	238
		KAR_OPER_Level1b_20170416T175201_20170416T180826_levc.nc	518
		KAR_OPER_Level1b_20170416T180843_20170416T181500_levc.nc	135
18-04-2017	108	KAR_OPER_Level1b_20170418T135016_20170418T140219_levc.nc	175
		KAR_OPER_Level1b_20170418T140234_20170418T141230_levc.nc	123
		KAR_OPER_Level1b_20170418T142524_20170418T142820_levc.nc	38
		KAR_OPER_Level1b_20170418T143134_20170418T143742_levc.nc	96
		KAR_OPER_Level1b_20170418T143930_20170418T144342_levc.nc	58
		KAR_OPER_Level1b_20170418T144404_20170418T144608_levc.nc	24
		KAR_OPER_Level1b_20170418T144755_20170418T145441_levc.nc	87
		KAR_OPER_Level1b_20170418T145629_20170418T150226_levc.nc	78

		KAR_OPER_Level1b_20170418T150359_20170418T151106_levc.nc	101
		KAR_OPER_Level1b_20170418T151217_20170418T151853_levc.nc	102
		KAR_OPER_Level1b_20170418T152023_20170418T152650_levc.nc	81
		KAR_OPER_Level1b_20170418T152842_20170418T153456_levc.nc	88
		KAR_OPER_Level1b_20170418T153638_20170418T154313_levc.nc	90
		KAR_OPER_Level1b_20170418T155020_20170418T155624_levc.nc	89
		KAR_OPER_Level1b_20170418T155837_20170418T160526_levc.nc	180
		KAR_OPER_Level1b_20170418T160545_20170418T161456_levc.nc	168
		KAR_OPER_Level1b_20170418T161519_20170418T162603_levc.nc	209
		KAR_OPER_Level1b_20170418T162616_20170418T163536_levc.nc	252
		KAR_OPER_Level1b_20170418T163718_20170418T164255_levc.nc	149
		KAR_OPER_Level1b_20170418T164346_20170418T165114_levc.nc	222
		KAR_OPER_Level1b_20170418T165127_20170418T170024_levc.nc	177
		KAR_OPER_Level1b_20170418T170040_20170418T170836_levc.nc	166
		KAR_OPER_Level1b_20170418T170912_20170418T171025_levc.nc	10
24-04-2017	114	KAR_OPER_Level1b_20170424T162936_20170424T163852_levc.nc	862
		KAR_OPER_Level1b_20170424T163905_20170424T164750_levc.nc	935
		KAR_OPER_Level1b_20170424T164853_20170424T165811_levc.nc	175
		KAR_OPER_Level1b_20170424T165836_20170424T170721_levc.nc	151
		KAR_OPER_Level1b_20170424T170734_20170424T171616_levc.nc	147
		KAR_OPER_Level1b_20170424T171629_20170424T172515_levc.nc	165
		KAR_OPER_Level1b_20170424T172533_20170424T173431_levc.nc	230
		KAR_OPER_Level1b_20170424T173444_20170424T174343_levc.nc	185
		KAR_OPER_Level1b_20170424T174354_20170424T175312_levc.nc	255
		KAR_OPER_Level1b_20170424T175324_20170424T180210_levc.nc	164
		KAR_OPER_Level1b_20170424T180225_20170424T181406_levc.nc	321
		KAR_OPER_Level1b_20170425T115656_20170425T120506_levc.nc	267
25-04-2017	115	KAR_OPER_Level1b_20170425T102824_20170425T104556_levc.nc	2034
		KAR_OPER_Level1b_20170425T104737_20170425T105252_levc.nc	214
26-04-2017	116	KAR_OPER_Level1b_20170426T084727_20170426T085805_levc.nc	745
		KAR_OPER_Level1b_20170426T085816_20170426T091405_levc.nc	1062
		KAR_OPER_Level1b_20170426T091418_20170426T092842_levc.nc	1398
		KAR_OPER_Level1b_20170426T092950_20170426T093450_levc.nc	247
		KAR_OPER_Level1b_20170426T093726_20170426T094625_levc.nc	322
		KAR_OPER_Level1b_20170426T094903_20170426T095041_levc.nc	26
		KAR_OPER_Level1b_20170426T095611_20170426T100321_levc.nc	448
		KAR_OPER_Level1b_20170426T101544_20170426T102131_levc.nc	314
		KAR_OPER_Level1b_20170426T102515_20170426T103119_levc.nc	292
		KAR_OPER_Level1b_20170426T103445_20170426T104036_levc.nc	311
		KAR_OPER_Level1b_20170426T104340_20170426T104932_levc.nc	257
		KAR_OPER_Level1b_20170426T105358_20170426T105950_levc.nc	251
		KAR_OPER_Level1b_20170426T110853_20170426T111509_levc.nc	262
		KAR_OPER_Level1b_20170426T111744_20170426T112502_levc.nc	312
		KAR_OPER_Level1b_20170426T112853_20170426T113449_levc.nc	275
		KAR_OPER_Level1b_20170426T113928_20170426T114439_levc.nc	329

22 APPENDIX Processed ASIRAS data

The following recorded data are available for the ASIRAS radar system and given in the ESA format described in Cullen (2010).

