ESA CryoVEx/KAREN 2016 fall Campaign

First airborne field campaign with combined Ku/Ka-band radars
over the EGING-line with coincident in situ measurements

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DTU Space
National Space Institute
Technical University of Denmark

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Authors:

H. Skourup¹, S. B. Simonsen¹, A. Coccia², A. Hogg³, A. Shepard³,
K. Macedo², S. M. Hvidegaard¹, V. Helm⁴, I. Ootosaka³, and R. Forsberg¹,

¹ National Space Institute, DTU Space, Denmark

² MetaSensing BV, The Netherlands

³ University of Leeds, UK

⁴ Alfred Wegener Institute for Polar and Marine Research, Germany

DTU Space
National Space Institute
Danish Technical University

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Front page: A view from below the aircraft of the whole in the aircraft with the mounted Ka-band radar antennas and the laser scanner (top left). Overflight of the ground team at EGIG-line T5 (top right). Sunset over Jakobshavn isbræ as seen from the TF-POF (bottom).

ESA contract report
Version: 1.2

ESA STUDY CONTRACT REPORT			
ESA CONTRACT NO 4000120131/17/NL/FF/mg	SUBJECT Technical Support for CryoVEx/KAREN first airborne campaign with combined Ku/Ka-band radar and coincident in situ measurements over the EGIG line in fall 2016		CONTRACTOR National Space Institute (DTU Space)
ESA CR No	STAR CODE	No of volumes 1 This is Volume No 1	CONTRACTORS REFERENCE CryoVEx/KAREN 2016
<p>ABSTRACT</p> <p>The ESA CryoVEx/KAREN campaign 2016 is the first combined Ka- and Ku-band airborne campaign in Greenland to exploit the dual-frequency concept for future polar satellite missions. The primary measurements were obtained over the Greenland Ice Sheet along the EGIG-line on October 25 and 27, 2016. The airborne team covered all different glacial facies including the ablation, the percolation, and the dry snow zone. The in situ team supported by helicopter took measurements of snow density profiles from shallow ice cores and SFL SnowMicroPen at EGIG-line points T1, T4 and T5, and could not make it further inland due to a persistent layer of low clouds east of T5.</p> <p>The campaign was coordinated by DTU Space using the Norlandair Twin Otter for airborne surveillance and Air Greenland helicopter AS350 to support the ground team from University of Leeds, UK. The airborne Ka-band SARIn altimeter (KAREN) from Dutch company MetaSensing was operated for the first time during an actual campaign and the radar altimeter performed better than expected even at high altitude (3,500 m above ground). The Ku-band altimeter carried along was the ESA airborne interferometric radar (ASIRAS) and DTU Space near-infrared Airborne Laser Scanner (ALS), also flown during previous CryoVEx campaigns.</p> <p>The CryoVEx/KAREN 2016 fall campaign was a success and the processed data is of high quality. There now exists a routine processing tool for KAREN similar to ASIRAS in High Altitude Mode (SARIn), which provides multi-looked echoes at a slightly coarser range-resolution than ASIRAS. The campaign took place in late October, opposed to previous ESA CryoVEx campaigns, which usually takes place in the spring (March-May). Thus, the collected data adds valuable information about the seasonal radar behavior over the Greenland Ice Sheet to validate the radar altimeter satellites CryoSat and SARAL/AltiKa and to assist on-going calibration and validation activities.</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, S. B. Simonsen, A. Coccia, A. Hogg, A. Shepard, K. Macedo, S. M. Hvidegaard, V. Helm, I. Otosaka, and R. Forsberg</p>			
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1 Introduction

The ESA CryoVEx/KAREN campaign 2016 is the first combined Ka- and Ku-band campaign in Greenland to exploit the dual-frequency concept for future polar satellite missions. The campaign took place in late October, opposed to previous ESA CryoVEx campaigns, which usually takes place in the spring (March-May). Thus, the collected data adds valuable information about the seasonal radar behavior over the Greenland Ice Sheet to validate the radar altimeter satellites CryoSat and SARAL/AltiKa and to assist on-going calibration and validation activities.

The Ka-band altimeter (KAREN) was flown for the first time. It is a modified version of the operational airborne side-looking interferometric radar developed and operated by the Dutch company MetaSensing. Various tests were performed in the air to test the instrument for interference and performance at different altitudes. The Ku-band altimeter carried along was the ESA airborne interferometric radar (ASIRAS), also flown during previous CryoVEx campaigns. Additional DTU Space near-infrared Airborne Laser Scanner (ALS) was flown to collect coincident measurements of the snow surface.

This report outlines the airborne field operations conducted during October 21-29, 2016. The campaign was coordinated by National Space Institute, Technical University of Denmark (DTU Space) in collaboration with MetaSensing. In addition to the Danish/Dutch airborne-team, ground validation was carried out by scientist from the University of Leeds, UK.

The primary objectives achieved during the campaign were to:

- Fly new Ka-band radar technology radar altimeter, provided by MetaSensing
- Collect simultaneous Ku-band radar altimeter data with ESA ASIRAS and ALS data, to study penetration of radar signals into the ice sheet
- Repeat of the earlier flown EGIG-line to detect ice sheet changes
- Surface measurements (shallow ice cores and ice densities) on the ice sheet inland of Ilulissat at T1, T4 and T5 on EGIG-line and in the Ilulissat glacier region using helicopter
- Investigate dependencies of SARIn phase information from coincident measurements of KAREN and ASIRAS in high-altitude mode

Figure 1: Overview of the flight tracks (black lines) from the CryoVEx/KAREN 2016 campaign. The star marks the location of the in situ site October 25 and the circle marks their location October 27.

2 Summary of operation

The airborne campaign was conducted in the period October 21-29, 2016. An overview of the flight tracks, together with markings of the in situ sites, is presented in Figure 1. The instrument installation and test flights took place in Akureyri (AEY), Iceland, followed by survey flights along the EGIG-line based out of Ilulissat (JAV). Unfortunately, the weather did not allow any surveying on the transit flights between Akureyri and Ilulissat, except one test of the Ka-band radar in the Denmark Strait at high altitude ~3,500 m above ground.

A Norlandair Twin Otter (reg: TF-POF), which is the same aircraft as used throughout previous CryoVEx campaigns, was chartered for the airborne part of the campaign. In order to adapt the Ka-band radar the whole in the back of the aircraft had been enlarged prior to the campaign, see pictures in Section 3. The general instrument certification for the aircraft was obtained in 2006 (Hvidegaard and Stenseng, 2006). 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.

An Air Greenland helicopter AS350 was chartered to support the in situ team permitting landings on the ice sheet. A fuel cache of 2 drums was positioned at glacier lodge Egi north of Ilulissat prior to the flights for maximal range of the helicopter along EGIG-line.

The CryoVEx/KAREN 2016 overall aim was to sample different snow conditions on the Greenland ice sheet along the EGIG-line to document the different glacial facies, i.e. the dry snow zone, the percolation zone, and the ablation zone (see Figure 2). Studies of radar backscatter from high-resolution SAR images from Sentinel-1 prior to the campaign, shows that in 2016 the inland limit of melt seems to have reached its maximum between 19th and 26th of July in between EGIG-line points

T12 and T21. Thus, the highest priority field site was to reach as far inland on the Greenland ice sheet as possible and preferable reach T21 located at 43°W, or as close to T21 as the helicopter range allowed given the weather conditions and final weight carried on the day. The second flight was planned to be the shortest flight to site T1, and the final flight to visit site T12. However, due to persistent low clouds in the area east of 47.25°W and strong winds the point furthest inland ended up being T5 on April 25, followed by T1 and T4 on April 27.

