ESA CryoVEx/EU ICE-ARC 2016 - Airborne field campaign with ASIRAS radar and laser scanner over Austfonna, Fram Strait and the Wandel Sea

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ESA CryoVEx/EU ICE-ARC 2016
Airborne field campaign with ASIRAS radar and laser scanner over Austfonna, Fram Strait and the Wandel Sea

H. Skourup, S. B. Simonsen, L. Sandberg Sørensen, V. Helm, S. M. Hvidegaard, A. Di Bella, and R. Forsberg

DTU Space
National Space Institute
Technical University of Denmark

Technical Report,
September 2018
ESA CryoVEx/EU ICE-ARC 2016

Airborne field campaign with ASIRAS radar and laser scanner over Austfonna, Fram Strait and the Wandel Sea

Authors:
H. Skourup¹, S. B. Simonsen¹, L. Sandberg Sørensen¹, V. Helm², S. M. Hvidegaard¹, A. Di Bella¹ and R. Forsberg²

¹ National Space Institute, DTU Space, Denmark
² Alfred Wegener Institute for Polar and Marine Research, Germany

DTU Space
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Danish Technical University

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Front page: TF-POF at Station Nord and Romer Lake glacier also known as the Elephant Foot (NE-Greenland), credits S. B. Simonsen

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<th>ABSTRACT</th>
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<td>This report outlines the airborne field operations with the ESA airborne Ku-band interferometric radar (ASIRAS) and coincident airborne laser scanner (ALS) to acquire gridded data over Austfonna ice cap in Svalbard for CryoSat-2 validation, first direct Sentinel-3A underflight over sea ice in the Fram Strait and additional repeat some previously flown sea tracks in Fram Strait and the Wandel Sea. Vertical photography was acquired during sea ice flights to support analysis of ASIRAS and ALS observations.</td>
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The airborne campaign took place April 4-16, 2016, operating out of Svalbard and Station Nord. The campaign was coordinated by DTU Space using the Norlandair Twin Otter (TF-POF). It was partly funded by ESA CryoVEx (Austfonna ice cap flights) and partly by EU FP7 project ICE-ARC (Fram Strait and Wandel sea ice flights). The mobilization costs were shared equally between the projects.

The CryoVEx/ICE-ARC 2016 campaign was a success and the processed data is of high quality. Preliminary comparisons between CryoSat-2 and ALS data at Austfonna ice cap, proves the concept of using a gridded ALS data set of lines parallel to CryoSat-2 ground tracks in areas with varying topography. First direct comparisons of Sentinel-3A and ALS also show consistent results.

The work described in this report was done under ESA Contract. Responsibility for the contents resides in the author or organisation that prepared it.

Names of authors:
H. Skourup, S. B. Simonsen, L. Sandberg Sørensen, V. Helm, S. M. Hvidegaard, A. Di Bella, and R. Forsberg

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1 Introduction

The 2016 airborne campaign was conducted during April 4-16, 2016, with the ESA airborne Ku-band interferometric radar (ASIRAS), coincident airborne laser scanner (ALS) and vertical photography. It was partly funded by ESA CryoSat-2 Validation Experiment (CryoVEx) and partly by EU FP7 project on Ice, Climate, Economics – Arctic Research on Change (ICE-ARC). As the same aircraft and instrument installation were used for both campaigns this report includes both the CryoVEx and ICE-ARC campaign data. Below is given an overview of which data belongs to which project. The mobilization costs were shared equally between the projects. The campaign was coordinated by National Space Institute, Technical University of Denmark (DTU Space) using a Twin Otter (reg. TF-POF) chartered from Norlandair, Iceland.

The ESA CryoVEx 2016 was primarily carried out to follow up on a recommendation given within ESA CryoVal Land Ice project (2014-2015), where it was found that the traditional under-flights of the Cryosat-2 satellite were inadequate. This is primarily due to uncertainties in the radar-echo location (POCA) due to topography. To account for this effect, the 2016 ESA CryoVEx airborne campaign was aimed at flying dense grids of parallel lines at Austfonna ice cap along CryoSat-2 ground tracks, to cover a broad range of possible POCA locations from different retrackers (CryoVal-LI D4).

The ICE-ARC campaign was mainly used to repeat some previously flown sea ice flights into the Wandel Sea and the Fram Strait, which had partly failed in 2015 due to problems with the ALS logging system. The opportunity was taken to make the first Sentinel-3A under-flight over sea ice in Fram Strait.

This report is the final report and summarizes the airborne field operations, instrument description and data processing together with first results of Austfonna flight and Sentinel-3A underflight. The report is an ESA CryoVEx contract report and part of EU ICE-ARC deliverable 1.62.

1.1 The primary objectives achieved during the campaign

- Land ice validation of CryoSat-2 – Austfonna ice cap, Svalbard to follow up on ESA CryoVal-LI recommendations (ESA CryoVEX).
- First Sentinel-3 underflights over sea ice in Fram Strait (EU FP7 ICE-ARC).
- Monitoring sea ice thickness north of Greenland and Fram Strait, repeat lines (EU FP7 ICE-ARC).
- Overflight of upward looking sonars moored in Fram Strait to support CryoSat-2 sea ice freeboard-to-thickness conversion (EU FP7 ICE-ARC).
- Repeated flights from earlier campaigns, to monitor the interaction between the ice shelf and the buttressing sea ice in the Nioghalvfjerdsfjorden glacier complex (EU FP7 ICE-ARC).
Figure 1 Overview of the flight tracks (blue lines) from the CryoVEx/ICE-ARC 2016 airborne campaign. Dates of the respective flights are marked next to the flight lines. Yellow star marks the location of the NPI Fram Strait ULS buoys.

2 Summary of operation

The CryoVEx/ICE-ARC 2016 airborne campaign was conducted in the period April 4-16, 2016. An overview of the ground tracks of the airborne campaign is presented in Figure 1. The campaign was based out of Station Nord (STN), Northeast Greenland, and Longyearbyen (LYR), Svalbard, Norway.

A Norlandair Twin Otter (reg: TF-POF), which is the same aircraft as used throughout previous CryoVEx campaigns, was chartered for the entire campaign. The instrument certification for the aircraft was obtained in 2006 (Hvidegaard and Stenseng, 2006). The flight altitude is typically 300 m above ground level, 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. Due to shared logistics of the Twin Otter with Danish company Polar Logistics Group ApS (POLOG), the installation and de-installation of the ASIRAS radar and laser scanner (ALS) took place in Lufttransport AS hangar in LYR and was performed by DTU Space personnel.

As the first part of the campaign was aimed at measuring sea ice in the proximity of the Station Nord, North-East Greenland the ferry flight was used to seek the opportunity of the first under-flight of ESA Sentinel-3A SAR altimeter only 51 days after the launch. At Station Nord the weather conditions
proved optimal for aerial surveying, despite low temperatures (down to -35°C). The low temperatures resulted in long start-up time for the ALS as fog was frozen on the inside of the instrument window during take-off, preventing the laser to penetrate through the window, see Section 4. Despite the difficulties with the start-up of the scanner, all planned sea-ice flights north of Greenland and in the Fram Strait were surveyed between April 6 and April 10. Unfortunately a planned coincident flight with NASA Operation IceBridge (OIB) was not performed due to unexpected aircraft maintenance of the OIB aircraft. A more detailed description of the flights and first results are given in Section 6.