Date	DOY	File name	Size (MB)
19-03-2017	78	AS6OA00_ASIWL1B040320170319T091111_20170319T091215_0001.DBL	1.7
		AS6OA01_ASIWL1B040320170319T111001_20170319T112951_0001.DBL	30.7
20-03-2017	79	AS6OA00_ASIWL1B040320170320T111135_20170320T144307_0001.DBL	312.2
		AS6OA01_ASIWL1B040320170320T170611_20170320T174033_0001.DBL	51.6
21-03-2017	80	AS6OA00_ASIWL1B040320170321T103056_20170321T145631_0001.DBL	381.5
		AS6OA01_ASIWL1B040320170321T160529_20170321T203821_0001.DBL	398.9
24-03-2017	83	AS6OA00_ASIWL1B040320170324T142820_20170324T194516_0001.DBL	423.7
27-03-2017	86	AS6OA00_ASIWL1B040320170327T135900_20170327T181741_0001.DBL	409.2
28-03-2017	87	AS6OA00_ASIWL1B040320170328T135837_20170328T144625_0001.DBL	61.2
		AS6OA01_ASIWL1B040320170328T151757_20170328T171842_0001.DBL	183.5
29-03-2017	88	AS6OA00_ASIWL1B040320170329T132551_20170329T143431_0001.DBL	107.9
		AS6OA01_ASIWL1B040320170329T143832_20170329T144221_0001.DBL	4.2
		AS6OA02_ASIWL1B040320170329T144831_20170329T145138_0001.DBL	2.5
		AS6OA03_ASIWL1B040320170329T145210_20170329T152353_0001.DBL	34.5
		AS6OA04_ASIWL1B040320170329T153052_20170329T161746_0001.DBL	60
		AS6OA05_ASIWL1B040320170329T161932_20170329T175059_0001.DBL	94.8
30-03-2017	89	AS6OA00_ASIWL1B040320170330T115810_20170330T120728_0001.DBL	12.9
		AS6OA01_ASIWL1B040320170330T122245_20170330T152741_0001.DBL	266.9
		AS6OA02_ASIWL1B040320170330T155449_20170330T155949_0001.DBL	6.7
31-03-2017	90	AS6OA00_ASIWL1B040320170331T090044_20170331T110329_0001.DBL	183.8
		AS6OA01_ASIWL1B040320170331T143546_20170331T155542_0001.DBL	123.5
		AS6OA02_ASIWL1B040320170331T170132_20170331T170922_0001.DBL	10.9
01-04-2017	91	AS6OA00_ASIWL1B040320170401T103244_20170401T122820_0001.DBL	186.7

23 APPENDIX Final ASIRAS profiles

Following plots show all processed ASIRAS profiles using the OCOG retracker. Each profile plot consists of four parts:

1. Header composed of daily profile number and the date and a sub-header with the filename.
2. Geographical plot of the profile (diamond indicates the start of the profile).
3. Rough indication of the heights as determined with the OCOG retracker plotted versus time of day in seconds.
4. Info box with date, start and stop times in hour, minute, seconds, and in square brackets seconds of the day, acquisition mode etc.

It should be emphasized that the surface height determined by the OCOG retracker is a rough estimate and not necessarily a true height.

A170319_00

AS60A00_ASIWL1B040320170319T091111_20170319T091215_0001.DBL

Date	2017-03-19	Instrument Mode	Adv. Low Altitude
Start Time	09:11:13 (33073)	Aircraft	BAS Twin Otter
Stop Time	09:12:16 (33136)	Retrocker	OCOG
Distance	4.421 km	INS Resolution	50 Hz
Duration	00 h 01 m 04 s	Processor Version	0403

A170319_01

AS60A01_ASIWL1B040320170319T11001_20170319T112951_0001.DBL

Date	2017-03-19	Instrument Mode	Adv. Low Altitude
Start Time	11:10:03 (40203)	Aircraft	BAS Twin Otter
Stop Time	11:29:52 (41392)	Retrocker	OCOG
Distance	81.863 km	INS Resolution	50 Hz
Duration	00 h 19 m 49 s	Processor Version	0403

A170320_00

AS60A00_ASIWL1B040320170320T111135_20170320T144307_0001.DBL

Date	2017-03-20	Instrument Mode	Adv. Low Altitude
Start Time	11:11:37 (40297)	Aircraft	BAS Twin Otter
Stop Time	14:43:08 (52988)	Retrocker	OCOG
Distance	854.639 km	INS Resolution	50 Hz
Duration	03 h 31 m 32 s	Processor Version	0403

A170320_01

AS60A01_ASIWL1B040320170320T170611_20170320T174033_0001.DBL

Date	2017-03-20	Instrument Mode	Adv. Low Altitude
Start Time	17:06:13 (61573)	Aircraft	BAS Twin Otter
Stop Time	17:40:34 (63634)	Retrocker	OCOG
Distance	139.700 km	INS Resolution	50 Hz
Duration	00 h 34 m 22 s	Processor Version	0403

A170321_00

AS60A00_ASIWL1B040320170321T1103056_20170321T145631_0001.DBL

Date	2017-03-21	Instrument Mode	Adv. Low Altitude
Start Time	10:30:58 (37858)	Aircraft	BAS Twin Otter
Stop Time	14:56:32 (53792)	Retracker	OCOG
Distance	1056.135 km	INS Resolution	50 Hz
Duration	04 h 25 m 35 s	Processor Version	0403

A170321_01

AS60A01_ASIWL1B040320170321T160529_20170321T203821_0001.DBL

Date	2017-03-21	Instrument Mode	Adv. Low Altitude
Start Time	16:05:31 (57931)	Aircraft	BAS Twin Otter
Stop Time	20:38:22 (74302)	Retracker	OCOG
Distance	1095.631 km	INS Resolution	50 Hz
Duration	04 h 32 m 52 s	Processor Version	0403

A170324_00

AS60A00_ASIWL1B040320170324T142820_20170324T194516_0001.DBL

Date	2017-03-24	Instrument Mode	Adv. Low Altitude
Start Time	14:28:22 (52102)	Aircraft	BAS Twin Otter
Stop Time	19:45:17 (71117)	Retracker	OCOG
Distance	1213.158 km	INS Resolution	50 Hz
Duration	05 h 16 m 55 s	Processor Version	0403

A170327_00

AS60A00_ASIWL1B040320170327T135900_20170327T181741_0001.DBL

Date	2017-03-27	Instrument Mode	Adv. Low Altitude
Start Time	13:59:02 (50342)	Aircraft	BAS Twin Otter
Stop Time	18:17:42 (65862)	Retracker	OCOG
Distance	1078.659 km	INS Resolution	50 Hz
Duration	04 h 18 m 41 s	Processor Version	0403