Three science experiments were conducted at each in situ site:

- Shallow firn/ice cores to directly measure the density of the top 3-5 metres of snow
- Upper layer density profiles by use of SnowMicroPen (SMP)
- metal surface reflectors to calibrate the snow surface in the dual frequency Ku- and Ka-band airborne measurements

The airborne activities were collocated with the ground work, and field site T5 was overflown on April 25, followed by T1 and T4 on April 27. As the airborne survey were based out of Ilulissat, each of the two survey flights to the EGIG-line were started and concluded with a survey of the outermost of the Jakobshavn Isbræ. Climbing the ice sheet from Jakobshavn isbræ, the survey passed the Swiss Camp, which when it was established in the early 1990'es where located on the Equilibrium-Line Altitude (ELA), however at present the camp is in the ablation area. The turn-around point of survey flight on April 25 was at T9 due to persistent low clouds east of T9. On the route to T9 the ground site at T5 was overflown four times from different directions. The flight on April 27 passed the ablation and percolation zones, and turned around deep into the dry snow zone about 55 nm west of T41 at 42.5°W, and thereby documenting the autumn conditions of all glacial facies encountered on the Greenland ice sheet. The in situ site at T1 was overflown from 2 directions. With the arrival of low clouds at about 48°W the aircraft ascended to measure in high-altitude mode with the KAREN and ASIRAS systems. Further inland at about 45°W the cloud cover disappeared, which demonstrated the flexibility of using a ski-equipped Twin Otter in the future for landings on the ice cap supporting the in situ work, instead of a helicopter.

During the campaign the opportunity was taken to test a new super precise iMAR RQH system purchased by DTU Space and to acquire gravity measurements, but also to support exact geolocation of attitude (pitch, roll and heading), see Section 5.2. On the return flight on April 25 a few flight lines (P3-P4, P5-P6) in the upper part of Jakobshavn drainage basin, previously flown in August 2016 to test the iMAR system (Jensen and Forsberg, 2018), were repeated.

Following the CryoVEx/KAREN campaign October 30 - November 12, the Twin Otter was used to support a team from University of Kansas in testing of low-frequency radar for measuring the ice thickness of Jakobshavn glacier. Logistics and expert knowledge was supported by DTU Space (Arne Vestergaard Olesen) and the DTU Space near-infrared ALS remained in the aircraft for surface reference. Three flight lines following Jakobshavn glacier was repeated multiple times November 7-12 see Appendix A.

The CryoVEx/KAREN airborne team consisted of Henriette Skourup (HSK) and Sebastian B. Simonsen (SSIM) from DTU Space and Alex Coccia (AC) from MetaSensing. Calibration flights of the instruments over buildings and runways were performed in Akureyri and Ilulissat. An overview of the flights is found in Table 1 along with a detailed “day-to-day”-report in Section 2.1. Operator logs and detailed plots of flight tracks are provided in Appendix B.

The in situ team consisted of Anna Hogg (AH), and Andy Shephard (AS) from University of Leeds. Technical officer Malcolm Davidson, together with journalist Sander Koenen represented ESA during the campaign.

Figure 2: Glacial Facies (Benson, 1960)

Table 1: Overview of CryoVEx/KAREN 2016 flights.

Date	DOY	Flight	Track	Take off UTC	Landing UTC	Airborne	Airborne accumulated [dd:hh:mm]	Survey operator
October 23, 2016	297		Test flight AEY	15:45	16:18	00:33	00:00:33	SSIM/HSK/AC
October 24, 2016	298	a	Test flight AEY	08:55	09:31	00:36	00:01:09	SSIM/HSK/AC
October 24, 2016	298	b	Transport flight AEY-JAV	13:36	18:19	04:43	00:05:52	SSIM/HSK/AC
October 25, 2016	299		JAV-EGIG-P-JAV	15:27	18:45	03:18	00:09:10	SSIM/HSK/AC
October 27, 2016	301		JAV-EGIG-JAV	12:16	16:28	04:12	00:13:22	SSIM/HSK/AC
October 28, 2016	302		JAV-AEY	14:12	19:26	05:14	00:18:36	SSIM/HSK/AC
Total							00:18:36	

2.1 Day to day

The airborne part of CryoVEx/KAREN 2016 fall campaign progressed as follows:

October 20	HSK and SSIM from CPH to KEF
October 21	HSK and SSIM from RKV to AEY. Begin installation of instruments in TF-POF. AC (MetaSensing) arrived in the evening to AEY.
October 22	Started to assemble and mount the Ka-band radar-system, together with the ASIRAS and the ALS into the hole of the TF-POF.
October 23	Finalized the installation of the equipment and first test flight in AEY. Both the ASIRAS- and Ka-systems worked well. However, the ALS lost signal after takeoff, due to an unexpected shadow effect from the hull of the aircraft. The ALS was refitted by tilting the ALS mount-brackets.
October 24	Test flight of the system with only Ka and ALS running, the refitting of the ALS was a success and it was decided to head for Greenland. Due to bad weather on the east-coast a direct transit flight from AEY to JAV was the only option. During this flight the only instrument recording data was the INS systems.
October 25	The planned survey on the EGIG-line, was delayed due to heavy cross-winds on the runway. Once airborne the survey was only able to reach a little further inland than T9 due to a persistent layer of low clouds. The ground crew was at T5. The site surveyed on ground was overflown four times from different directions. On the return flight from Swiss camp the opportunity was taken to repeat a few lines (P3-P6) from a test flight of the iMAR system obtained in August 2016.
October 26	Weather day. No survey, high winds and low clouds.
October 27	Second survey flight of the EGIG-line. The survey started at Swiss camp and between SWC and T1 we spotted the ground team with the helicopter off the line, close to T1. The ground site was overflown from two directions. The survey was continued along the EGIG-line. With the arrival of low clouds, we ascended to measure in high-altitude mode with the Ka- and Ku-systems. About 55 nautical miles from T41, the aircraft had to turn back towards JAV following the EGIG-line in LAM.
October 28	The persistent unusual weather conditions at east-coast of Greenland, made a refueling stop on the east-coast impossible and it was decided to conduct a no survey flight to AEY.
October 29	Un-mounting the equipment.
October 30	HSK and SSIM return to CPH, AC return to Netherlands.

3 Hardware installation

The hardware installation in the 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 dedicated 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 (test and backup)
- A NovaTel integrated GPS-INS system of type SPAN-CPT to support KAREN (used as backup)

To accommodate the KAREN horn-antenna array in the hole of the aircraft the mounting plate for the ALS was moved about 10 cm forward and raised 3 cm. In addition, the ALS was tilted backwards to avoid shadow effects from the hull of the aircraft. The KAREN control unit was fitted into the rear ASIRAS rack, see Figure 3.

The installation of the ASIRAS system was identical to the setup used throughout the previous CryoVEx campaigns (2011, 2012, 2014, and 2016). An ASIRAS system upgrade was performed at Radar System Technologie, Germany, prior to the campaign to allow use of an additional type of GPS receiver, Javad, to support ASIRAS time tagging. As DTU Space has several Javad receivers, the upgrade was made to secure proper availability of a backup system through a campaign.

The three geodetic dual-frequency GPS receivers (AIR1, AIR2 and AIR3), mounted 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. Receiver types, antenna information, as well as logging rates for the GPS receivers are given below:

- AIR1 Receiver type Javad Delta front antenna logging rate 1 Hz
- AIR2 Receiver type Javad Delta rear antenna logging rate 2 Hz
- AIR3 Receiver type Javad Delta front antenna logging rate 0.2/1 Hz

The higher logging rate for AIR2 was chosen to obtain a higher precision for the on-board navigation system. Offsets between GPS antennas and ASIRAS/ALS reference points are given in Table 2.

To record the attitude (pitch, roll and heading) of the aircraft, three inertial navigation systems (INS) were installed. 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. 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. As an opportunity a new super-precise INS strap-down unit purchased from iMAR RQH, which has the capability 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. Both the Honeywell INS and the iMAR were connected to the front GPS antenna, whereas the NovaTel was connected to the rear antenna.