During the second part of the campaign, the weather presented itself more challenging with Austfonna ice cap covered in low clouds. This together with strong winds postponed the survey flights at Austfonna to the very last days of operations. On April 15 and 16, two dense grids were flown along two CryoSat-2 tracks, during two long flights.

The airborne team consisted of Henriette Skourup (HSK), Louise Sandberg Sørensen (SLSS), and Sebastian B. Simonsen (SSIM). Calibration flights of the instruments over buildings and runways were performed whenever possible. The CryoVEx/ICE-ARC 2016 campaign ended on April 16 where the equipment was uninstalled in Longyearbyen. An overview of the flights is found in Table 1. For clarity specified CryoVEx flights are marked by blue, whereas ICE-ARC flights are left unmarked throughout the report. A day-to-day overview is given in Section 2.1 and operator logs and plots of flight tracks are provided in Appendix A.

The CryoVEx/ICE-ARC 2016 campaign was a success and the scientific community now has another unique collection of measurements to analyze as an extension to the data time series from the previous campaigns.

Table 1 Overview of CryoVEx/ICE-ARC 2016 flights.

<table>
<thead>
<tr>
<th>Date</th>
<th>DOY</th>
<th>Flight</th>
<th>Track</th>
<th>Take off UTC</th>
<th>Landing UTC</th>
<th>Airborne</th>
<th>Airborne Accum. [dd:hh:mm]</th>
<th>Survey operator</th>
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<td>Test flight Lyr</td>
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<td>00:00:29</td>
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<td>00:00:48</td>
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<td>17:24</td>
<td>03:21</td>
<td>00:04:09</td>
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<td></td>
</tr>
<tr>
<td>April 8, 2016</td>
<td>99</td>
<td>STN-F1-F2-STN</td>
<td>11:26</td>
<td>16:28</td>
<td>05:02</td>
<td>00:09:11</td>
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<td></td>
</tr>
<tr>
<td>April 9, 2016</td>
<td>100</td>
<td>STN-ULS-STN</td>
<td>11:03</td>
<td>15:38</td>
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<td>00:13:46</td>
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<tr>
<td>April 10, 2016</td>
<td>101</td>
<td>STN- S3 (#769) – Lyr</td>
<td>15:04</td>
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<td>Lyr - CS2 (#32066) - Lyr</td>
<td>08:28</td>
<td>14:08</td>
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<td>April 16, 2016</td>
<td>107</td>
<td>Lyr - CS2 (#31971) - Lyr</td>
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<td>01:04:23</td>
<td>SLSS/SSIM</td>
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<tr>
<td><strong>Total</strong></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>28h 23min</td>
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</table>
2.1 Day to day

The airborne part of CryoVEx/ICE-ARC 2016 progressed as follows:

April 3: Scientists HSK and SSIM CPH to LYR
April 4-5: Installation of equipment and test flight over the fjord together with overflight of calibration building. The ASIRAS PC2 was not operational and had to be bypassed with the help of RST.
April 6: Local test flight in LYR with runway overflight. The flight was successful with ASIRAS only running on PC1. Second flight on route STN following Sentinel-3A orbit 712.
April 7: Low clouds in the area around STN, no flights.
April 8: Triangle flight north of Station Nord (STN-F1-F2-STN). Cold morning (-34°C), caused the scanner to freeze and had to be heated before the flight to make it operational. The weather was excellent for the survey.
April 9: Flight to 79-glacier and moored upward looking sonars in Fram Strait. Slightly warmer this morning, but still problems with ALS condensation, due to cold temperatures. SLSS from Copenhagen to LYR.
April 10: Second Sentinel-3A under flight (orbit 769) on route STN to LYR. Planned CS-2 under flight (orbit 31841) was cancelled, due to low clouds in the area north of Svalbard.
April 11-14: HSK from LYR to Copenhagen.
Windy and cloudy conditions at Austfonna, no survey.
April 15: First Austfonna flight. Despite persistent cloudy conditions at the ice cap a survey of parallel lines of the CS2 orbit 32066, which will pass Austfonna on April 26, were possible. The planned tracks had to be shortened due to clouds on the north side of the ice cap.
April 16: Second Austfonna flight. Again cloudy condition at Austfonna, but it was possible to conduct a survey around the CS2 orbit 31971, which will pass Austfonna on April 19. After the survey the equipment was un-mounted and packed for shipping.
April 17: SLSS and SSIM LYR to Copenhagen.
3 Hardware installation

The installation of the ASIRAS system was identical to the setup used throughout the previous CryoVEx campaigns (see e.g. Hvidegaard et al (2016), Skouroi et al (2013a, 2013b)). To support the ASIRAS system a Novatel GPS DL-V3 was kindly loaned from the Alfred Wegener Institute (AWI). The ALS equipment was of type Riegl LMS Q-240i-60. To prevent malfunction of the ALS during the extreme low temperatures (-25°C and below) in the first part of the campaign, the ALS was wrapped with external heater pads. In addition, an external heater fan as well as an electrical heater, were installed in the instrument bay in the rear baggage compartment of the aircraft, see Figure 6. An older version of the ALS Riegl (LMS Q-140i) was carried along as backup unit.

In addition, three geodetic dual-frequency GPS receivers were mounted for precise aircraft positioning. The receivers (AIR1, AIR2 and AIR3) 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 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 are given in Table 2.

To record the attitude (pitch, roll and heading) of the aircraft, two inertial navigation systems (INS) were used. The primary unit is a medium grade INS of type Honeywell H-764G. 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 backup INS is provided by an OxTS Inertial+2 integrated GPS-INS unit, with a nominal similar accuracy as the H-764G. The Honeywell INS was connected to the front GPS antenna. During most of the campaign the OxTS used dual antenna setup with the rear GPS antenna as primary antenna.

To collect visual imagery of the surfaces surveyed during the sea ice flights, two cameras were mounted next to the ALS in the rear baggage compartment of the aircraft, see Figure 7. The cameras were a GoPro photo/video camera in time lapse mode (to limit the data volume) and a uEye webcam as backup system. Both collect nadir looking images.

The setup of the instruments in the aircraft is shown in Figure 2 and pictures of the various instruments are shown in Figure 3-7.

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<th>dx (m)</th>
<th>dy (m)</th>
<th>dz (m)</th>
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<td>- from AIR1/AIR3 (front)</td>
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<td>+0.52</td>
<td>+1.58</td>
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<tr>
<td>- from AIR2/AIR4 (rear)</td>
<td>+0.00</td>
<td>-0.35</td>
<td>+1.42</td>
</tr>
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</table>
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

Reference point for antenna offset measurements

Figure 2 Overview of instrument setup in the TF-POF Twin Otter aircraft.

Figure 3 ASIRAS antenna.
Figure 4 View of cabin in aircraft; Rack with ASIRAS PC’s (front right), rack for ALS, GPS and INS (rear left). Spare fuel tank for extra airborne time (front left) Photo: SSIM.

Figure 5 Snapshot of ASIRAS operation display over land ice.
Figure 6 Instrument bay in rear baggage compartment of the aircraft. In front laser scanner RIEGL LMS Q-240i with heater pads (grey/orange instrument). H-764G INS (grey box) and OXTS INS (red box) in the back. Between the two INS instruments are mounted two external heaters.

Figure 7 Photo taken from below through hole in aircraft; visible instruments are laser scanner (purple windows) and nadir looking cameras (left).
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.