A170328_00

AS60A00_ASIWL1B040320170328T135837_20170328T144625_0001.DBL

Date	2017-03-28	Instrument Mode	Adv. Low Altitude
Start Time	13:58:39 (50319)	Aircraft	BAS Twin Otter
Stop Time	14:46:26 (53186)	Retrocker	OCOG
Distance	178.639 km	INS Resolution	50 Hz
Duration	00 h 47 m 47 s	Processor Version	0403

A170328_01

AS60A01_ASIWL1B040320170328T151757_20170328T171842_0001.DBL

Date	2017-03-28	Instrument Mode	Adv. Low Altitude
Start Time	15:17:59 (55079)	Aircraft	BAS Twin Otter
Stop Time	17:18:43 (62323)	Retrocker	OCOG
Distance	496.274 km	INS Resolution	50 Hz
Duration	02 h 00 m 45 s	Processor Version	0403

A170329_00

AS60A00_ASIWL1B040320170329T132551_20170329T143431_0001.DBL

Date	2017-03-29	Instrument Mode	Adv. Low Altitude
Start Time	13:25:53 (48353)	Aircraft	BAS Twin Otter
Stop Time	14:34:32 (52472)	Retrocker	OCOG
Distance	285.936 km	INS Resolution	50 Hz
Duration	01 h 08 m 39 s	Processor Version	0403

A170329_01

AS60A01_ASIWL1B040320170329T143832_20170329T144221_0001.DBL

Date	2017-03-29	Instrument Mode	Adv. Low Altitude
Start Time	14:38:34 (52714)	Aircraft	BAS Twin Otter
Stop Time	14:42:22 (52942)	Retrocker	OCOG
Distance	14.653 km	INS Resolution	50 Hz
Duration	00 h 03 m 49 s	Processor Version	0403

A170329_02

AS60A02_ASIML18040320170329T144831_20170329T145138_0001.DBL

Date	2017-03-29	Instrument Mode	Adv. Low Altitude
Start Time	14:48:33 (53313)	Aircraft	BAS Twin Otter
Stop Time	14:51:40 (53500)	Retrocker	OCOg
Distance	12.586 km	INS Resolution	50 Hz
Duration	00 h 03 m 07 s	Processor Version	0403

A170329_03

AS60A03_ASIML18040320170329T145210_20170329T152353_0001.DBL

Date	2017-03-29	Instrument Mode	Adv. Low Altitude
Start Time	14:52:12 (53532)	Aircraft	BAS Twin Otter
Stop Time	15:23:54 (55434)	Retrocker	OCOg
Distance	131.076 km	INS Resolution	50 Hz
Duration	00 h 31 m 42 s	Processor Version	0403

A170329_04

AS60A04_ASIML18040320170329T153052_20170329T161746_0001.DBL

Date	2017-03-29	Instrument Mode	Adv. Low Altitude
Start Time	15:30:54 (55854)	Aircraft	BAS Twin Otter
Stop Time	16:17:47 (58667)	Retrocker	OCOg
Distance	197.282 km	INS Resolution	50 Hz
Duration	00 h 46 m 53 s	Processor Version	0403

A170329_05

AS60A05_ASIML18040320170329T161932_20170329T175059_0001.DBL

Date	2017-03-29	Instrument Mode	Adv. Low Altitude
Start Time	16:19:34 (58774)	Aircraft	BAS Twin Otter
Stop Time	17:51:00 (64260)	Retrocker	OCOg
Distance	309.418 km	INS Resolution	50 Hz
Duration	01 h 31 m 26 s	Processor Version	0403

A170330_00

AS60A00_ASIWL1B040320170330T115810_20170330T120728_0001.DBL

Date	2017-03-30	Instrument Mode	Adv. Low Altitude
Start Time	11:58:12 (43092)	Aircraft	BAS Twin Otter
Stop Time	12:07:29 (43649)	Retracker	OCOG
Distance	39.451 km	INS Resolution	50 Hz
Duration	00 h 09 m 17 s	Processor Version	0403

A170330_01

AS60A01_ASIWL1B040320170330T122245_20170330T152741_0001.DBL

Date	2017-03-30	Instrument Mode	Adv. Low Altitude
Start Time	12:22:47 (44567)	Aircraft	BAS Twin Otter
Stop Time	15:27:41 (55661)	Retracker	OCOG
Distance	741.478 km	INS Resolution	50 Hz
Duration	03 h 04 m 55 s	Processor Version	0403

A170330_02

AS60A02_ASIWL1B040320170330T155449_20170330T155949_0001.DBL

Date	2017-03-30	Instrument Mode	Adv. Low Altitude
Start Time	15:54:51 (57291)	Aircraft	BAS Twin Otter
Stop Time	15:59:50 (57590)	Retracker	OCOG
Distance	21.000 km	INS Resolution	50 Hz
Duration	00 h 04 m 60 s	Processor Version	0403

A170331_00

AS60A00_ASIWL1B040320170331T090044_20170331T110329_0001.DBL

Date	2017-03-31	Instrument Mode	Adv. Low Altitude
Start Time	09:00:46 (32446)	Aircraft	BAS Twin Otter
Stop Time	11:03:30 (39810)	Retracker	OCOG
Distance	498.698 km	INS Resolution	50 Hz
Duration	02 h 02 m 45 s	Processor Version	0403

A170331_01

AS60A01_ASIWL18040320170331T143546_20170331T155542_0001.DBL

Date	2017-03-31	Instrument Mode	Adv. Low Altitude
Start Time	14:35:48 (52548)	Aircraft	BAS Twin Otter
Stop Time	15:55:43 (57343)	Retracker	OCOG
Distance	332.817 km	INS Resolution	50 Hz
Duration	01 h 19 m 56 s	Processor Version	0403