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 2: The dx, dy and dz offsets for the lever arm from the GPS antennas to the origin of the laser scanner, to the back center of the ASIRAS antenna (see arrow Figure 3), and KAREN reference point (centered between the reference points of the 2 antennas)

To laser scanner	dx (m)	dy (m)	dz (m)
from AIR1/AIR3 (front)	- 3.60	+ 0.49	+ 1.55
from AIR2/AIR4 (rear)	+ 0.10	- 0.38	+ 1.39
to ASIRAS antenna	dx (m)	dy (m)	dz (m)
from AIR1/AIR3 (front)	-3.37	+0.47	+2.005
from AIR2/AIR4 (rear)	+0.33	-0.40	+1.845
to KAREN reference point	dx (m)	dy (m)	dz (m)
from AIR1/AIR3 (front)	-3.70	+0.49	+1.75
from AIR2/AIR4 (rear)	+0.00	-0.38	+1.59

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

Figure 4: ASIRAS antenna together with the Ka-band horn 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: The mount-plate seen from below. The upper part is the flight-direction.

4 Overview of acquired data

Data from the various instruments were acquired where feasible, considering the limited height range of the ALS system and the weather. An overview of all acquired data is listed in Table 3.

The Ka-band altimeter has been operated for the first time during an actual campaign and the results were very good, even beyond expectations. The system was able to correctly acquire data despite the extreme low temperatures (the RF module with antennas is directly exposed externally). The additional RF power amplifier which was brought in case of power budget limitations was never installed, even when performing acquisitions at altitudes well above the designed 300 m AGL (up to 2000 m AGL good quality data could be acquired).

The sampling frequency was set to 25 MHz and the data rate is 360 GB of raw data per hour, plus few MB of navigation data (dedicated GPS/IMU module). Solid State Hard Drives (SSHD) have been used during the campaign. Acquisitions have been manually started and stopped by the operator according to the area which was flown; data sets of ~10 minutes or ~20 minutes, duration have been logged. Shorter acquisitions have been performed too. At the end of the campaign the raw data amount is ~1.1 TB. During the flight and at the end of each acquisition day a quick data quality control was performed on randomly selected dataset both to assess the quality and eventually adjusting the Pulse Repetition Frequency (PRF) according to the flight altitude.

Most of the ASIRAS data were acquired in Low Altitude Mode (LAM) with low along-track resolution (LAMa). This allows flights 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. Due to test of the Ka-band range part of the flight on October 27, were acquired in High Altitude Mode (HAM) at approximately 1,200-1,500 m above ground.

A total of 175 GB raw ASIRAS data were collected during the CryoVEx/KAREN 2016 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. However, during take-off icing of the instrument window occurred, which partly blocked the laser. This was circumvented by using the last pulse option in the retrieval software. 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 7.6 GB ALS data were acquired.

The airborne GPS units logged data internally in the receivers (AIR1, AIR2 and AIR3) during flight, which were downloaded upon landing on laptop PCs. GPS files were recovered for all receivers at all flights. The GPS reference stations listed in Table 3 are described in further detail in Section 5.1. Both INS systems logged continuously throughout the campaign and no problems were observed with the systems.

Table 3: Data acquisition overview

Date	DOY	AIR1	AIR2	AIR3	EGI H-764G	IMar INS	ALS	ASIRAS	Ka-band radar	GPS REF1	ALS Log	ASIRAS log	Remarks
23-10-2016	297	-	X	-	-	-	X ¹	LAMa	X	X	X	X	Test flight, no signal on Air2 and no EGI
24-10-2016	298a	X	X	X ²	X	X	X	-	X	-	X	X	Test flight AEY, building calib.
24-10-2016	298b	X	X	X ²	X	X ³	-	-	-	-	X	X	Transport flight AEY-JAV
25-10-2016	299	X	X	X ²	X	X	X	LAMa	X	X	X	X	JAV-EGIG-P-JAV. Runway overflight
27-10-2016	301	X	X	X ²	X	X	X	LAMa/HAM	X	X	X	X	JAV-EGIG-JAV. Runway overflight
28-10-2016	302	X	X	X	-	X	-	-	X	-	X	X	JAV-AEY transport

¹ No time sync and no signal during flight

² Was set to a record rate of 5 sec

³ Due to power failure, the data recording is split in multiple files, and about 30 minutes of data is missing

5 Data handling

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.

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 Section 3. Two methods can be used for post-processing of kinematic GPS data, differential (DIF) processing and precise point positioning (PPP). Whereas the first method uses information from base stations in the processing procedure, the PPP method is only based on precise information of satellite clock and orbit errors.

The GPS base stations used as reference stations for differential post processing of the GPS data are listed in Table 4. A Javad Maxor Receiver (REF1) with internal antenna and logging rate 1 Hz were used as base station. The base station was mounted on DTU Space small tripods (vertical height 12 cm) and placed near the airport before flights.

The positions of the 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/KAREN 2016 fall campaign are found in Appendix C.

Table 4: Overview of CryoVEx/KAREN 2016 fall GPS reference stations

Name	Site	Comment
AEY1	Akureyri	Between the apron and the runway
JAV1	Ilulissat	Next to the wind-indicator at the airport

The GPS processing were performed with Waypoint GrafNav (version 8.30) 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 5 and used in the further processing.

5.2 Inertial Navigation System

The position and attitude information (pitch, roll and heading) recovered from the raw Honeywell (H-764G) INS data 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.

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

This way a smooth GPS-INS solution is obtained, which is used for geolocation of the laser and radar systems.

The best solutions of both GPS and INS data based on Table 5 are packed as binary files in the special ESA file format described in Cullen (2010). As seen, all flights are using solutions from primary Honeywell INS (H-764G). The final GPS and INS files are listed in Appendix J and K with file name convention according to Appendix I.

To explore the iMAR and NovaTel systems, as potential backup systems, we have made a comparison between those and the primary Honeywell INS. A short section (marked by red in Figure 8 upper left inset) covering approx. 37.5 km from the flight on October 25 was selected for this purpose. The attitude of the Honeywell vs iMAR is plotted in Figure 8 (left) and as scatterplot color-scaled according to time (right). A sub-section of this track (black box in Figure 8) is shown in Figure 9 and represents the Honeywell vs. NovaTel inter-comparison at the most straight section of the track. The Honeywell and iMAR align well (Figure 8) and show consistent high-precision accuracy in all attitude components throughout the selected flight section including turns. Thus, the iMAR is providing the accuracy and precision similar to the current primary Honeywell instrument and can be used as primary instrument in future campaigns. The Honeywell and NovaTel (Figure 9) roll angles compares well, except for a small off-set caused by the different installation configurations, but show large differences in pitch and yaw by several degrees even at straight sections. Pitch seems to be sensitive to relative small changes in roll angles, where it drifts by up to 1 degree and yaw is off by up to 7-10 degrees, compared to the Honeywell INS. Thus, the NovaTel system needs further investigation before being used as primary instrument.

Table 5: Best combined solutions of GPS/INS to support KAREN, ASIRAS and ALS processing. GPS time is 17 seconds ahead of and UTC.

Date	DOY	File name	Reference	Processin	INS	Rover
23-10-2016	297	AIR2/297_AIR2.p	None	PPP	-	AIR2
24-10-2016	298	AIR2/298a_AIR2.p	None	PPP	H-764G	AIR2
24-10-2016	298	AIR2/298b_AIR2.p	None	PPP	H-764G	AIR2
25-10-2016	299	AIR2/299_AIR2.p	None	PPP	H-764G	AIR2
27-10-2016	301	AIR2/301_AIR2.p	None	PPP	H-764G	AIR2
28-10-2016	302	AIR3/302_AIR3.txt	None	PPP	-	AIR3

Figure 9

Figure 8: Inter-comparison of attitudes obtained by the Honeywell (H-764G) and iMAR INS.