All the 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 604 TB raw ASIRAS data were collected during the CryoVEx/ICE-ARC 2016 campaign. The data were stored on hard discs as ASIRAS level 0 raw data in the modified compressed format (Cullen, 2010). The ASIRAS system performed well during the campaign only using PC1, due to a malfunction of PC2 detected during the first test flight in Longyearbyen.

In general, the ALS worked well. At low temperatures (below -25°C) encountered at Station Nord, icing of the instrument window during take-off and steep climbs/descends prevented the laser to see through the instrument window. Partly blocking of the laser signals was apparent for the first hour of operation resulting in no surface return or a narrow scan width. Slow climbs during take-off reduced the icing on the scanner window. The actual loss of data was limited since most of the flights included some ferry flight to the designated survey areas. To circumvent the laser to lock on the frozen instrument window, the ALS was switched to measure the “last laser pulse”. 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. The Novatel GPS was dedicated to support ASIRAS and was not part of the logging system. 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.

Vertical photography was collected during sea ice flights. Pictures were acquired every 2 seconds for most flights by nadir-looking photography. Due to problems with the data system running the uEye webcam, this camera was only used on the first flight from Longyearbyen to Station Nord. The GoPro camera recorded nadir-photography from the remaining sea ice flights.

All data are stored on external hard discs, as well as the DTU Space servers with tape backup system.
Table 3 Overview of acquired data.

<table>
<thead>
<tr>
<th>Date</th>
<th>DOY</th>
<th>AIR1</th>
<th>AIR2</th>
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<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>LAMa</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
<td></td>
<td>Stn-S3-Lyr</td>
</tr>
<tr>
<td>15-04-2016</td>
<td>106</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>LAMa</td>
<td>X</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
<td>Lyr-Cs2-Lyr</td>
</tr>
<tr>
<td>16-04-2016</td>
<td>107</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>LAMa</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
<td>Lyr-Cs2-Lyr</td>
</tr>
</tbody>
</table>

1 Icing of the scanner window during take-off and steep climbs/descends
2 The cold conditions made the GPS run out of battery 16:24, but the TF-POF landed at STN 16:28
3 The GoPro image-file G0017431.jpg was corrupted
5 Processing and final data

The data processing is divided between DTU Space and AWI. ASIRAS data is processed by AWI using GPS and INS data supplied by DTU Space. GPS differential positioning together with combined INS-GPS integration is done by DTU Space followed by processing of laser distance measurement into elevation above a reference ellipsoid. This is supplemented by geo-reference of the images taken along the flights, see Section 5.5.

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

- CryoVEx flights, Austfonna April 15-16 can be requested at the ESA portal: https://earth.esa.int/web/guest/campaigns
- ICE-ARC flights, April 6-10 can be downloaded through: https://www.ice-arc.eu/data/

5.1 GPS

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 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 with internal antenna and logging rate 1 Hz was 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/ICE-ARC 2016 are provided in Appendix B.
Table 4 Overview of CryoVEx/ICE-ARC 2016 GPS reference stations

<table>
<thead>
<tr>
<th>Name</th>
<th>Site</th>
<th>Site description</th>
</tr>
</thead>
<tbody>
<tr>
<td>STN1</td>
<td>Station Nord</td>
<td>On snow field between building 9 and runway*</td>
</tr>
<tr>
<td>LYR1</td>
<td>Longyearbyen</td>
<td>Next to parking lot outside airport for test-flights/Airport next to apron for Austfonna flights</td>
</tr>
</tbody>
</table>

*The usual spot near fuel pump was not used due to fuel-lift (operation northern Falcon)

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 was 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) and the Oxford Inertial 2+ (OxTS) 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.

\[ \epsilon(t) = P_{GPS}(t) - P_{INS}(t) \]

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 5. As seen, all solutions are based on input from the Honeywell instrument, avoiding solutions based on the OxTS INS, which has degraded accuracy during acceleration, which includes turns and rapid changes of altitude (Skourup et al., 2012).

The best solutions of both GPS and INS data based on Table 5, is packed as binary files in the special ESA file format (Cullen, 2010). An overview of the final GPS and INS files is listed in Appendix F and G with file name convention according to Appendix E.

Table 5 List of best combination of GPS and INS data

<table>
<thead>
<tr>
<th>Date</th>
<th>DOY</th>
<th>GPS file names</th>
<th>GPS rover</th>
<th>GPS Reference</th>
<th>GPS Processing</th>
<th>INS</th>
</tr>
</thead>
<tbody>
<tr>
<td>05-04-16</td>
<td>96</td>
<td>AIR2REF1/096_AIR2_REF1.p</td>
<td>AIR2</td>
<td>STN1</td>
<td>DIF</td>
<td>H-764G</td>
</tr>
<tr>
<td>06-04-16</td>
<td>97a</td>
<td>AIR2REF1/097a_AIR2_REF1.p</td>
<td>AIR2</td>
<td>None</td>
<td>PPP</td>
<td>H-764G</td>
</tr>
<tr>
<td>06-04-16</td>
<td>97b</td>
<td>AIR2/097b_AIR2.p</td>
<td>AIR2</td>
<td>None</td>
<td>PPP</td>
<td>H-764G</td>
</tr>
<tr>
<td>08-04-16</td>
<td>99</td>
<td>AIR2/099_AIR2.p</td>
<td>AIR2</td>
<td>None</td>
<td>PPP</td>
<td>H-764G</td>
</tr>
<tr>
<td>09-04-16</td>
<td>100</td>
<td>AIR2/100_AIR2.p</td>
<td>AIR2</td>
<td>None</td>
<td>PPP</td>
<td>H-764G</td>
</tr>
<tr>
<td>10-04-16</td>
<td>101</td>
<td>AIR2/101_AIR2.p</td>
<td>AIR2</td>
<td>None</td>
<td>PPP</td>
<td>H-764G</td>
</tr>
<tr>
<td>15-04-16</td>
<td>106</td>
<td>AIR2LYR1/106_AIR2_LYR1.p</td>
<td>AIR2</td>
<td>LYR1</td>
<td>DIF</td>
<td>H-764G</td>
</tr>
<tr>
<td>16-04-16</td>
<td>107</td>
<td>AIR2/107_AIR2.p</td>
<td>AIR2</td>
<td>None</td>
<td>PPP</td>
<td>H-764G</td>
</tr>
</tbody>
</table>
5.3 Airborne Laser Scanner

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 C.

5.3.1 Calibration

The calibration of the misalignment angles between ALS and INS can be estimated by analyzing crossovers of a ground segment. The calibration is further assisted by successive overflights from different directions of the same building, where the position of the corners is known with high precision from GPS measurements. These dedicated calibration maneuvers over building have been carried out twice during the 2016 campaign:

- 05-04-2016 DOY 096 Longyearbyen
- 08-04-2016 DOY 099 Station Nord

Examples of calibration overflights of buildings are given in Figure 8 and 9.

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 C.

5.3.2 Laser scanner outlier detection and removal

No major problems were encountered with the instrument. Due to the problems with moisture on the inside of the ALS (see Chapter 4), some of the flights out of Station Nord have reduced scan width down to about 100m. The largest effects were obtained during the first 30-45 minutes of the survey flights until the external and internal heaters had melted the ice. For most of the flights this effect of icing of the scanner window was reduced by setting the instrument to the TS1 mode that detects the last return pulse. 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 50m to the aircraft, by using input from processed GPS-heights.
Figure 8 Building overflight in Longyearbyen on April 5. The black lines indicate the in-situ measurements of the building.