A170331_02

AS60A02_ASIWL18040320170331T170132_20170331T170922_0001.DBL

Date	2017-03-31	Instrument Mode	Adv. Low Altitude
Start Time	17:01:34 (61294)	Aircraft	BAS Twin Otter
Stop Time	17:09:23 (61763)	Retracker	OCOG
Distance	32.276 km	INS Resolution	50 Hz
Duration	00 h 07 m 50 s	Processor Version	0403

A170401_00

AS60A00_ASIWL18040320170401T103244_20170401T122820_0001.DBL

Date	2017-04-01	Instrument Mode	Adv. Low Altitude
Start Time	10:32:46 (37966)	Aircraft	BAS Twin Otter
Stop Time	12:28:21 (44901)	Retracker	OCOG
Distance	487.395 km	INS Resolution	50 Hz
Duration	01 h 55 m 36 s	Processor Version	0403

24 APPENDIX KAREN processing documentation

KAREN Altimeter

Processing chain and file format

Reference Code : MS-DTU-KAR-03- PFF-032
Issue : 3.2
Date : 4th July 2019

MetaSensing BV
Huygensstraat 44
2201DK Noordwijk, The Netherlands
Tel.: +31 71 751 5960
Email: info@metasensing.com

Document Status Log

Issue	Change description	Date
1.0	First version	13 Aug 2018
1.1	Additional sections included	20 Aug 2018
1.2	Editing correction and formatting	22 Aug 2018
2.0	Approval	29 Aug 2018
2.1	Implemented comments from DTU	25 Oct 2018
2.2	Implemented comments from ESA	5 Nov 2018
2.3	Implemented additional comments from ESA	12 Dec 2018
3.0	Approval	14 Dec 2018
3.1	Minor correction and approval	10 Jan 2019
3.2	Added the .levc description in Table 2	4 July 2019

Table of contents

1	Introduction.....	4
2	Backprojection algorithm.....	7
3	Processing chain.....	8
3.1	Raw-data unpacking.....	9
3.2	Range Compression	10
3.3	Zero-Doppler Filtering.....	11
3.4	Navigation data post-processing	12
3.5	GBP Focusing	12
3.5.1	Run-time performance	14
3.6	Multilooking	15
3.7	NetCDF Encapsulation	17
4	NetCDF File Content	18
4.1	File Name.....	18
4.2	Variables	20

1 Introduction

MetaSensing is a Dutch/Italian company offering radar sensors and services [Ref. 1]. MetaSensing's radar products cover a wide range of applications as mapping, deformation monitoring, weather monitoring, coastal surveillance and harbor management. During the past few years the MetaSensing Ka-band radar altimeter, KAREN, has been deployed in the framework of the ESA's CryoVEx validation and monitoring activities for sea ice and land ice. In particular, three airborne campaigns have been performed with KAREN in October 2016 (EGIG line, Greenland), Spring 2017 (Arctic) and Winter 2017/2018 (Antarctic).

The KAREN system is an interferometric frequency modulated continuous wave (FMCW) SAR altimeter working at the Ka frequency band. A block scheme of the radar instrument is shown in Figure 1. A baseband signal is up-shifted to the Ku band before being frequency-doubled to 34.5 GHz. The transmitting antenna continuously radiates linear chirps centered at this frequency, eventually amplified by the High Power Amplifier (HPA); the echoes scattered by the monitored scenario are received by two separate receiving antennas. The system works according to a deramping principle: a replica of the transmitted signal is mixed with the received signal which has been amplified by a Low Noise Amplifier (LNA). The Intermediate Frequency deramped signal (beat frequency) is sampled and stored as raw data, without any range windowing applied.

Figure 1: Block diagram of the KAREN system, the Ka band radar altimeter by MetaSensing.

The KAREN system is controlled by the user friendly MetaSAR GUI, see Figure 2. By that it is possible to configure the system parameters, to start and stop each acquisition and to monitor if eventual alerts or error messages occur.

Figure 2: Configuration window of the MetaSAR AirGUI, the software tool to control the MetaSensing airborne radar sensors.

In particular on the right part of the GUI a configuration tab is selected, in which the main configuration parameters can be set.

Central frequency (F_c) Ideally, it can be tuned; however, it has been kept fixed to the value of 34.5 GHz during any KAREN campaign, as the one providing maximum transmitted bandwidth possible. The value of this parameter is provided within the delivered NetCFD file.

Bandwidth (B_w) 0-600 MHz. where 0 corresponds to a single tone transmission at the central frequency, any other specified transmitted bandwidth is centered at the central frequency. When possible, it has been kept to its maximum value of 600MHz, in order to maximize the slant range resolution to 25 cm (value shown in the GUI as a direct consequence of the set bandwidth). Sometimes, especially when high altitude acquisitions were performed, the bandwidth needs to be reduced to lower values, in order to increase the maximum operational range of the radar (in FMCW

systems the maximum range is inversely proportional to the transmitted bandwidth). The value of this parameter is provided within each delivered NetCFD file.

Pulse Repetition Frequency (PRF) The repetition rate of the linearly frequency modulated chirps can vary between 0.5 and 25 KHz (list of discrete values). This parameter should be traded off between maximum operation range and Doppler ambiguities. The value of this parameter is provided within each delivered NetCFD file.

Sampling frequency (F_s) The sampling frequency can be selected by GUI to be 10 MHz, 25 MHz or 50 MHz. However, the pre-sampling Nyquist filters should be manually changed according to the chosen F_s value, which is not a trivial operation during flights. Therefore, the sampling frequency has been selected to 25MHz and kept as such for all KAREN campaigns.

Once set, the values of these parameters are stored in the header of the performed acquisition files. Most of them have been included in the list of parameters within the delivered NetCDF files, see chapter 4.

As reference, a typical acquisition during the KAREN campaigns in Low Altitude Mode (LAM, the terrain is expected ~300 meters below the aircraft) is performed with the following parameters: $F_c = 34.5$ GHz, $B_w = 600$ MHz, $F_s = 25$ MHz, $PRF = 6.15$ KHz, to which corresponds a maximum operational range of 508 meters and an unambiguous Doppler bandwidth wide enough at the considered aircraft speed and antenna beamwidth.