Figure 9: Inter-comparison of attitudes obtained by the Honeywell (H-764G) and NovaTel INS.

5.3 Airborne Laser Scanner (ALS)

The laser scanner operates with wavelength 904 nm. The pulse repetition frequency is 10,000 Hz and the ALS scans 40 lines per second, thus the data rate is 251 pulses per line. This corresponds to a horizontal resolution of 0.7 m x 0.7 m at a flight height of 300 m and a ground speed of 250 kph. The across-track swath width is roughly equal to the flight height, and the vertical accuracy is in the order of 10 cm depending primarily on uncertainties in the kinematic GPS-solutions. The raw logged files with start/stop times are listed in Appendix D.

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, a building overflight was performed on October 24 in Akureyri, Iceland, see Figure 10.

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 D and Section 5.3.3.

Figure 10: Map of the calibration building at Akureyri, October 24.

5.3.2 Laser scanner outlier detection and removal

No major problems were encountered with the instrument. The moisture on the inside of the ALS (see Chapter 4), did not affect the quality of the final ALS data, as the instrument were performing 100% at the start of the planned acquisitions. Due to the tight installation of the instruments 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 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 overflights within an hour of the first overflight. The quality of these crossover statistics varies depending on surface type, incidence angle and level of processing. The statistics based on raw scanner data after outlier editing are summarized in Table 6, and an example of cross-over differences over the EGIG-line is given in Figure 11. The mean elevation differences in the cross-over points are less than 5 cm, and typically represent errors in the GPS solutions. The standard deviation of the cross-over differences is 7-10 cm over flat surfaces. These values are within the expected ranges and reflect data of high quality.

5.3.4 Final processed data

Processed 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 data are packed in netcdf4 format. An overview of the processed data is plotted in Figure 12 and listed in Appendix L.

Table 6: Cross-over statistics

Date	DOY	XO number of the day	Mean (m)	St. Dev (m)	Min (m)	Max (m)	Comments
2016-10-25	299	0	0.00	0.76	-9.98	9.66	Crevassed field
		1	-0.02	0.08	-0.39	0.35	
		2	-0.05	0.07	-0.47	0.34	Example Figure 11
2016-10-27	301	0	0.02	0.10	-0.49	0.44	
		1	0.01	0.09	-0.47	1.58

Figure 11: Example of ALS derived cross-over elevation with helicopter marked by circle (upper plot) and elevation differences (lower plot) from cross-over number 2 (Table 6) at validation site T5 on the EGIG-line, October 25, 2016

Figure 12: Mission overview of the 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. An overview of the acquired ASIRAS log-files together with start/stop times, range window and number of pulses are listed in Appendix E.

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. Information of antenna phase differences and coherences are also provided for SARIn acquisition in ASIRAS High Altitude Mode (HAM).

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 N and a summary of the processing is given in Appendix O together with plots of each profile.

Table 7: Specifications of ASIRAS and KAREN at 300m flight altitude above the surface

Instrument	Frequency (GHz)	Footprint size		Range resolution (m)
		Along-track	Across-track	
ASIRAS	13.5	3	10	0.1098
KAREN	34.525	5	20	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 horn antennas with a gain of ~25 dB and a 3dB aperture of 10°x8° (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 40m when flying at 300 m AGL, respectively. The vertical resolution is 0.1650 m when transmitting 600 MHz of bandwidth (tunable). An example of an inflight acquisition over the EGIG-line is provided in Figure 13. An overview of the acquired data is provided in Appendix G. 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, or particular 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) even if KAREN uses a time-domain Ground-Back Projection (GBP) approach. The processing steps leading to the final delivered data format (level 1B) from the raw data format (level-0), include range compression (FFT and Hamming filtering), zero-Doppler filtering, and multi-looking. For a more detailed description see the “KAREN altimeter - Processing chain and file format” documentation (MS-DTU-KAR-03-PFF-032) to be found in Appendix H. 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 5, and corrected for lever-arms between GPS antenna and KAREN reference points provided in Table 2. All examples in this report are based on version “levc”, unless otherwise stated.

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 off-set 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 Data final data is packed in netcdf format

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 M.

Figure 13: The upper part is the flight-direction. First look at Ka-band radar altimeter data. The strength of the radar echoes are coded in colour (blue = very weak; red = strong). The strongest echoes come from close to the surface, showing potential of Ka-band to measure ice-sheet height.

5.6 Calibration and absolute heights 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.

During the campaign runway overflights were performed at:

- 25-10-2016 DOY 97 JAV (2 overflights)
- 27-10-2016 DOY 99 JAV (2 overflights)

The data from the runway overflights are available in the delivered data set, except ALS data of first overflight on April 25.

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 Table 8 and 9. In addition standard deviation and percentage of accepted points due to the limits on roll are also provided. In general, the offsets from successive runway overflights vary by up to 16 cm for ASIRAS and 10 cm for KAREN. Thus, the variation of the offsets is smaller for KAREN than ASIRAS with a lower standard deviation. The best estimate of offsets during the CryoVEx/KAREN 2016 fall campaign from second overflight on April 25 using the OCOG retracker is 3.54 m for ASIRAS and -0.42 m for KAREN (marked by red in Table 8 and 9). This overflight was selected as the best runway overflight as no points have been discarded due to waveform blurring and where both radar and ALS elevations are coincident in time. These off-sets have to be applied to all OCOG-re-tracked ASIRAS and KAREN elevations prior to any analysis using absolute heights.

The second runway overflight on April 25 is visualized in Figure 14 and 15. The along-track comparison of the ALS surface elevations (blue) and the ASIRAS OCOG retracked elevations (red) is shown in Figure 14 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).

Table 8: Runway overflights offsets between ALS and ASIRAS using OCOG retracker

Profile	Site	Overflight ASIRAS/ALS	Start time UTC	End time UTC	# points	Off-set (m)	Std (m)	Roll (%)
A20161025_03	JAV	1/2*	66390	66402	448	3.54	0.05	100
A20161025_03	JAV	2/2	67262	67277	432	3.54	0.11	100
A20161027_04	JAV	1/1	58823	58836	167	3.59	0.11	39
A20161027_04	JAV	2/2	59045	59052	103	3.70	0.16	25

*No independent ALS data using RWY2

Table 9: Runway overflights offsets between ALS and KAREN using OCOG retracker

Profile	Site	Overflight ASIRAS/ALS	Start time UTC	End time UTC	# points	Off-set (m)	Std (m)	Roll (%)
KA20161025_182506	JAV	1/2*	66390	66403	174	-0.41	0.04	100
KA20161025_184034	JAV	2/2	67262	67277	176	-0.42	0.04	100
KA20161027_161741	JAV	1/1	58823	58836	71	-0.36	0.04	39
KA20161027_162334	JAV	2/2	59045	59052	42	-0.32	0.08	24

Figure 14: Comparison of ALS, KAREN and ASIRAS elevations over runway in Ilulissat, October 25, 2016 (2nd overflight). ALS (red), KAREN (blue) and ASIRAS (green) elevations (upper left), and respective histograms of ALS-KAREN (upper right) and ALS-ASIRAS (lower right) elevation differences. Aircraft attitudes of roll (black dots) and pitch (grey crosses) are shown in lower left plot.

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 are:

$$dx=+0.33\text{m}, dy=-0.02\text{m}, dz=+0.255\text{m}$$

taken with respect to the aircraft coordinate system as outlined in Figure 3. A swath of the ALS surface elevations of the runway including the ASIRAS profile (black line) and markings of the runway (outlined box) is shown in Figure 15 left. As the location of the ASIRAS and KAREN measurements are almost coincident in the across-track direction (x-direction) in Figure 15 (center) we conclude that the two radar systems are well aligned in the across-track direction.

