Technical Assistance during the 2012 ICESAR Validation Campaign; Final Report

ESA Contract No. 4000106112/12/NL/FK

Jørgen Dall, Technical University of Denmark
Anders Kusk, Technical University of Denmark
Ulrik Nielsen, Technical University of Denmark
Francesco Banda, Politecnico di Milano
Stefano Tebaldini, Politecnico di Milano
Fabio Rocca, Politecnico di Milano
Roderik van de Wal, Utrecht University

June 2013
# ESA STUDY CONTRACT REPORT

<table>
<thead>
<tr>
<th>ESA CONTRACT No</th>
<th>SUBJECT</th>
<th>CONTRACTOR:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Technical Assistance during the 2012 ICESAR Validation Campaign</td>
<td>Technical University of Denmark</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>SUBCONTRACTORS:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Politecnico di Milano</td>
</tr>
<tr>
<td>Utrecht University</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>* ESA CR( )No</th>
<th>* STAR CODE</th>
<th>No of volumes: 1</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>This is Volume No: 1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Contractor's Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>FR_v2</td>
</tr>
</tbody>
</table>

## ABSTRACT:

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:  Jørgen Dall, Anders Kusk, Ulrik Nielsen, Francesco Banda, Stefano Tebaldini, Fabio Rocca, Roderik van de Wal

** NAME OF ESA STUDY MANAGER **

** ESA BUDGET HEADING 

DIV:

DIRECTORATE:
# Table of contents

1 Introduction ................................................................................................................................. 3  
1.1 Objectives ................................................................................................................................ 4  
2 Data acquisition campaigns ....................................................................................................... 5  
2.1 Radar system and observation modes ....................................................................................... 5  
2.2 Test sites ................................................................................................................................... 6  
2.3 Flight patterns .......................................................................................................................... 7  
2.4 Radar data overview ................................................................................................................ 11  
2.5 In-situ data ................................................................................................................................ 15  
2.5.1 Data processing GPS data ................................................................................................... 16  
2.5.2 Velocity results .................................................................................................................... 16  
2.5.3 Water pressure measurements .............................................................................................. 16  
3 Data pre-processing .................................................................................................................. 19  
3.1 Navigation data ....................................................................................................................... 19  
3.2 Level 0c processing .................................................................................................................. 19  
3.3 Level 1c processing - SAR focusing ......................................................................................... 19  
3.3.1 Output grid definition .......................................................................................................... 19  
3.3.2 SAR focusing algorithm ...................................................................................................... 20  
3.4 Calibration ............................................................................................................................... 21  
3.4.1 Radiometric and polarimetric calibration ............................................................................. 21  
3.4.2 Focusing quality and geometric calibration ......................................................................... 22  
4 P-band ice signatures .................................................................................................................. 25  
4.1 Radiometric signature .............................................................................................................. 25  
4.1.1 K-transit backscatter over time .......................................................................................... 25  
4.1.2 Polarimetric signatures at selected sites ............................................................................. 26  
4.2 Interferometric signature ......................................................................................................... 30  
5 Ice displacement mapping .......................................................................................................... 35  
5.1 Offset tracking ........................................................................................................................ 35  
5.1.1 Error characterization .......................................................................................................... 35  
5.1.2 Measurements ..................................................................................................................... 37  
5.1.3 Comparison of offset-tracking and in-situ GPS measurements .......................................... 37  
5.2 Interferometry ......................................................................................................................... 45  
5.3 BIOMASS simulation ............................................................................................................... 47
7 Tomography

7.1 Introduction ........................................................................................................51
7.2 SAR Tomography: basic principles .................................................................52
7.3 Description of the data ..................................................................................53
7.4 Data focusing ....................................................................................................54
  7.4.1 Pre-processing ............................................................................................54
  7.4.2 Azimuth focusing with time domain back-projection ............................54
7.5 Single pass tomography at SHR .................................................................56
  7.5.1 Baseline planning .....................................................................................56
  7.5.2 Results ......................................................................................................57
7.6 Interferometric analysis .................................................................................58
  7.6.1 SHR May ..................................................................................................58
  7.6.2 SHR June ................................................................................................61
  7.6.3 S10 ...........................................................................................................63
7.7 Algebraic analysis of the covariance matrix of the data ...............................66
  7.7.1 SHR May ................................................................................................67
  7.7.2 SHR June ................................................................................................68
  7.7.3 S10 ...........................................................................................................68
7.8 Multi-pass tomographic processing ...............................................................70
7.9 Tomographic profiles .....................................................................................80
  7.9.1 SHR May ................................................................................................80
  7.9.2 SHR June ................................................................................................81
  7.9.3 S10 ...........................................................................................................82
7.10 Differential tomographic analysis at SHR ....................................................84
7.11 Algebraic Synthesis from multibaseline full-pol S10 data .............................87
7.12 Large scale tomographic analysis .................................................................91
  7.12.1 SHR May ...............................................................................................91
  7.12.2 SHR June ..............................................................................................96
  7.12.3 S10 .........................................................................................................102
7.13 Surface height and penetration depth ..........................................................108
7.14 Differential analysis May/June at SHR .........................................................131
7.15 Subsurface motion via 3D DInSAR (synthetic data) ....................................133
8 Conclusions .......................................................................................................135
9 References .........................................................................................................137
1 Introduction