The remaining of this document describes the steps implemented in the processing of data acquired by the KAREN system aiming at delivering level-1b data, i.e. focused multilooked data. Besides this introductory chapter, a short overview of the ground-backprojection (GBP) algorithm is given in chapter 2, while the processing chain is documented step by step in chapter 3; finally, chapter 4 describes the data format of delivered files.

2 Backprojection algorithm

The processor for the KAREN altimeter data is based on a time-domain ground-backprojection (GBP) method ([Ref. 2], **Error! Reference source not found.**). Opposite to the frequency-domain approach, separate motion compensation and range migration correction steps are not required because the GBP algorithm handles non-ideal motion/sampling implicitly and can precisely perform beam-steering [Ref. 6]. Therefore, the GBP algorithm can be used for any imaging geometry. This gives flexibility to use the same algorithm core to process data acquired at diverse configurations (side-looking, nadir-looking, bistatic), trajectories or modes.

The GBP algorithm interpolates and phase-compensates each received echo at the desired positions to be focused. Because the radar echo has been sampled according to the Nyquist criterion, it can be interpolated with arbitrary accuracy at any illuminated image position. By coherently adding the contributions of each echo to each desired position, the focusing is performed. The contribution of each echo is computed according to the acquisition geometry.

The drawback of time-domain GBP is that it is more computationally expensive than the frequency domain methods, because the geometry of each echo is taken into consideration. However, because technology is constantly increasing the speed and the ability to perform parallel computations (GBP is highly parallelizable), the computational expense of GBP is becoming less and less a concern if compared to its inherent advantages over frequency-domain approaches [Ref. 7]. GBP offers several opportunities for seamless parallelisation based in NVIDIA graphic cards. In Figure 3 it is shown a computer at MetaSensing laboratory busy processing KAREN data with eight graphic processing units (GPU) of last generation visible on top of the machine.

Figure 3: Processing machine at MS labs with 8 GPUs.

3 Processing chain

The MetaSAR Processor is the tool by MetaSensing to elaborate SAR images from the collected raw data. It is a generic software which can be used for any radar system by MetaSensing to generate both strip images (typical of side looking SAR instruments) and altitude profiles (typical of altimeters, as the ones discussed in this document). Figure 4 shows the block diagram implemented by the processor for the KAREN data, with fundamental steps leading from collected Level-0 data to the delivered Level-1B data. Each step is described in the following sub-sections.

Figure 4: Block diagram for the KAREN processor.

3.1 Raw-data unpacking

Figure 5 shows the contents of a typical acquisition file from the KAREN altimeter. The deramped radar data for both channels are stored in fixed-dimensions *.msr* files, whose number depends on the length (in time) of the acquisition. These are joined together during the ingestion phase. Together with radar data, the corresponding configuration file (*.msmpl*) and time synchronization file (*.msmtl*) are provided. A real-time navigation file (*.gps*) is also associated to each acquisition. The GPS file contains both real time navigation information and GPS raw data which can be used during post processing in order to improve the accuracy of the navigation data.

20170321121804.gps	14,139 KB	GPS File
20170321121804.msmpl	557 KB	MSMPL File
20170321121804.msmtl	343 KB	MSMTL File
20170321121804_1.msr	20,001 KB	MSR File
20170321121804_2.msr	20,001 KB	MSR File
20170321121804_3.msr	20,001 KB	MSR File
20170321121804_4.msr	20,001 KB	MSR File
20170321121804_5.msr	20,001 KB	MSR File
20170321121804_6.msr	20,001 KB	MSR File
20170321121804_7.msr	20,001 KB	MSR File
20170321121804_8.msr	20,001 KB	MSR File

Figure 5: Example of the contents of a KAREN acquisition file.

The KAREN instrument data extraction is organized in two steps:

- Header extraction.
- Level-0 data extraction.

Using the information included in the header, i.e. instrument configuration and user settings such as used Pulse Repetition Frequency (PRF), Sampling Frequency (F_s), etc, the time-tagged observation data is arranged in a raw-data matrix, one for each receiving channel: rows represent slow time domain, which parametrizes the along track position of the platform (sampled at PRF), while columns represent the fast time domain, which parametrizes the beat frequency (sampled at F_s).

3.2 Range Compression

Raw data of each channel (deramped frequency-modulated continuous waveforms) are the input for this step. The range compression is implemented as a simple Fast Fourier Transform (FFT) in range. Furthermore, a Hann window is applied to trade-off side-lobes level and resolution.

Figure 6 shows an example of Range-Doppler map for the KAREN range compressed data, which have been acquired at an altitude of ~ 365 m AGL during March 19th, 2017, for one of the two receiving channels.

Figure 6: Example of processed Range-Doppler map. The colormap is expressed in dB.

To reduce the processing effort during further steps, the range compressed output is analyzed in the Range-Time domain to roughly estimate the range-delay of the signal and to determine the minimum and maximum slant range limits to the grid used for the backprojection beam steering.

3.3 Zero-Doppler Filtering

The main interest of altimeter data lies in the echoes coming from the nadir direction of the aircraft during its motion. Therefore, the range compressed data are filtered around the Zero Doppler in the Doppler dimension with a Doppler bandwidth corresponding to half the used PRF. Eventual folding effects at the extremities of the Doppler spectrum are avoided in this way. This is shown in Figure 7. By filtering half of the bandwidth, it is possible focusing the data with 100 looks and 5 m resolution along track.

Figure 7: Zero-Doppler filtering (black rectangle) by half of the spectrum width, corresponding to $PRF/2$.

3.4 Navigation data post-processing

The KAREN system is equipped with a dedicated navigation unit, a compact, single enclosure GNSS+INS receiver. The accuracy of the real-time solution computed by the unit can be improved by post-processing. This is usually done in the KAREN processing flow.