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. The metal plates placed on the snow during CryoVEx/KAREN 2016 are difficult to locate in the radar waveforms and the exact locations are not known. However, during overflight at T1 the tail of the helicopter has been identified in both ASIRAS and KAREN data (Figure 15 right) and can be used a point-target to test the alignment between the two radars. The distance between the two measurements of the tails is 0.24m and is thus within 0.09m of the actual difference ($dx=0.33\text{m}$) between the two radars reference systems in the along-track direction. Even though we cannot conclude anything about the absolute timing of the respective radar measurements, the radar measurements are aligned within the expected accuracy. This is extremely important for e.g. the phase inter-comparison study presented in Section 6.

Figure 15: ALS elevations of runway in Ilulissat, Greenland, October 25, 2016 (2nd overflight) with KAREN and ASIRAS tracks on top (left). Zoom-in on red box to highlight across-track alignment of KAREN (black) and ASIRAS (green, center) plot. Along-track alignment of helicopter at T1 in ASIRAS (top right) and KAREN (bottom right)

6 Phase differences KAREN vs ASIRAS

Here we make a preliminary investigation of the correlation between the phases of KAREN and ASIRAS when both radars acquire data in SARIn mode. This was the case on the flight of October 27, along the flight line in the blue box marked on Figure 16 top left, where ASIRAS was in High Altitude Mode. The analysis is based on the KAREN product version “levc”. The along-track phases corresponding to the OCOG retracked heights are provided for ASIRAS (blue) and KAREN (red) in Figure 16 bottom plot. By first inspection, the phases seem to be anti-correlated. When ASIRAS and KAREN phases are plotted in a scatterplot, Figure 16 (top right) there are no direct correlation, but there is a higher density cluster of data points within the black circle. The OCOG retracker might not be the most optimal retracker for this study, however, this topic needs a much more in depth analysis in order to draw any conclusions, which is outside the scope of this report.

Figure 16: Location of SARIn box (top left) from flight October 27, 2016. Along-track phases from ASIRAS (blue) and KAREN (red) (bottom). ASIRAS vs KAREN phases (top right).

7 Calibration and Validation sites

At the three validation sites T1, T4 and T5 the vertical firn and ice densities were measured in detail by drilling shallow cores of the upper 3-4.5 m. This was supplemented by several measurements of the snow densities by using a SnowMicroPen at each location. For the overflights aluminum plates were placed on the top of the snow to provide surface reflections for the radar-altimeters and to document the upper structure of the EGIG-line. An overview of the in situ measurements is provided in Table 10. The following Sections provide more information of the in situ measurements, together with results from these and the airborne measurements.

Table 10: Overview of in situ measurements

Site	Date	Latitude Ice cores	Longitude Ice cores	Ice core depths (cm)	Number of vertical measure- ments	SnowPen # measure- ments	Overflight reflectors
T1	20161027	69.731 N	48.133 W	0-319.5	9	2	
T4	20161027	69.811 N	47.510 W	0-446.5	44	23	
T5	20161025	69.851 N	47.253 W	0-452.0	48	41	X

7.1 Vertical firn density profiles

Vertical ice core firn density profiles were taken at T1, T4 and T5, see Table 10. The firn density profiles are derived from snow pits and shallow firn cores using 5 different methods:

- Method 1 is by measuring the firn density in a snow pit as the ratio of mass to volume.
- Method 2 is by setting the section density to snow (350 kg/m³).
- Method 3 is the average density of an ice core section, as the ratio of its mass to volume.
- Method 4 is the average density of an ice core section minus layers of ice, as the ratio of its mass to volume.
- Method 5 is by setting the section (layer) density to ice (917 kg/m³).

Data is provided in an excel spread sheet with each sheet representing the data set in each region. Each excel sheet gives information of ice density, driller diameter, position, site number, start- and end depth together with densities and method used (1-5 described above) to calculate the density at the given depth interval, see Appendix P.

7.2 WSL, SnowMicroPen

The SnowMicroPen (SMP) was originally developed by the WSL Institute for Snow and Avalanche Research SLF for snow profiling to support avalanche risk analysis, but has been proven to be

successfully in several polar expeditions and shows its strengths in measuring the snow and firn stratigraphy, see e.g. Sturm et al., (2004). The SMP was kindly loaned by SFL. It measures indirectly the hardness, density, moisture, and other properties to provide a picture of the layers of snow and their stability. The sensor rod is automatically driven through the snow, see Figure 17 (top left), and measures mechanically the penetration resistance.

The raw data is provided as zipped files (one for each day) with each measurement added as a single binary file (.pnt). Codes to convert raw files into density profiles and first results are reported in Appendix Q. The raw measurements are converted into Force Units and later to densities using the "ConvertForceFactor" provided in the header. However, the conversion is at present not clear. The location of the 41 measurements from April 25 at T5 is shown in Figure 17 (top right) with the corresponding density profiles in the lower plot with each profile given its own color. The maximum depth is 0.70 m and shows large variation over the relative small area.

During the CryoVEx/KAREN 2016 campaign the SMP was used to demonstrate the potential to obtain many shallow measurements within short time. However, it was a challenge for the rod to penetrate the more icy layers and the maximum depth was found to be 0.70 m.

Figure 17: The SMP in action at T4 (upper left). Location of post-processed data at T5 (upper right) and depth (units: mm) distribution of force range (units: N).

7.3 Reflectors

To get a surface reference in the airborne measurements small metal plates (approx. 20x50 cm) were placed on the ground in a line as shown in Figure 18. It is in general difficult to locate the reflectors in the airborne data, but further analysis is needed.

Figure 18: Overflight of the ground team. The metal plates placed on the ground above the tail of the helicopter is acting as surface reflectors in the radar return signal.

7.4 Airborne results

Examples of ASIRAS and KAREN radar echograms and single waveforms from the percolation zone (T1) and the dry snow zone (55nm west of T41) from flight on October 27 are shown in Figure 19 and 20, respectively. Each echogram corresponds to approximately 3 km along-track (x-axis) and 30 m range (y-axis). Thus, the waveforms are to scale. Under these conditions KAREN show primarily surface scattering with little penetration, whereas ASIRAS show primarily surface scattering in the percolation zone and penetration down to about 15 m in the dry snow zone with several visible melt layers. There is a very distinct peak in the single ASIRAS waveform from the dry snow zone about 4 m below the surface which could potentially correspond to the 2012 melt layer. Figure 19 and 20 also highlights the different along-track and range resolutions of KAREN and ASIRAS.

Figure 19: Radar echograms (center) and single (right) waveforms from ASIRAS (top) and KAREN (bottom) in the percolation zone (validation site T1), October 27, 2016.

Figure 20: Radar echograms (center) and single (right) waveforms from ASIRAS (top) and KAREN (bottom) in the dry snow zone (55nm west of T41), October 27, 2016.

8 Conclusion

Despite the marginal weather conditions and limited daylight hours, the CryoVEx/KAREN 2016 campaign has been a success. The Ka-band (KAREN) was operated for the first time during an actual campaign and the radar altimeter performed better than expected even at high altitude (3,500 m above ground), and showed no interference with the other instruments.

Airborne data was acquired over the Greenland Ice Sheet along the EGIG-line at different altitudes as far inland as -42.5°W (55nm West of T41), representing both the ablation, percolation and the dry snow zone. This data set along with the in-situ observations of density profiles from shallow ice cores and SFL SnowMicroPen adds valuable information of the seasonal behavior of the radar signals, which has so far only been obtained in the spring during previous CryoVEx campaigns. The larger range and the potential to “jump” over cloud covered areas demonstrated the flexibility of using a ski-equipped Twin Otter in the future for landings on the ice cap supporting the in situ work, instead of a helicopter.

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 5 cm and standard deviation within 7-10cm over flat areas at cross-over points.

The horizontal location of the KAREN and ASIRAS reference points from the post-processed data are within the expected accuracies of their physical displacement. Comparison of phases of coincident SARIn acquisition from KAREN and ASIRAS data show no direct dependencies. However, the phases seem to be anti-correlated, which is currently being investigated.