Figure 9 Building overflight at Station Nord on April 8. The black lines indicate the in-situ measurements of the building.
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. In general statistics over sea ice is poor due to the drift of sea ice between inter-section. The statistics based on raw scanner data before outlier editing are summarized in Table 6, and an example of cross-over differences for Austfonna ice cap is given in Figure 11. Based on statistics from Table 6 it is concluded that the ALS is of high quality with mean differences typically less than 3 cm and standard deviation of cross-over differences less than 10 cm.

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 dedicated CryoVEx flights are packed in netcdf4 format, whereas the dedicated ICE-ARC flights are packed in DTU Space binary data format see Appendix H. An overview of the processed data is given in Figure 10 together with Appendix I.

Figure 10 Mission overview of the ALS data, all recorded heights is given as geo-located point-clouds in respect to the WGS-84 reference ellipsoid.
### Table 6 Cross-over statistics

<table>
<thead>
<tr>
<th>Date</th>
<th>DOY</th>
<th>XO number of the day</th>
<th>Mean (m)</th>
<th>St. Dev (m)</th>
<th>Min (m)</th>
<th>Max (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>05-04-2016</td>
<td>096</td>
<td>0</td>
<td>-0.01</td>
<td>0.08</td>
<td>-0.3</td>
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<td></td>
<td></td>
<td>3</td>
<td>-0.01</td>
<td>0.07</td>
<td>-0.24</td>
<td>0.23</td>
</tr>
<tr>
<td></td>
<td></td>
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<td>0.05</td>
<td>-0.37</td>
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</tr>
<tr>
<td></td>
<td></td>
<td>6</td>
<td>-0.04</td>
<td>0.06</td>
<td>-0.29</td>
<td>0.14</td>
</tr>
<tr>
<td></td>
<td></td>
<td>7</td>
<td>-0.05</td>
<td>0.05</td>
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<td></td>
<td></td>
<td>9</td>
<td>-0.01</td>
<td>0.07</td>
<td>-0.24</td>
<td>0.23</td>
</tr>
<tr>
<td>06-04-2016</td>
<td>097a</td>
<td>0</td>
<td>0.02</td>
<td>0.08</td>
<td>-0.34</td>
<td>0.43</td>
</tr>
<tr>
<td></td>
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<td>0.43</td>
</tr>
<tr>
<td>06-04-2016</td>
<td>097b</td>
<td>No suitable XO’s during the sea ice flight</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>08-04-2016</td>
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</tr>
<tr>
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<td>No suitable XO’s during the sea ice flight</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10-04-2016</td>
<td>101</td>
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<tr>
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<td>0.08</td>
<td>-0.44</td>
<td>0.44</td>
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<td>0.07</td>
<td>-0.61</td>
<td>0.72</td>
</tr>
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<td></td>
<td>10</td>
<td>0.01</td>
<td>0.08</td>
<td>-0.44</td>
<td>0.44</td>
</tr>
<tr>
<td></td>
<td></td>
<td>11</td>
<td>0.02</td>
<td>0.07</td>
<td>-0.61</td>
<td>0.72</td>
</tr>
<tr>
<td>16-04-2016</td>
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<td>0</td>
<td>0.00</td>
<td>0.06</td>
<td>-0.23</td>
<td>0.28</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1</td>
<td>-0.00</td>
<td>0.05</td>
<td>-0.27</td>
<td>0.24</td>
</tr>
</tbody>
</table>

**Figure 11 Example of cross-over elevation differences at Austfonna ice cap, April 16, 2016**
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. An overview of the acquired ASIRAS log-files together with start/stop times, range window and number of pulses are listed in Appendix D.

5.4.1 CryoVEx 2016 ASIRAS 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 and some sea ice areas, 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 (±1.5°) due to waveform blurring.

To obtain absolute surface heights from ASIRAS an offset needs to be applied to account for internal delays in cables and electronics. As the offset is dependent on the choice of retracker it has not been applied in the ASIRAS Level 1b processing. The offset is estimated by comparing ASIRAS 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 was performed at:

- 06-04-2016 DOY 97 Longyearbyen
- 08-04-2016 DOY 99 Station Nord
- 15-04-2016 DOY 106 Longyearbyen

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

5.4.2 Runway overflights and comparison with ALS-DEM

In this section, the offset between the ASIRAS and ALS surface heights are found, using the OCOG retracked surface elevations as provided in the ESA format. Similar procedures have to be applied by the user of the ASIRAS data when using other retrackers.
The statistics of all successful runway overflights are given Table 7. A total mean difference of 3.53 m \( \pm 0.06 \) m is found between ALS and ASIRAS elevations by using the OCOG retracker. The last column in Table 7 states how many percentage of the total number of ASIRAS observations is left after observations with roll angles above/below 1.5° has been removed.

Table 7 ASIRAS -over statistics

<table>
<thead>
<tr>
<th>Profile</th>
<th>Site</th>
<th>Overflight</th>
<th>Start time</th>
<th>End time</th>
<th># points</th>
<th>Off-set (m)</th>
<th>Std (m)</th>
<th>Roll (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A20160406_00</td>
<td>Lyr</td>
<td>1</td>
<td>36386</td>
<td>36421</td>
<td>1515</td>
<td>3.48</td>
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<td>89</td>
</tr>
<tr>
<td>A20160406_00</td>
<td>Lyr</td>
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<td>36610</td>
<td>36643</td>
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<td>3.52</td>
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</tr>
<tr>
<td>A20160408_05</td>
<td>STN</td>
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<td>58735</td>
<td>58759</td>
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<td>25</td>
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<td>50667</td>
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<td>3.55</td>
<td>0.07</td>
<td>77</td>
</tr>
</tbody>
</table>

An example of the laser scanner elevations of the runway overflight in Longyearbyen April 6, 2016, 2\textsuperscript{nd} overflight is given in Figure 12 and 13. A swath of the ALS surface elevations of the runway including the ASIRAS profile (black line) and marking of the runway (outlined black box) is shown in Figure 12. The along-track comparison of the ALS surface elevations (blue) and the ASIRAS OCOG retracted elevations (red) is shown in Figure 13 upper left, together with aircraft roll-angles (black) in lower left. The statistical distribution of the offset between the elevations is shown in the histogram (upper right).

Figure 12 ALS elevation model (w.r.t. WGS-84) of runway in Longyearbyen, April 6, 2016
Figure 13 Comparison of ALS and ASIRAS elevations over runway in Longyearbyen, April 6, 2016. ALS elevation in blue and OCOG retracted ASIRAS elevation in red (upper left) and histogram of ALS-ASIRAS elevation differences (upper right). Roll angles are shown in lower plot.

5.4.3 Corner reflector overflight

No corner reflector overflights were performed during the campaign.

5.4.4 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 L and a summary of the processing is given in Appendix M together with plots of each profile.
5.5 Vertical images

To support the analysis of ALS and ASIRAS data over sea ice high-resolution images were collected along the flights.

Two nadir-looking cameras were mounted next to the ALS instrument in the rear baggage compartment, see Figure 14. On the right, a GoPro camera in time lapse mode collected photos at a 2 second interval. Next to this a backup uEye webcam was installed also acquiring images at 2 second interval but with slightly lower resolution. An overview of the properties of the cameras is given in Table 8 and examples are shown in Figure 15. Both cameras were remote controlled and time tagged using the internal PC/camera clock. By combining the time-tag of the images with GPS data the images have been geo-referenced along the flight lines. Positions of each image are given in a position file (see format in Appendix J), and the raw images are packed in zip-files of about 2 MB (see overview Appendix K).