However, to have consistency with other on-board remote sensing instruments (ASIRAS Ku-band altimetry, Airborne Laser Scanner, etc) during the campaigns, it has been agreed with final users to adopt a common navigation solution for all provided datasets. The navigation units deployed by DTU is the most accurate one among the on-board units during the KAREN acquisitions. Different models have been used in different campaigns, so the reader is invited to refer to dedicated campaign reports. An importing step has been implemented in the KAREN processing to properly convert the DTU navigation data into an acceptable format to the KAREN processor. The same navigation data is provided in the delivered NetCDF files.

3.5 GBP Focusing

As introduced in chapter 2, the backprojection algorithm implements the beam steering for the Doppler-filtered range compressed data for each sample on any arbitrary surface grid. The geometry of the output grid can be set to follow any direction: for example, the processed data can be directly projected on the Universal Transverse Mercator (UTM) system. The post-processed navigation information is used to determine the vectors joining the position of the beam center and the position of the point-target in the grid. With the knowledge of the ranges and angles relative to each point-target the vectors are phase compensated and then coherently summed up to form the focused beam. This is repeated for each point-target of the grid. As a result, a 2D image is obtained, as the one shown in Figure 10, characterized by a resolution of 0.05 m X 0.2 m (along track X nadir).

The main features of the backprojection algorithm are described in detail in the following:

- 1) The target function in the spatial domain $f[i, j]$ is created with the same dimensions of the reconstruction grid (output matrix).
- 2) The Nadir Coordinate System (NCS) T_{xyz} is defined for each output pixel. The NCS is aligned with the x-axis pointing in the direction of the aircraft forward motion, the z-axis pointing downward to the centre of the earth, and the y-axis pointing to the right direction to form an orthogonal right-handed system, as shown in Figure 8

Figure 8: Nadir Coordinate System. Note, in this figure the aircraft is supposed flying with some yaw angle: the aircraft velocity vector is not parallel to the aircraft longitudinal direction.

3) The slant-range values $r(u, i, j)$ to the target are calculated for each pixel point $[i, j]$ on the output grid (NCS) and for each antenna position $P(u)$ on the synthetic aperture:

$$r(u, i, j) = \sqrt{(T_x - P_x(u))^2 + (T_y - P_y(u))^2 + (T_z - P_z(u))^2}$$

Note, as mentioned in chapter 2, the range cell migration and the motion compensation steps are implicitly performed in the backprojection, as the actual antenna positions are accounted for each pixel in the determination of the slant range to the target.

4) A coherent summation is performed by iteratively using the following formula along the synthetic aperture:

$$f[i, j] = f[i, j] + S_D[u] e^{j \frac{4\pi}{\lambda} [r(u, i, j) - r_{ref}(i, j)]}$$

where S_D refers to the range compressed data. In this way, the portion of each range compressed pulse that corresponds to the range to a given pixel from each aperture position is multiplied by the expected phase for that range and it is summed up across the entire collection.

It is worth to underline that no Fourier transform is involved in the GBP focusing: for every single pixel in the raw data the above coherent summation is performed to integrate the pulses in the slow-time domain. The number of integrated pulses for each pixel depends on the length of the synthetic aperture and it is computed based on the desired resolution and on the actual trajectory.

3.5.1 Run-time performance

As mentioned in chapter 2, KAREN data is processed by using multiple video cards in a single computer. The parallel computing is now implemented on the only focusing step. As a reference, Table 1 shows the overall run-time performance to process 1 minute of acquisitions by KAREN, represented by 6 GB of raw data (2 interferometric channels, 25MHz sampling frequency, 2 bytes per sample). The mentioned GPU's are Geforce GTX 1080 model by Asus.

Table 1 - Run-time performance to process 1 minute of KAREN raw data (6GB, given by two interferometric channels sampled at 25 MHz and stored with 2 bytes)				
Nr. of GPUs	Range Compression	Doppler Filtering	GBP Focusing	Total
1	4 min	27 min	40 min	72 min
6			7 min	38 min

One of the current developments undergoing at MetaSensing is the implementation of parallel processing also in the Doppler Filtering step, to further improve the overall run-time performance. Additionally, an adaptative range gating filter is being designed, so that only the actual range bins with meaningful data will be processed along the nadir direction, rather than the entire range profiles.

3.6 Multilooking

To reduce the inherent speckle noise of radar images, either spatial filtering or multi-look processing can be applied, both at the expense of spatial resolution ([Ref. 3], [Ref. 4]). The KAREN processor implements the multi-look method. Figure 9 shows the principle. The radar beam is divided into several sub-beams (three in the figure), each one providing an independent “look” at the illuminated scene. The final output image is obtained by summing and averaging together the output of each look, in which the amount of speckle is reduced.

Figure 9: Principle of multi-look processing [Ref. 5].

The KAREN processor implements the multilooking by applying a FFT in the Doppler dimension to the back-projected data and dividing the spectrum in the desired number of looks. Hamming windowing is performed in the along-track direction and an IFFT is applied to each look to restore the backprojected data domain.

In the delivered Level-1b data, the power (*pwr*), the phase (*pha*) and coherence (*coh*) are computed according to:

$$pwr(rg) = \frac{1}{L} \sum_{l=1}^L \left(\frac{|S(l, rg, 1)|^2 + |S(l, rg, 2)|^2}{2} \right)$$

$$X(rg) = \frac{1}{L} \sum_{l=1}^L \left(\frac{S(l, rg, 1) \cdot conj(S(l, rg, 2))}{\sqrt{|S(l, rg, 1)|^2 \cdot |S(l, rg, 2)|^2}} \right)$$

$$pha(rg) = \arg(X(rg))$$

$$coh(rg) = \text{abs}(X(rg))$$

Where $S(l, rg, 1)$ and $S(l, rg, 2)$ refer to the back-projected data for look number l at range rg of channel 1 and channel 2, respectively, where L represents the total number of looks.

As mentioned, a loss of resolution is obtained within this step. Typically, the backprojected data (SLC) have a grid spacing and resolution of 0.05 m, while the delivered multilooked data have 5 m resolution and 100 looks.