As expected KAREN show primarily surface scattering with little penetration, whereas ASIRAS show primarily surface scattering in the percolation zone and penetration down to about 15 m in the dry snow zone with several visible melt layers.

A new ultra-precise Inertial Navigation System (iMAR RQH) purchased by DTU Space with the ability to acquire gravity measurements along with information of attitude was tested. Post-processed attitudes from the iMAR INS is providing the accuracy and precision similar to the current primary Honeywell instrument and can be used as primary instrument in future campaigns.

With the CryoVEx/KAREN 2016 campaign data the scientific community now has a unique collection of measurements to support decision-making of future dual frequency satellite missions, and a seasonal component of the Greenland Ice Sheet to validate the radar altimeter satellites CryoSat and AltiKa and to assist on-going calibration and validation activities.

9 References

- Benson, Carl S. (1960): Stratigraphic studies in the snow and firn of the Greenland ice sheet. Dissertation (Ph.D.), California Institute of Technology.
<http://resolver.caltech.edu/CaltechETD:etd-03232006-104828>
- Cullen, R.: CryoVEx Airborne Data Products Description, Issue 2.6.1, ESA, Ref. CS-LI-ESA-GS-0371, 2010
- Hvidegaard, S. M., and L. Stenseng (2006): Test of ASIRAS installation in Air Greenland Twin-Otter. Field report, National Space Center
- Jensen, T.E., and R. Forsberg (2018). Helicopter Test of a Strapdown Airborne Gravimetry System. MDPI Sensors, 18, page 3121; doi:10.3390/s18093121
- Jensen, T.E., J. E. Nielsen, A. V. Olesen, and R. Forsberg (2018). Strapdown Airborne Gravimetry Using a Combination of Commercial Software and Stable-Platform Gravity Estimates. In: . International Association of Geodesy Symposia. Springer, Berlin, Heidelberg
- Sturm, M., J. Johnson, and J. Holmgren (2004), Variations in the mechanical properties of arctic and subarctic snow at local (1-m) to regional (100-km) scales, in Proceedings of the International Symposium on Snow Monitoring and Avalanches (ISSMA-2004), Manali, India, pp. 233–238.

A University of Kansas, Jakobshavn Glacier test

October 30 – November 12, 2016

October 30-November 1, Installation and test flights, Akureyri

November 2, Flight Akureyri to Ilulissat

November 2-November 12, Survey flights Jakobshavn Glacier

November 12, Flight Ilulissat to Akureyri

B Operator logs

DOY 297, October 23, 2016: Test flight AEY

ALS-log:

Delayed due to aircraft issues

The scanner is showing a strange reflection in middle of the scan.

Front GPS system not working, only logging AIR2, no INS (EGI nor iMar)

15:40

Taxi

15:45

Take off

15:46

Start scanner file, but no signal

15:53:00

New scanner file, no signal from ground

16:00

Turning home to AEY

16:05

Stop scanner

16:18

On ground

ASIRAS-log:

15:45

Take off

Start up ASIRAS, LAM

ASIRAS OK

Turn off ASIRAS

16:18

On ground

DOY 298a, October 24, 2016: Test flight AEY, calibration of building

ALS-log:

Test over the fjord – Alex Ka-band, no ASIRAS

08:52	Taxi
08:55	Take off, ALS, IMar, GPS's, EGI all up and running.
09:05:00	New scanner file
09:12:30	Building overflight N->S
09:16:45	S->N
09:21	W->E
09:27:30	E->W
09:28	Stop logging
09:31	On Ground

DOY 298b, October 24, 2016: AEY-JAV (transport flight)

ALS-log:

No survey, but running EGI and IMar

13:36 Take-off AEY

14:18 Power at IMar fails (the fault was found to be a cable connection which were detached.)

14:45 IMar up and running

~16:20 Visual view of the ice ~approx 36.45 W

18:19 On ground JAV

DOY 299, October 25, 2016: JAV-EGIG-JAV with runway overflight

ALS-log:

During the start-up the GPS position on the EGI was faulty, tried restart of system, with little luck. Just before movement of the POF the position was ok.

15:24 Taxi
15:27 Take-off
15:33:50 New scanner file, no vis. Scan line, the signal was lost at the climb from JAV.
15:41 Stop logging
15:43:30 New scanner file, scanner set to last pulse. The signal was retrieved just before the front of the glacier.
15:48 JAHG3
15:50 Past P-line
15:52 Turn right to make XO
15:55 XO of line
16:06 visual of Swiss camp.
16:07 SWC
16:19 T1
16:23 T3
16:28 T5 (ground work at this site)
16:34 Clouds is approaching still ok
16:38 T9
16:41:30 New scanner file
16:42 turn 180 deg. due to the clouds is expected to be on the rest of the EGIG line.
16:48 T9
16:58 T5
16:59 turn
17:04 XO T5
17:06 turn
17:09 T5
17:14 T3
17:18 T1
17:28 Clouds at 600 ft above ground
17:30 turn
17:32:00 New scanner file, in clouds

17:33 ALS only return from clouds
17:35 Stopped scanner logging this file only contains cloudy data.
17:38 climbed to 6200 ft. for IMar after P5
17:45:30 new scanner file and descending to survey altitude.
17:48 P6
17:50 clouds but signal from the ground
~17:52 P3
18:02 P4 and turned for the middle of Jakobshavn Isbræ.
18:07 heading down glacier
18:09 XO line P3-P4
18:19 Flying over thin new-formed sea ice.
18:26 Runway overflight S-N
18:41 Runway overflight N-S
18:42:40 Stop Scanner
18:45 On ground

ASIRAS-log:

15:24 Taxi
15:27 Take off
15:35 Turn on ASIRAS
Start logging, A161025_00
SDS at T5
16:33 New file, A161025_01
16:42 Break the line, low clouds
16:58 T5
17:05 SDS at T5
17:30 New file, A161025_02
18:24 New file, A161025_03
18:24 Runway overflight JAV
18:42 Runway overflight JAV
18:46 On ground, JAV

DOY 301, October 27, 2016: JAV-EGIG-JAV with runway overflight

ALS-log:

Scanner set to last pulse

12:13 Taxi
12:16 Take-off
12:29 resync scanner
12:31:30 New scanner file
12:35 SWC
12:44 Turn and break line, for xo between swc and t1. Helicopter on the ground aiming at an overflight.
12:48 xo of line swc-t1, heading for helicopter
12:49:21 over helicopter
12:50 turn for second overflight
12:55:48 overflight
12:57 on line swc-t1 again
13:00 T1
13:04 T3
13:10 T5
13:17 climb lost scanner signal
13:18 stop scanner
13:21 Heading directly for T19
13:30 at 12.000 ft, (GPS height) for ASIRAS HAM
13:55 T21
14:22 Turn and descend 55nm from T41, going back in LAM
14:23:50 New scanner file
14:27 only about half scanner line starting heater
14:29 at line T41-T21
14:30 scanner ok
14:50 T21
14:55 T19
14:56 clouds lost half scanner-line
14:59 full scanner
15:01 T17
15:06 T15
15:10 half scanner, clouds
15:12 weak signal, and lost
15:14 T12, no scanner line
15:15:30 New scanner file, in clouds
15:17 Measuring clouds ☺
15:24 T9 clouds
15:31 stop logging no need for processing this file, all is clouds

15:33 T5
15:38:30 New scanner file, below clouds
~15:38 T3, off line
15:40 back on line T3-T1
~15:43 T1
15:56 SWC
16:20:25 Runway S-N
16:24 Runway N-S
16:28 On ground

ASIRAS-log:

12:13 Taxi
12:15 Take off
12:30 Turn on ASIRAS
Calibration
12:35 New file, A161027_00
12:44 Break the line to overfly ground site
12:49 On top of helicopter (seen in ASIRAS), T1
12:56 On top of helicopter, T1
13:16 Stop logging, poor visibility
Calibration
Change to HAM
13:31 ASIRAS turn on
Calibration
13:35 New file, A161027_01, HAM
14:22 Stop logging
Calibration
Change to LAM
14:30 Turn on ASIRAS
Calibration
New file, A161027_02
15:30 New file, A161027_03
Sea ice with thin snow layer (~5cm)
16:20 New file, A161027_04*
Rwy overflight ?
16:23 Rwy overflight
16:27 On ground

*Problems to start logging, restart Asicc.exe

DOY 302, October 28, 2016: JAV-AEY (Transport flight)

Only instrument measuring is GPS and IMar, test of
Ka-band radar in the Denmark Strait at ~3.500 m
above the ocean

14:02	Taxi
14:12	Take-off
19:26	On-Ground

C GPS reference stations

Date	DOY	Reference	Latitude (DMS)	Longitude (DMS)	Ellipsoidal Height (m)
23-10-2016	297	AEY1	65 39 09.44704	-18 04 26.64757	67.636
25-10-2016	299	JAV1	69 14 24.42611	-51 03 53.63469	52.949
27-10-2016	301	JAV1	69 14 24.45030	-51 03 53.54344	52.998

D Overview of acquired ALS data

Date	DOY	Raw ALS file	Start time (dechr)	Stop time (dechr)	Angles (pitch, roll, heading)	dt (s)
23-10-2016	297	297_154655.2dd 297_155300.2dd	-	-'	-	
24-10-2016	298a	298_090500.2dd	09.08342	09.47372	-2.55 -0.15 0.50	0
25-10-2016	299	299_153350.2dd	15.56403	15.68875^	-2.50 -0.16 0.20	0
		299_154330.2dd	15.72522	16.41358^	-2.50 -0.16 0.20	0
		299_164130.2dd	16.69181	17.38019	-2.50 -0.16 0.20	0
		299_173200.2dd	17.53347	17.58914*	-2.50 -0.16 0.20	0
		299_174530.2dd	17.75847	18.44687	-2.50 -0.16 0.20	0
27-10-2016	301	301_123130.2dd	12.52516	13.21352	-2.58 -0.18 0.20	0
		301_142350.2dd	14.39737	15.08579	-2.58 -0.18 0.20	0
		301_151530.2dd	15.25853	15.52618	-2.58 -0.18 0.20	0
		301_153830.2dd	15.64182	16.33020	-2.58 -0.18 0.20	0

' No INS, No data from ground, and wrong timestamp

^ Scan line lost during climb after take-off. The scan line was recovered by applying last pulse

* Only clouds in data file

E Overview of acquired ASIRAS data

Date	File name	Start time (UTC)	End time (UTC)	Range window (m)	# Pulses
23-10-2016	A161023_00.log	17:48:15	17:57:35	90.00	1,397,492
25-10-2016	A161025_00.log	17:31:50	18:30:56	90.00	1,397,492
	A161025_01.log	18:30:59	19:27:56	90.00	8,539,943
	A161025_02.log	19:28:20	20:21:06	90.00	7,912,445
	A161025_03.log	20:21:12	20:38:57	90.00	2,659,982
	A161025_04.log	20:38:59	20:39:03	90.00	5,001
27-10-2016	A161027_00.log	14:33:04	15:13:53	90.00	6,117,461
	A161027_01.log	15:33:15	16:20:03	18.00	7,017,461
	A161027_02.log	16:27:31	17:26:40	90.00	8,869,941
	A161027_03.log	17:26:42	18:11:55	90.00	6,779,955
	A161027_04.log	18:16:42	18:21:58	90.00	784,995

F Overview of acquired iMAR data data

Name	Date	Start time (UTC)	Size (bytes)
Meas_000			73,295,625
Meas_001			689,929
Meas_002	23/10/2016	18:03:20	100,382,492
Meas_003	24/10/2016	08:56:20	446,883,612
Meas_004	24/10/2016	13:20:20	529,381,148
Meas_005	24/10/2016	14:18:50	8,152,865
Meas_006	24/10/2016	14:20:50	10,782,492
Meas_007	24/10/2016	14:23:20	14,722,844
Meas_008			3,417,865
Meas_009			4,466,441
Meas_010	24/10/2016	14:45:51	2,054,113,052
Meas_011	25/10/2016	15:03:20	2,144,622,364
Meas_012	27/10/2016	12:06:50	2,519,791,388
Meas_013	28/10/2016	14:03:20	3,103,065,884

G Overview of acquired KAREN data

25th October 2016		
Name/starting time	Size	Notes
Disk 2		
20161025152954	407 MB	Test
20161025152955	539 MB	Test over water at ~340 m ASL
20161025153339	155 GB	PRF 8.1 KHz, acquisition over ice at 330-700 m ASL, ~25 mins
20161025154417	931 MB	Test at ~750 mASL
20161025154500	24 GB	800-~1150 m ASL; acquisition stopped for a "8" maneuver of aircraft for IMU calibration, ~ 5 mins
20161025155132	53 GB	1100-1430 m ASL, ~10 mins
20161025160552	55 GB	1430-2030 m ASL, ~ 10 mins
20161025161748	100 GB	2030- 2440 m ASL. Pass over the helicopter and calibration targets. Whether turning bad forces to go back after this acquisition -> 180° turn, ~20 mins
20161025164144	80 GB	2500-2230 m ASL. Pass over the helicopter and calibration targets on final part of acquisition. Stopped because we maneuver to pass over them again. .~15 mins
20161025165957	14 GB	Pass over the helicopter and calibration targets in direction perpendicular to previous ones. ` 2 mins
20161025170510	60 GB	2226-1935 m ASL. At 17:16:14 switched system off to change SSHD. ~11 mins
Total	543 GB	
Disk 3		
20161025172437	33 GB	Changing flying altitude over ground to avoid layers of clouds ~ 5 mins
20161025172833	19 GB	PRF 6.2 KHz,, altitude >300m AGL
20161025173300	13 GB	PRF 4.8 KHz, ~1750 m ASL,
20161025173734	6 GB	Test 1 min: increasing AGL -> PRF 1 KHz
20161025174519	18 GB	Back at designed altitude AGL ~300 m, 1200 ASL, PRF 8.1 KHz, ~3 mins
20161025175033	55 GB	1000- 500-1070 m ASL.~ 10 mins
20161025180244	5 GB	Test, 1 min
20161025180443	61 GB	.~ 11 mins
20161025181559	23 GB	Acquisition over the airport, ~4 mins
20161025182123	11 GB	Acquisition over the airport, ~2 mins
20161025183018	3 GB	Test 0.5 min
20161025183650	6 GB	Test 1 min
Total	253 GB	