Table 8 Overview of camera types and settings

<table>
<thead>
<tr>
<th>Camera type</th>
<th>View</th>
<th>Interval (sec)</th>
<th>Resolution (pixels)</th>
<th>Image size (MB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>uEye</td>
<td>Nadir-looking</td>
<td>2</td>
<td>1280x1024</td>
<td>~5</td>
</tr>
<tr>
<td>GoPro</td>
<td>Nadir-looking</td>
<td>2</td>
<td>2592x1944</td>
<td>~1.6</td>
</tr>
</tbody>
</table>

Figure 14 Camera installation of nadir-looking cameras for CryoVEx 2016; uEye (left) and GoPro (right).
Figure 15  Examples of nadir-looking images. (Upper) uEye image (lower) GoPro.
6 Calibration and validation sites

6.1 Land ice

The primary flights during CryoVEx 2016 airborne campaign were the flights at Austfonna ice cap, see below. As an opportunity, the Nioghalvfjerdsfjorden glacier system was re-flown from EU ICE-ARC 2015 airborne campaign, together with measurements of the local ice cap Flade Isblink (FIB) near Station Nord.

6.1.1 Austfonna

The Austfonna ice cap (Figure 16) was flown on April 15 and 16, 2016. The flight lines were prepared to form a dense grid of parallel lines centered around CS-2 orbits 31971 (eastern) and 32066 (western) tracks with passage dates on April 19 and April 26, respectively. The grid flown at Austfonna, were aimed at covering the total POCA area along the selected CS-2 orbits to make the best possible reference surface for validation of CS-2, and were designed in close collaboration with the ESA CryoVal-Land-Ice team members. Two approaches were tested with line spacing of 1 and 2 km, respectively. In addition, an East-West oriented line (Eton East) was re-flown from previous campaigns. It is seen that the length of the lines were limited towards north; this was a consequence of low clouds in this area of the ice cap.

Unfortunately, it was not possible to coordinate the flights directly with the Norwegian ground team, as they were based on the western most part of the ice cap. However, daily contact by iridium phone with the ground team prior to flights has been invaluable to receive updates on weather conditions.

Figure 16 Austfonna ALS surface elevations in meters w.r.t. WGS-84. Insert show the coverage of ALS swaths (~300 m) in the 1 km grid.
Preliminary surface elevations were presented at the ESA Living Planet Symposium by Davidson and Parrinello (2016) and Sørensen et al. (2016). An inter-comparison with ESA Baseline C L2 data and the acquired ALS measurements are shown in Figure 17. First of all it is noticed that all the POCA locations of CryoSat-2 (colored dots) are within the across-track grid spanned by the ALS measurements (green lines). Prior to the comparison the ALS observations were averaged to a resolution of 50m x 50m. Then for each of the POCA locations of CryoSat-2 the nearest neighbor of the averaged ALS observation were found using a 500m search radius. The differences between the POCA located CryoSat-2 elevation and the corresponding ALS elevation are shown as color-coded dots in Figure 17 left. The histograms of elevation differences and time differences between CryoSat-2 and ALS acquisitions are shown in Figure 17 right. There were not found any advantages in using the 1 versus 2 km grid spacing.

The same methodology was used in Sørensen et al. (2018), to analyse six different CryoSat-2 retrackers, including the ESA Baseline C L2 (Figure 17). The supporting on-line material (SOM) of Sørensen et al. provide all CryoSat-2 and ALS data used in the study, along-side the scripts to derive relevant statistics. This valuable CryoVEx dataset may serve as a benchmark for future retracker development for CryoSat-2.

![Figure 17 Inter-comparison of ESA Cryosat-2 L2 data and the ALS data obtained in April 2016](image)
6.2 Sea ice

6.2.1 Sentinel-3 underflight

As an opportunity Sentinel-3A (S3A) under-flight over sea ice in Fram Strait was acquired on April 6 along orbit 712. The satellite passed above the aircraft 16:30 UTC at position 81° 24.43’N and 04° 50.03’W. At the passage time only ASIRAS was recording, due to low thick clouds, which appeared on the track 5 minutes before the satellite passage. This direct under-flight of the S3A over sea ice is to our knowledge the first successful under-flight for this satellite.

On transit flight from Station Nord to Longyearbyen, April 10, a planned CryoSat-2 under-flight (orbit 31841) was cancelled due to low clouds in the area north of Svalbard, and instead a second S3A under-flight was prioritized. The flight followed S3A ground track orbit 769 with passage time of the satellite at 16:27 UTC at position 81° 20.24’N 01° 07.00’E. The weather for this flight was excellent and we only encountered low clouds when approaching Svalbard.

ESA has confirmed that S3A operated in SAR-mode on April 6 and provided the respective level 1b products (i.e. waveforms) so that a first comparison with ALS results could be performed. On the flight on April 10 S3A was switched to Low resolution mode (LRM). A preliminary inter-comparison study of S3A and ALS data from underflight on April 6 was presented at AGU fall meeting 2016 by Di Bella et al. (2016). A short update of the presentation is given below. The S3A waveforms have been classified using their pulse peakiness as being generated by reflections from sea ice or leads. While sea ice waveforms have been retracked using a threshold algorithm (TFMRAS0%), lead elevations are estimated using a Gaussian retracker.

Elevation profiles from S3A and ALS can be observed in figure 18, where the blue dots in the upper plot show the sea ice elevations retrieved processing S3A data, while those in the bottom plot show the snow elevations obtained from ALS measurements. Both elevations have been detrended using the DTU15 mean sea surface (MSS). The red solid lines in the plots represent the sea surface anomalies (SSA), which have been determined by interpolating along track lead elevations.

Comparing the two profiles, an average bias of a couple of meters can be observed between S3A and ALS elevations. This is due to the geophysical corrections not being available for S3A measurements at the time when the processing was performed.

Additionally, the upper plot shows a series of extremely high elevations, up to 18 m, estimated by S3A around 275 km along track which is not observed in the bottom plot. The cause for these extreme elevations has been investigated by analyzing one of the waveforms, corresponding to the circled point in the upper plot of figure 18. Inset in Figure 18 upper plot shows that the TFMRA50% algorithm retracks the half-power point of the first peak around bin number 10 (green dot) instead of the main one around bin number 45. This kind of waveforms is not unusual in sea-ice-covered areas and might be associated with an iceberg inside the satellite footprint. In this case, however, ALS was...
not able to detect the iceberg, possibly due to its smaller footprint. In fact, while S3A coverage extends up to 1.6 km across track, ALS only covers 0.3 km in the same direction.

Overall, a fairly good agreement between S3A and ALS elevations has been found, especially taking into account that, in the situation of snow-covered sea ice, the radar onboard S3A are assumed to measure the height of the snow/ice surface in cold dry snow conditions, whereas ALS measures the height of the snow-air surface.

Figure 18 Sentinel-3A sea ice underflight in Fram Strait April 6, 2016. Sentinel-3A (upper plot) and ALS (lower plot).
6.2.2 Triangle flight north of Station Nord

The triangle flight (STN-F1-F2-STN), has been flown repeatedly since 2003, and with a single beam laser in 1998. The primary aim of the 2016 flight was to get continuation in the data set, as there were problems with retrieval of ALS measurements during a similar flight flown within the EU ICE-ARC 2015 campaign.