3.7 NetCDF Encapsulation

The final step of the KAREN processing chain is represented by the NetCDF encapsulation of the processed data and of all the relevant ancillary data such as time tags, geographical position, and other radar/processing parameters. The required fields to be included have been agreed with final users.

During this step the transformation from NCS to geographical coordinate system is also performed. Additionally, the time reference grid is converted from the GPS time to UTC (Universe Time Coordinates) in seconds since the midnight of the 1st of January 2000.

Figure 3 shows an example of a delivered KAREN waveforms plotted in terms of range-delay versus time acquired on the 31st of March 2017, beginning at 15:32:53 (GPS time). For convenience, the time axes is shown in time since the beginning of acquisition.

Figure 10: Example of KAREN Range-delay versus time dataset provided in the delivered NetCDF files.
The colormap is expressed in dB.

4 NetCDF File Content

KAREN data are provided in NetCDF format (.nc extension). Each NetCDF file contains:

- Focused multilooked altimeter waveforms
- Multilooked phase differences between the two channels
- Coherence between the two channels
- Waveform position
- Sensor attitude data
- Radar and processing parameters.

The NetCDF files are three dimensional, with *Range* (size 247), *Time* (4767) and *space_3d* (3). The *range* and *time* dimensions are related to the pre-defined grid in which the focused SAR pixels are projected. This grid is regular in space.

The *Range* dimension refers to the range delays to the pixels, in nadir direction, equally spaced.

The *Time* dimension refers to the UTC time since the midnight of the 1st of January 2000, during which the pixel data have been acquired, equally spaced.

The *space_3d* dimension is used to write the three-dimensional position and velocity vector coordinates of the sensor.

The file name format and the detailed contents of the NetCDF files are explained in the following paragraphs.

4.1 File Name

The delivered NetCDF files are named according to a defined structure, as in the following example:

KAR_OPER_Level1b_20170331T104652_20170331T105245_hamh.nc

KAR_OPER: Indicates that that data have been acquired by the KAREN system in its full operational mode.

Level1b: Processing level, i.e. focused multilooked SAR data.

20170331T104652: Date and time of the start of acquisition, in the format YYYYMMDDTHHMMSS, where YYYY is the year, MM the month, DD the day, *T* is a separator character indicating Time, HH is the hour, MM the minutes and SS the seconds, in UTC time.

20170331T105245: Date and time of the end of acquisition in the format YYYYMMDDTHHMMSS where YYYY is the year, MM the month, DD the day, *T* is a separator character indicating time, HH the hour, MM the minutes and SS the seconds, in UTC time.

hamh: Additional info. The last four digits before the *.nc* file extension are used to differentiate the various dataset KAREN datasets versions which have been delivered. In Table 2 an overview is given about the different versions, including a short description of the kind of processing which has been differently done with respect to previous version. It is advised to use the most recent one.

Table 2 – Versions of KAREN datasets		
Version	Info	Delivery date (KAREN dataset)
*_vvvv	First version processed with Hann window.	Jun 2018 (Spring 2017)
*_hamh	Changed the Hann by the Hamming window ($\alpha=0.54$)	Aug 2018 (Fall 2016, spring 2017)
*_leva	The RF antenna position has been corrected, measured lever arms have been introduced w.r.t. IMU reference point	Nov 2018 (Fall 2016, Spring 2017 and Antarctica 2018)
*_levb	A bug in the processing has been corrected, which was causing sudden jumps in longitude values in the <i>_leva</i> version	Dec 2018 (Fall 2016, Spring 2017 and Antarctica 2018)
*_levc	Doppler filtering improvement preventing high sidelobes contribution in the slant-range direction	Few samples delivered in June 2019 for assessment of users

4.2 Variables

range

Size: 247x1

Dimensions: range

Datatype: double

Attributes: long_name = range-delay in nadir direction. The difference between the samples of the range variable gives the range spacing.

units = '[m]'

time_ka

Size: 4767x1

Dimensions: time

Datatype: double

Attributes: long_name = Time to the instant the L1B waveform touches the surface. Time in UTC representing the seconds since the midnight of the 1st of January 2000. The difference between the samples of the time_ka variable gives the time spacing.

units = '[s]'

com_altitude_ka

Size: 4767x1

Dimensions: time

Datatype: double

Attributes: long_name = Altitude of the aircraft navigation unit above the reference ellipsoid (WGS84)

units = '[m]'

com_altitude_rate_ka

Size: 4767x1

Dimensions: time

Datatype: double

Attributes: long_name = Instantaneous altitude rate at aircraft navigation unit with respect to the reference ellipsoid (WGS84)

units = '[m/s]'

com_position_vector_ka

Size: 3x4767
Dimensions: space_3d, time
Datatype: double
Attributes: long_name = Position vector (x, y, z) at the aircraft navigation unit
units = '[m]'

com_velocity_vector_ka

Size: 3x4767
Dimensions: space_3d,time
Datatype: double
Attributes: long_name = Velocity vector (x, y, z) at the aircraft navigation unit
units = '[m/s]'

hr_power_waveform_ka

Size: 247x4767
Dimensions: range,time
Datatype: double
Attributes: long_name = 'level-1B multi-looked power waveform'(2 channels)
units = '[]'

latitude_ka

Size: 4767x1
Dimensions: time
Datatype: double
Attributes: long_name = 'Latitude of measurement [-90, +90]: Positive at North, Negative at South'
units = '[deg]'

longitude_ka

Size: 4767x1
Dimensions: time
Datatype: double
Attributes: long_name = 'Longitude of measurement [0, 360]'
units = '[deg]'

off_nadir_pitch_angle_pf_ka

Size: 4767x1

Dimensions: time
Datatype: double
Attributes: long_name = 'Pitch angle with respect to the nadir pointing direction'
units = '[deg]'

Off_nadir_roll_angle_ka

Size: 4767x1
Dimensions: time
Datatype: double
Attributes: long_name = 'Roll angle with respect to the nadir pointing direction'
units = '[deg]'