27th October 2016		
Name/starting time	Size	Notes
Disk 3		
20161027121722	695 MB	Short test after take off
20161027122915	5 GB	PRF 8.1 KHZ, 1365-1420 m MSL, 1 min
20161027123048	60 GB	1446-1860 m MSL, 11 mins, after this AC maneuvers to get helicopter on ground
20161027124443	12 GB	1808-1830 m MSL, 2 mins, passing over targets direction ~150°
20161027124716	791 MB	Test
20161027125015	17 GB	1820- 1810 m MSL, 3 mins, passing over targets direction ~350°
20161027125451	24 GB	1892- 2046 m MSL, ~4 mins,
20161027125942	63 GB	2060-2308 m MSL, ~10 mins
Tot	182 GB	
Disk 4		
20161027132522	1 GB	Due to bad weather conditions AC climbs -> HAM Test PRF 2 KHZ. ~1120 m AGL, (aliasing) Request to reduce AC speed
20161027132812	1 GB	HAM Test PRF 2.45 KHZ, ~1000 m AGL, (less aliasing, but still there) Request to reduce AC speed (-> Higher pitch angle)
20161027133151	26 GB	HAM Test ~ 5 mins
20161027134321	4 GB	HAM Test PRF 3.05 KHZ
20161027134808	118 GB	HAM PRF 2.45 KHZ, 3800- 4024 m ASL, 20 mins, Request to reduce AC speed
20161027140948	7 GB	HAM PRF 2 KHZ 1 min
20161027141128	12 GB	HAM PRF 3 KHZ ~ 2 mins
20161027141358	26 GB	HAM PRF 2.4 KHZ, 1200 m AGL ~ 5 mins Turn 180° and go on way back on LAM
20161027142947	114 GB	LAM PRF 8 KHZ ~20 min
20161027145119	31 GB	~5 min, 288 m AGL
20161027145922	53 GB	~9 min
20161027151425	17 GB	Presence of clouds makes AC climb up (hAGL>500m)
20161027152101	24 GB	h MSL 2700m - 2700m , ~4 mins
Tot	438 GB	
Disk 2		
20161027154155	80 GB	h MSL 2031m - 1450m , ~11 mins
20161027155324	10 GB	h MSL 1417m - 1363m , ~2 mins
20161027155548	39 GB	h MSL 1334m - 642m , ~7 mins
20161027160311	215 MB	test
20161027160311	15 GB	h MSL 575m - 338m , ~3 mins
20161027160635	32 GB	h MSL 338m - 333m , ~6 mins
20161027161358	17 GB	h MSL ~338m, ~4 mins
20161027161951	9 GB	h MSL ~338m-310m, ~2 mins
Tot	202 GB	

H KAREN documentation

KAREN altimeter - Processing chain and file format" documentation (MS-DTU-KAR-03-PFF-032)

I 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 product version, e.g. leva applied hamming filter

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

J 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]
23-10-2016	297	GPS_R_20161023T154042_162040_0001.DBL	0.1
24-10-2016	298	GPS_R_20161024T084220_093253_0001.DBL	0.2
24-10-2016	298	GPS_R_20161024T131739_182236_0001.DBL	1.1
25-10-2016	299	GPS_R_20161025T151351_184928_0001.DBL	0.8
27-10-2016	301	GPS_R_20161027T120450_163051_0001.DBL	1.0
28-10-2016	302	GPS_F_20161028T140119_192904_0001.DBL	1.2

K 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]
24-10-2016	298	INS_20161024T084621_093300_0001.DBL	4.8
24-10-2016	298	INS_20161024T133319_182137_0001.DBL	29.8
25-10-2016	299	INS_20161025T151521_184826_0001.DBL	22.0
27-10-2016	301	INS_20161027T120705_163018_0001.DBL	27.2

L Processed ALS data

Date	DOY	Final file:	File size (MB)
24-10-2016	298a	ALS_20161024T090500_092825.nc	60.4
25-10-2016	299	ALS_20161025T154330_163854.nc	194.0
		ALS_20161025T164130_173129.nc	182.2
		ALS_20161025T174530_184200.nc	199.3
27-10-2016	301	ALS_20161027T123130_131731.nc	147.9
		ALS_20161027T142350_151459.nc	134.5
		ALS_20161027T151530_151532.nc	0.026
		ALS_20161027T153830_162504.nc	162.2

M Processed KAREN data

The following recorded data are available for the KAREN radar system and given in netcdf format. Files marked with bold include data collected over runways.

Date	DOY	File name	Size (MB)
25-10-2016	299	KAR_OPER_Level1b_20161025T153723_20161025T154647_levc.nc	725
		KAR_OPER_Level1b_20161025T154843_20161025T155217_levc.nc	281
		KAR_OPER_Level1b_20161025T155516_20161025T160306_levc.nc	578
		KAR_OPER_Level1b_20161025T160935_20161025T161741_levc.nc	652
		KAR_OPER_Level1b_20161025T162131_20161025T163838_levc.nc	1569
		KAR_OPER_Level1b_20161025T164547_20161025T165857_levc.nc	897
		KAR_OPER_Level1b_20161025T170341_20161025T170618_levc.nc	19
		KAR_OPER_Level1b_20161025T170853_20161025T171943_levc.nc	766
		KAR_OPER_Level1b_20161025T172436_20161025T173003_levc.nc	338
		KAR_OPER_Level1b_20161025T173217_20161025T173520_levc.nc	61
		KAR_OPER_Level1b_20161025T174902_20161025T175215_levc.nc	96
		KAR_OPER_Level1b_20161025T175417_20161025T180313_levc.nc	1042
		KAR_OPER_Level1b_20161025T180936_20161025T181921_levc.nc	1078
		KAR_OPER_Level1b_20161025T181943_20161025T182351_levc.nc	59
		KAR_OPER_Level1b_20161025T182506_20161025T182659_levc.nc	35
		KAR_OPER_Level1b_20161025T183401_20161025T183428_levc.nc	3
		KAR_OPER_Level1b_20161025T184034_20161025T184132_levc.nc	16
27-10-2016	301	KAR_OPER_Level1b_20161027T123432_20161027T124350_levc.nc	843
		KAR_OPER_Level1b_20161027T124827_20161027T125034_levc.nc	27
		KAR_OPER_Level1b_20161027T125358_20161027T125653_levc.nc	31
		KAR_OPER_Level1b_20161027T125834_20161027T130248_levc.nc	197
		KAR_OPER_Level1b_20161027T130326_20161027T131430_levc.nc	768
		KAR_OPER_Level1b_20161027T135151_20161027T141302_levc.nc	1262
		KAR_OPER_Level1b_20161027T141741_20161027T142215_levc.nc	65
		KAR_OPER_Level1b_20161027T143330_20161027T145354_levc.nc	1337
		KAR_OPER_Level1b_20161027T145502_20161027T150032_levc.nc	138
		KAR_OPER_Level1b_20161027T150305_20161027T151227_levc.nc	360
		KAR_OPER_Level1b_20161027T152444_20161027T152903_levc.nc	57
		KAR_OPER_Level1b_20161027T154311_20161027T155552_levc.nc	1246
		KAR_OPER_Level1b_20161027T155708_20161027T155858_levc.nc	46
		KAR_OPER_Level1b_20161027T160001_20161027T160629_levc.nc	731
		KAR_OPER_Level1b_20161027T160716_20161027T161000_levc.nc	159
		KAR_OPER_Level1b_20161027T161018_20161027T161559_levc.nc	84
		KAR_OPER_Level1b_20161027T161741_20161027T162040_levc.nc	65
		KAR_OPER_Level1b_20161027T162334_20161027T162508_levc.nc	21

N Processed ASIRAS data

The following recorded data are available for the ASIRAS radar system and given in the ESA format described in Cullen (2010). Files marked with bold include data collected over runways.

Date	DOY	File name	Size (MB)
25-10-2016	299	AS3OA00_ASIWL1B040320161025T153431_201 61025T163335_0001.DBL	104.0
		AS3OA01_ASIWL1B040320161025T163339_201 61025T173035_0001.DBL	41.2
		AS3OA02_ASIWL1B040320161025T173100_201 61025T182345_0001.DBL	79.1
		AS3OA03_ASIWL1B040320161025T182352_201 61025T184136_0001.DBL	33.0
27-10-2016	301	AS3OA00_ASIWL1B040320161027T123545_201 61027T131632_0001.DBL	68.5
		AS3OA01_ASIHL1B040320161027T133556_2016 1027T142243_0001.DBL	92.7
		AS3OA01_ASIWL1B040320161027T133556_201 61027T142243_0001.DBL	8.6
		AS3OA02_ASIWL1B040320161027T143012_201 61027T152920_0001.DBL	90.3
		AS3OA03_ASIWL1B040320161027T152923_201 61027T161435_0001.DBL	63.6
		AS3OA04_ASIWL1B040320161027T161924_201 61027T162438_0001.DBL	8.1

O 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.

P In situ ice core density data description

Q In situ SnowMicroPen density data description