The first part of the flight STN-F1 was originally planned as a coincident flight with NASA’s Operation IceBridge (OIB) P-3 aircraft equipped with multiple sensors for sea ice and snow retrievals, where especially the snow depth radar is valuable for snow depth information to support estimation of ASIRAS penetration depths. Unfortunately this coincident flight was canceled due to unexpected aircraft maintenance of the OIB aircraft.

An example of the distribution of ALS freeboard heights from repeated flight tracks (2003-2016) of the sea ice north of Greenland (81-87°N), was presented at the ESA Living Planet Symposium by S. M. Hvidegaard et al. (2016), and is shown in Figure 19. The data set is unique and covers 13 years of observations – from April or May. The freeboard heights are retrieved from ALS by selecting the lowest values in the track data as described in Hvidegaard et al. (2002). The dotted lines mark datasets not covering the full flight line. Data from various campaigns show an overall thinning of the sea ice with large inter-annual changes overlaid.

![Figure 19 Sea ice freeboard heights from repeated flights north of Station Nord 2003 – 2016.](image)
6.2.3 Upward looking sonars

Norwegian Polar Institute (NPI) maintains an array of upward looking sonar moorings located in the Fram Strait measuring the sea ice draft continuously in time. One of these buoys F14 at position 78 48.87N, 06 30.03W was overflown on April 9, along a straight N/S line to account for sea ice drift, see star in Figure 1. Similar over-flights have been collected in April 2012, 2014, 2015.

The airborne laser and radar measures, the sea ice freeboard (Hvidegaard and Forsberg (2002)), as is the case for CryoSat-2. Where the laser reflects on the top of the snow layer, the radar penetrates partly into the snow layer, depending on the snow conditions (Gerland et al. (2013), Hendricks et al. (2010), Willatt et al. (2011)). Thus, a combination of the airborne measurements complements the ULS measurements from below the ice to give an estimate of the thicknesses of the sea ice. These combined data sets are unique, and can be used to validate the sea ice freeboard to thickness conversion in a very dynamic sea ice area, to support CryoSat-2 sea ice thickness estimates. The data from the ULS have not yet been studied as there always is a lack in the availability of the buoy data, as these needs to be physically removed to download data.

Figure 20 Large scale snow drift pattern on sea ice, Fram Strait, April 2016.
7 Conclusion

The CryoVEx/ICE-ARC 2016 airborne campaign has been a success. In general, the weather was good in Greenland, which allowed data acquisition from all planned flights, and partially good in Svalbard allowing 2 out of 3 planned flights to be carried out. Thus, airborne measurements with the ASIRAS and coincident airborne laser scanner (ALS) have been collected to acquire gridded data over Austfonna ice cap in Svalbard for CryoSat-2 validation, first direct Sentinel-3A underflight over sea ice in the Fram Strait and additionally to repeat some previously flown sea tracks in Fram Strait and the Wandel Sea. Vertical photography was acquired during sea ice flights to support analysis of ASIRAS and ALS observations.

The ASIRAS and ALS instruments worked without any major problems. ASIRAS was only operated in LAM-mode, due to a mal-function of PC2. Comparison of ASIRAS to coincident ALS runway overflights concluded that ASIRAS level-1b processed with the ASIRAS processor version ASIRAS_04_03 shows overall good quality. The ALS data is likewise of high quality with mean difference less than 3 cm and standard deviation less than 10 cm at existing cross-over points. The actual loss of ALS data, due to freezing of moisture on the ALS window in extreme cold conditions (<−25°C) experienced at Station Nord was limited to ferry flights to the designated survey areas.

Preliminary comparisons between CryoSat-2 and ALS data at Austfonna ice cap, proves the concept of using a gridded ALS data set of lines parallel to CryoSat-2 ground tracks in areas with varying topography. First comparisons of Sentinel-3A and ALS also show consistent results, with some unexplained high freeboard values in the Sentinel-3A retracked data potentially originating from off-nadir icebergs.
8 References

Cullen, R.: CryoVEx Airborne Data Products Description, Issue 2.6.1, ESA, Ref. CS-LI-ESA-GS-0371, 2010
Davidson, M. and T. Parrinello: Overview of CryoSat Calval Field Activities and Data Analyses. Oral presentation, ESA Living Planet Symposium, Prague, Czech Republic, May 9-13, 2016
A Operator logs

DOY 96, April 5, 2016: Test flight LYR (fjord and building)

ALS-log:
14:45  Ready to Start
14:48  Take-off for overflight of fjord and building.
15:09  Building S -> N
15:11  Building W -> E
15:15  Building E -> W, On ground.

ASIRAS-log:
14:46  Taxi for test flight
14:47  Take-off
15:02  PC2 not working
DOY 97a, April 6, 2016: Test flight LYR (fjord and runway)

ALS-log:
- 09:53 Taxi
- 09:55 Take off
- 09:57:30 New scanner file, Asiras ok, Going for runway overflight at ~300 meters.
- 10:05 1st pass
- 10:09 2nd pass
- 10:10 Close scanner file
- 10:14 On ground

ASIRAS-log:
- 09:39 Ready for ASIRAS test
- 09:53 Taxi
- 09:55 Take off
- 09:57 ASIRAS started and running new rec.
- 10:04 1st pass Event 0
- 10:06 turn for second pass
- 10:07 2nd pass of runway Event 1
- 10:08 stopped rec.
- 10:09 PC1 off
- 10:14 On ground
ALS-log:

<table>
<thead>
<tr>
<th>hh:mm</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>14:20</td>
<td>Taxi</td>
</tr>
<tr>
<td>14:30</td>
<td>uEye started</td>
</tr>
<tr>
<td>14:35:57</td>
<td>uEye stopped</td>
</tr>
<tr>
<td>14:38:40</td>
<td>uEye stopped</td>
</tr>
<tr>
<td>14:40</td>
<td>uEye started new exp. Setting</td>
</tr>
<tr>
<td>14:40:45</td>
<td>Started new scanner file 097_150445.2dd</td>
</tr>
<tr>
<td>15:08</td>
<td>Ops. On S3A-S3B little clouds</td>
</tr>
<tr>
<td>15:27:50</td>
<td>uEye started new exp. Setting</td>
</tr>
<tr>
<td>15:32</td>
<td>at s3b</td>
</tr>
<tr>
<td>15:47</td>
<td>Ops. Low clouds but return on als</td>
</tr>
<tr>
<td>15:48</td>
<td>Ops. No clouds</td>
</tr>
<tr>
<td>15:51</td>
<td>uEye started new exp. Setting</td>
</tr>
<tr>
<td>15:55:10</td>
<td>new scanner file. Wrong sync in 097_155430.2dd, new file 097_155510.2dd</td>
</tr>
<tr>
<td>16:03</td>
<td>At s3c</td>
</tr>
<tr>
<td>16:03</td>
<td>At s3c</td>
</tr>
<tr>
<td>16:14</td>
<td>Ops. Normal</td>
</tr>
<tr>
<td>16:23</td>
<td>Ops. Ground fog</td>
</tr>
<tr>
<td>16:24</td>
<td>lost echo on scanner</td>
</tr>
<tr>
<td>16:27</td>
<td>Echo from clouds</td>
</tr>
<tr>
<td>16:29</td>
<td>Climbed 100ft</td>
</tr>
<tr>
<td>16:30</td>
<td>Sentinel-3 pass at N 81 24.43, W 04 50.03</td>
</tr>
<tr>
<td>16:31</td>
<td>Scanner stopped</td>
</tr>
<tr>
<td>16:32</td>
<td>Climbed 100ft</td>
</tr>
<tr>
<td>16:33</td>
<td>Climbed 100ft</td>
</tr>
</tbody>
</table>

ASIRAS-log:

15:02 cal file A160406_
15:06 started rec.
15:41 clouds no als
16:00 New file 02_1_00
16:20 Low thin layer
16:23 lost als signal
16:27 Climbed 100ft above clouds
16:30 Climbed 100ft above clouds
16:33 Climbed to 420
16:37 Climbed to 480
16:37 uEye stopped
16:44 tested cloud base but had to climb to 540
16:54 New file 03
17:15 stop rec and calb.