Off_nadir_yaw_angle_pf_ka

Size: 4767x1
Dimensions: time
Datatype: double
Attributes: long_name = 'Yaw angle with respect to the forward velocity vector'
units = '[deg]'

Heading_angle_ka

Size: 4767x1
Dimensions: time
Datatype: double
Attributes: long_name = 'Heading angle with respect to the true North'
units = '[deg]'

hr_coh_waveform_ka

Size: 247x4767
Dimensions: range,time
Datatype: double
Attributes: long_name = 'Waveform coherence between the 2 channels'
units = '[]'

hr_phase_waveform_ka

Size: 247x4767
Dimensions: range,time

Datatype: double

Attributes:

long_name = 'Waveform phase between the 2 channels'

units = '[]'

TxBw

Size: 1x1

Dimensions:

Datatype: double

Attributes:

long_name = 'Transmitted Bandwidth'

units = 'hertz [Hz]'

Fc

Size: 1x1

Dimensions:

Datatype: double

Attributes:

long_name = 'Central Frequency'

units = 'hertz [Hz]'

PRF

Size: 1x1

Dimensions:

Datatype: double

Attributes:

long_name = 'Pulse Repetition Frequency'

units = 'hertz [Hz]'

AzBw

Size: 1x1

Dimensions:

Datatype: double

Attributes:

long_name = 'Azimuth bandwidth prior to multilooking'

units = '[Hz]'

MeanForwardVelocity

Size: 1x1
Dimensions:
Datatype: single
Attributes:
long_name = 'Velocity in the flight direction'
units = '[m/s]'

Looks

Size: 1x1
Dimensions:
Datatype: int32
Attributes:
long_name = 'Number of looks'
units = '[]'

BaselineHor

Size: 1x1
Dimensions:
Datatype: single
Attributes:
long_name = 'Horizontal baseline (half of the physical baseline length)'
units = 'units [cm]'

BaselineVer

Size: 1x1
Dimensions:
Datatype: single
Attributes:
long_name = 'Vertical baseline (half of the physical baseline length)'
units = 'units [cm]'

StartYearUTC

Size: 1x1
Dimensions:

Datatype: int32

Attributes:

long_name = 'UTC Year of the Start of Acquisition'

units = '[year]'

StartMonthUTC

Size: 1x1

Dimensions:

Datatype: int32

Attributes:

long_name = 'UTC Month of the Start of Acquisition'

units = '[month]'

StartDayUTC

Size: 1x1

Dimensions:

Datatype: int32

Attributes:

long_name = 'UTC Day of the Start of Acquisition'

units = '[day]'

StartHourUTC

Size: 1x1

Dimensions:

Datatype: int32

Attributes:

long_name = 'UTC Hour of the Start of Acquisition'

units = '[hour]'

StartMinUTC

Size: 1x1

Dimensions:

Datatype: int32

Attributes:

long_name = 'UTC Minutes of the Start of Acquisition'

units = '[min]'

StartSecUTC

Size: 1x1

Dimensions:

Datatype: single

Attributes:

long_name = 'UTC Seconds of the Start of Acquisition'
units = '[sec]'

FinalYearUTC

Size: 1x1

Dimensions:

Datatype: int32

Attributes:

long_name = 'UTC Year of End of Acquisition'
units = '[year]'

FinalMonthUTC

Size: 1x1

Dimensions:

Datatype: int32

Attributes:

long_name = 'UTC Month of End of Acquisition'
units = '[month]'

FinalDayUTC

Size: 1x1

Dimensions:

Datatype: int32

Attributes:

long_name = 'UTC Day of End of Acquisition'
units = '[day]'

FinalHourUTC

Size: 1x1

Dimensions:

Datatype: int32

Attributes:

long_name = 'UTC Hour of End of Acquisition'

units = '[hour]'

FinalMinUTC

Size: 1x1

Dimensions:

Datatype: int32

Attributes:

long_name = 'UTC Minutes of End of Acquisition'

units = '[min]'

FinalSecUTC

Size: 1x1

Dimensions:

Datatype: single

Attributes:

long_name = 'UTC Seconds of End of Acquisition'

units = '[sec]'

Dummy

Size: 1x1

Dimensions:

Datatype: int32

Attributes:

long_name = 'Dummy value'

units = '[]'

References

- [Ref. 1] <https://www.metasensing-group.com/>
- [Ref. 2] L.M. H.Ulander, H. Hellsten, and G.Stenström, "Synthetic-aperture radar processing using fast factorized back-projection," IEEE Trans. Aerosp. Electron. Syst., vol. 39, pp. 760–776, Jul. 2003.
- [Ref. 3] J. M. Durand. et al., "Speckle in SAR images: An evaluation of filtering techniques," Adv. Space Res., vol. 7, no. 11, pp. 301-304, 1987.
- [Ref. 4] F. K. Li, C. Croft, and D. N. Held, "Comparison of several techniques to obtain multiple-look SAR imagery," IEEE Trans. Geosci. Remote Sensing, vol. GE-21, July 1983.
- [Ref. 5] F. Sarti, Remote sensing and SAR images processing characterization and speckle filtering in radar images, ESA radar remote sensing course, Tartu, Estonia, 16-20 April 2012
- On line: https://earth.esa.int/c/document_library/get_file?folderId=226458&name=DLFE-2125.pdf
- [Ref. 6] A. Egido and W. H. F. Smith, "Fully Focused SAR Altimetry: Theory and Applications," in *IEEE Transactions on Geoscience and Remote Sensing*, vol. 55, no. 1, pp. 392-406, Jan. 2017. doi: 10.1109/TGRS.2016.2607122
- [Ref. 7] Doerry, A.W., Bishop, E.E. Miller, J.A., "Basics of backprojections algorithm for processing SAR images", Sandia National Laboratories Albuquerque, New Mexico 87185 and Livermore, California 94550, Feb 2016.