DOY 97b, April 6, 2016: LYR – S3A – STN
DOY 99, April 8, 2016: STN-F1-F2-STN

ALS-log:
Before take-off (~30 deg laser cold had to heat it, the laser is set to last pulse
11:22 Taxi
11:26 Take-off
11:28 Lost scanner echo during the climb, icing on internal window.
11:45 Scanner slowly warming, weak echo
11:47:50 New scanner file, Weak echo about only half the width.
11:52 Lost echo on scanner clouds
11:53 Echo back
11:55 uEYE cannot be started
12:00 GoPro on
12:11 At F1 and turn for teardrop
12:29 At F1
12:30 Scanner looks better, now about 150m scan
12:40:55 New scanner file (good scanner echo)
13:37:30 New scanner file, notification about sync error
14:23 at F2 and turn for teardrop. Resync. Scanner
14:27:40 New scanner file, no data
14:28:10 New scanner file, file stopped to fast, might have the XO of the teardrop
14:29:15 New scanner file, just after the crossing at f2, missing the XO
15:22:30 New scanner file, the file 099_152200.2dd started, the right file is 099_152230.2dd
16:03 Fast ice started about 15 min/38 nm out of STN
16:18 1st pass of rwy
16:22 2nd pass of rwy
16:25 crossing the rwy
16:26 Stop scanner file
16:28 On ground STN

ASIRAS-log:
11:32 Startup ASIRAS
11:34 New ASIRAS File 00
12:21 F1
12:22 New ASIRAS File 01
13:16 Big ice islands
13:26 New ASIRAS File 02
14:22 F2
14:22 New ASIRAS File 03
15:20 New ASIRAS File 04
16:01 Ok conditions for work on the ice with snowmobile.
16:07 New ASIRAS File 05
16:16 Rwy overflight STN, 1 pass, event 1
16:20 Rwy overflight STN, 2 pass, event 1
16:27 On ground
DOY 100, April 9, 2016: STN-79Glac-TOB-ULS-STN

ALS-log:
10:43  GoPro started
10:58  Taxi
11:03  Take-off
11:05:30  New scanner file (using last pulse)
11:07  losing scanner echo, weak signal
11:16  Weak echo, flying high
11:20:00  Logging stopped
12:02:00  New scanner file, weak signal, high altitude ice on mirror, only half return.
12:06  scanner ok
12:07  turn for G9
12:18  weak return from half the scanner, icing??
12:23  At G8
12:29  Scanner ok, the icing on the mirror correlates to the change in altitude
12:31  At the front of 79glacier
12:32  At G7
12:49  at TOB
13:02:05  New scanner file
13:37  ULN15 and turn left to tear drop
13:43  at ULN 16
13:50  at UL34
13:55  at ULS16 and turn for teardrop
13:56:55  New scanner file
14:03  at ULS15

14:19  XO of line TOB-ULN15
14:44:05  New scanner file, called 100_1444405.2dd
15:17  front of FIB
15:34  Scanner stopped
15:38  On ground STN

ASIRAS-log:
11:03  Take-off at STN
11:07  Turned on ASIRAS and cal.
11:57  Started record
11:59  Ice edge
12:08  WP G1 79glacier
~12:30  At glacier front
12:53  New file 01
12:56  Fast ice / Drifting ice edge
13:35  ULSN15 -> ULSN16
13:48  ULSF14, event 1, Prevailing wind NE 45deg right of flight direction
13:55  ULS S16
13:56  New ASIRAS file 02
14:58  New ASIRAS file 03
15:15  Flade isblink
15:30  Shut down ASIRAS
DOY 101, April 10, 2016: STN-S3A– LYR

**ALS-Log:**
- 14:21 GoPro turn on
- 15:01 Taxi-off
- 15:05:55 New scanner file, scanner set to last pulse
- 15:15 At S3F
- 15:17 Strong winds at FIB, drifting snow. Almost no scanner echo
- 15:23 Echo back only half width
- 15:29 off FIB
- 15:30 scanner width increasing
- 15:47 at S3G
- 15:59:30 New scanner file
- 16:02 teardrop right
- 16:05 XO of track
- 16:09 Back on track and XO of XO

**ASIRAS-log:**
- 15:07 Turned on ASIRAS and Cal
- 15:08 Started log 00
- 16:00 New ASIRAS file 01, Tear drop
- 16:27 S3 passage time
- 17:00 New ASIRAS file 02
- 17:26 Stop file and cal
- 18:28 Landed, On ground LYR.

16:27 S3 passing, at 81 20.24N 01 07.00 E
16:58 At S3I
16:59:50 New scanner file
17:22 Low clouds, ok echo
17:28 Break line and heading for LYR, about 3 min from S3I
17:28 Stopping Scanner
17:41 GoPro stopped
18:27 On ground LYR
**Final Report**  
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**DOY 106, April 15, 2016: LYR-Austfonna-LYR**

**ALS-log:**

<table>
<thead>
<tr>
<th>Time</th>
<th>Action and Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>08:27</td>
<td>Taxi</td>
</tr>
<tr>
<td>08:29</td>
<td>Take off</td>
</tr>
<tr>
<td>09:23</td>
<td>Reached Austfonna. Cloudy.</td>
</tr>
<tr>
<td>09:26</td>
<td>New scanner file 106_092600.2dd</td>
</tr>
<tr>
<td>09:26-09:46</td>
<td>Many clouds in the area. When flying along the crossing (W-E) line only very little LiDAR could be collected. It was decided to try a different CS track. Aim for CS26.</td>
</tr>
<tr>
<td>09:46</td>
<td>Free of clouds on CS26N-CS26S. But Northern part of the planned tracks are completely cloud covered.</td>
</tr>
<tr>
<td>10:02</td>
<td>New scanner file 106_100230.2dd</td>
</tr>
<tr>
<td>10:04</td>
<td>At L11s26</td>
</tr>
<tr>
<td>10:19</td>
<td>Break line due to clouds</td>
</tr>
<tr>
<td>10:22</td>
<td>On track R5n26-R5s26</td>
</tr>
<tr>
<td>10:41</td>
<td>On track L9s26- L9n26</td>
</tr>
<tr>
<td>10:58</td>
<td>New scanner file 106_105800.2dd</td>
</tr>
<tr>
<td>11:00</td>
<td>On track R9s26- R9n26</td>
</tr>
<tr>
<td>11:18</td>
<td>On track R5s26- R5n26</td>
</tr>
<tr>
<td>11:37</td>
<td>On track R13n26- R13s26</td>
</tr>
<tr>
<td>11:54</td>
<td>New scanner file 106_115400.2dd</td>
</tr>
</tbody>
</table>

No more planned tracks as WPs. Decide to densify grid to 1km spacing. The following lines were flown as 1000m west of other tracks.

<table>
<thead>
<tr>
<th>Time</th>
<th>Action and Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>11:57</td>
<td>Start of track : 1000m west of L11 (&quot;L13&quot;)</td>
</tr>
<tr>
<td>12:15</td>
<td>Start of track : 1000m west of R5 (&quot;R3&quot;)</td>
</tr>
<tr>
<td>12:33</td>
<td>Start of track : 1000m west of L5 (&quot;L3&quot;)</td>
</tr>
<tr>
<td>12:51</td>
<td>New scanner file 106_125130.2dd</td>
</tr>
<tr>
<td>12:53</td>
<td>Start of track : 1000m west of L9 (&quot;L7&quot;)</td>
</tr>
<tr>
<td>13:10-13:18</td>
<td>Crossing all lines</td>
</tr>
<tr>
<td>13:54</td>
<td>New scanner file 106_135400.2dd two runway overflights</td>
</tr>
<tr>
<td>14:08</td>
<td>Landing</td>
</tr>
</tbody>
</table>

**ASIRAS-log:**

<table>
<thead>
<tr>
<th>Time</th>
<th>Action and Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>08:28</td>
<td>Take off</td>
</tr>
<tr>
<td>08:43</td>
<td>Cal</td>
</tr>
<tr>
<td>09:15</td>
<td>Cal</td>
</tr>
<tr>
<td>09:17</td>
<td>Started ASIRAS file 00_1_00</td>
</tr>
<tr>
<td>09:18</td>
<td>At 720 m alt.</td>
</tr>
<tr>
<td>09:24</td>
<td>At 300 m alt.</td>
</tr>
<tr>
<td>09:29</td>
<td>Low clouds</td>
</tr>
<tr>
<td>09:37</td>
<td>Changing plans for flight due to clouds. Going for the CS2 pass at the 26 of April</td>
</tr>
<tr>
<td>09:40</td>
<td>At new line</td>
</tr>
<tr>
<td>09:50</td>
<td>ops. Normal</td>
</tr>
<tr>
<td>10:00</td>
<td>turn and start/stop file 01_1_00, then started file 02_1_00</td>
</tr>
<tr>
<td>10:01</td>
<td>Northbound line</td>
</tr>
<tr>
<td>10:17</td>
<td>Turn</td>
</tr>
<tr>
<td>10:36</td>
<td>next line</td>
</tr>
<tr>
<td>10:39</td>
<td>on line and ice</td>
</tr>
<tr>
<td>10:55</td>
<td>turn</td>
</tr>
<tr>
<td>10:55</td>
<td>new file 03_1_00</td>
</tr>
<tr>
<td>11:03</td>
<td>turn clouds</td>
</tr>
<tr>
<td>11:32</td>
<td>turn end of line</td>
</tr>
<tr>
<td>11:51</td>
<td>turn and new file 04_1_00</td>
</tr>
</tbody>
</table>
DOY 107, April 16, 2016. LYR-Austfonna-LYR

ALS-log:
08:24 Taxi
08:26 Take off
09:22 At ETON1. Cloudy.
09:47 Clouds. We will have to skip the northern-most part of all tracks.
09:50 On track CS19n-CS19s
10:09 On track L13s19- L13n19
10:23 Break off line
10:25 New scanner file: 107_102500.2dd
10:27 On track R5n19- R5s19
10:43 On track L9s19- L9n19
10:59 Break off line
11:01 On track R9n19- R9s19
11:15 Break off line
11:16 New scanner file: 107_111630.2dd
12:11 New scanner file: 107_121100.2dd
12:13 Without WPs: on tracks 'R21n19-R21s19' followed by 'L21s19-L21n19'
14:02 Landing

ASIRAS-log:
08:26 Take-off
09:04 cal
09:09 cal
09:10 Record without return, altitude?
09:14 rec stop
09:16 cal
09:17 start new file 01_1_00
09:39 turn for grid around CS2 April 19
09:50 at CS2 line
10:04 turn at coast
10:07 on line northbound
10:22 new file 02_1_00
11:14 turn new file 03_1_00
12:08 turn new file 04_1_00
13:10 turn and end of rec
13:10 cal and closing down
## B Coordinates of GPS base stations

All processing of reference stations are done by the online services at http://www.ga.gov.au/scientific-topics/positioning-navigation/geodesy/auspos.

<table>
<thead>
<tr>
<th>Date</th>
<th>DOY</th>
<th>Reference</th>
<th>Latitude (DMS)</th>
<th>Longitude (DMS)</th>
<th>Ellipsoidal Height (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>05-04-2017</td>
<td>096</td>
<td>Lyr</td>
<td>78° 14' 51.54631''</td>
<td>15° 29' 31.23559''</td>
<td>50.197</td>
</tr>
<tr>
<td>06-04-2017</td>
<td>097a</td>
<td>Lyr</td>
<td>78° 14' 51.55234''</td>
<td>15° 29' 31.31248''</td>
<td>50.237</td>
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### Overview of acquired ALS data

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## D Overview of acquired ASIRAS log-files

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E File name convention

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

**ASIRAS:**

**AS30AXX** _ASIWL1BNNNN_**SSSSSSSSSSSSSSS_PPPPPPPPPPPPPPP_0001.DBL**

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

**GPS**

**GPS_ANT_VER_SSSSSSSSSSSSSSS_PPPPP_0001.DAT**

- **ANT** GPS antenna R for rear, and F for front
- **VER** Version
- **SSSSSSSSSSSS** Start time given as YYYYMMDDTHHMMSS
- **PPPPPP** Stop time given as HHMMSS

**Inertial Navigation System (INS)**

**INS_** _SSSSSSSSSSSSSSS_PPPPP_0001.DAT**

- **SSSSSSSSSSSSSS** Start time given as YYYYMMDDTHHMMSS
- **PPPPPP** Stop time given as HHMMSS

**Airborne laser scanner (ALS) full resolution**

**ALS__** _SSSSSSSSSSSSSSS_PPPPPPP.XXX**

- **SSSSSSSSSSSS** Start time given as YYYYMMDDTHHMMSS
- **PPPPPP** Stop time given as HHMMSS
- **XXX** Data format which is either sbi (binary) or nc (netcdf4)
**F 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).

<table>
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<th>Size [MB]</th>
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Processed INS data is delivered in binary, big endian format with each record formatted as described by Cullen (2010).

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<td>$10^{-7}$</td>
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<td>Int</td>
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<td>$10^{-7}$</td>
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<td>Scan no. in scanline</td>
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data['lat'] = data['lat'] * 1.0E-7
data['lon'] = data['lon'] * 1.0E-7
data['hoj'] = data['hoj'] * 1.0E-3
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### Processed ALS data

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<th>File size (MB)</th>
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### J Data format vertical images

Approximate time and position of the vertical camera when a picture is taken is delivered in windows ASCII format as described in Table below and all individual pictures are in JPEG format. Each ASCII line gives the filename, time and position for the named picture. If no DGPS data is available, the time and position is replaced with the string “No position available”.

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## Processed ASIRAS data

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

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M 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.