In the frame of IceSAR-2012, airborne SAR campaigns were carried out in Greenland in support of the Biomass candidate Earth Explorer mission. The secondary objectives suggested for Biomass include (i) ice velocity, (ii) ice extinction and subsurface structure of glaciers and ice sheets. For these applications, the larger wavelength and deeper penetration of P-band is expected to provide significant advantages over higher frequencies or to offer a complementary performance. IceSAR-2012 also addresses likely disadvantages of P-band, e.g. low backscatter, volume decorrelation, and the coarse resolution resulting from the small bandwidth allocated at P-band.

Ice velocities can be measured by means of SAR i.e. differential SAR interferometry (DInSAR) and offset tracking, which in turn comprises feature tracking and speckle tracking. Especially at X-band and C-band, temporal decorrelation calls for short temporal baselines, and in some ice regimes velocity measurements are confined to the melt-free season. Compared to C-band, L-band tends to provide better measurements of ice sheet motion because of a higher temporal coherence over snow and firm [1], [2]. Coherence is important for DInSAR and speckle tracking, while a fine spatial resolution is more important than coherence for feature tracking. P-band is expected to offer still higher temporal coherence, as the impact of near-surface change processes is further reduced due to the larger wavelength and penetration to deeper and more stable scatterers [3]. P-band is likely to be compatible with typical satellite repeat cycle times, while 1- or 3-day data (ERS tandem data or Ice Phase data) are typically preferred for DInSAR at C-band.

P-band benefits are expected in ice regions where coherence is crucial, i.e. where there are no crevasses and other surface features. Extrapolating from the C- and L-band data, P-band is expected to provide better spatial coverage and more precise velocity estimates. In Figure 1.1 a better coverage is obtained at L-band in spite of a longer temporal baseline.

![Figure 1.1 Ice velocity maps from the winter 2008-2009 based on L-band PALSAR data (left), C-band RADARSAT data (mid), and C-band ASAR data (right) [1].](image-url)
Due to the increased coherence DInSAR can probably be substituted for offset tracking, e.g. in the lower part of the drainage basins. This would be beneficial, as DInSAR offers a better velocity precision and a finer spatial resolution. On the other hand, DInSAR calls for a higher coherence than offset tracking. Over fast glaciers, velocity gradients can also inhibit application of DInSAR [4]. This is due to decorrelation and phase unwrapping issues, but at the longer P-band wavelength, the decorrelation is expected to be less pronounced, and the phase unwrapping less challenging [3].

Seasonal velocity variations of glaciers can be measured with feature tracking because the crevasses and other surface features are sufficiently stable year-round. However, in ice regimes having no crevasses and other surface features, ice velocities cannot be measured at higher frequencies in the melt season, where rapid wavelength-scale surface changes take place.

The increased penetration at P-band improves the ability to quantify the near-surface ice extinction (or the equivalent penetration depth). The extinction of the electromagnetic field with depth is related to geophysical parameters of glaciological interest. An unambiguous relationship, however, does not exist, because the extinction depends on several parameters, e.g. grain size, firm density, ice inclusions, and temperature. The penetration depth has also an impact on the temporal decorrelation, as the influence of near-surface change processes reduces with increasing penetration depth.

Recent improvements of topographic SAR (TomSAR) techniques might provide a better way of mapping ice extinction. In addition TomSAR has the potential of three-dimensional mapping of subsurface ice structures. Since the Biomass mission will include a TomSAR phase, it is natural to assess this novel technique in relation to ice mapping.

1.1 Objectives

In order to assess and quantify the potential P-band benefits, seven objectives have been defined in the IceSAR-2012 Statement of Work (SOW) [5]:

1) Documenting of P-band radiometric signatures over ice sheets for a range of sensor parameters (e.g. incidence angle, polarisation) and geophysical conditions on ground;

2) Documenting of P-band interferometric and tomographic signatures for a range of mission relevant parameters (e.g. baseline, orbital cycle time intervals) and geophysical conditions on ground;

3) Assessment of algorithms and their suitability in the Biomass context for generating ice motion products. Algorithms to be evaluated shall include interferometric phase-based and feature tracking algorithms;

4) Documenting quantitatively the impact of interferometric baseline diversity on the accuracy and robustness of ice motion and subsurface information products;

5) Documenting quantitatively the impact of temporal decorrelation on the accuracy and robustness of ice motion and subsurface information products;

6) Assess the information content of tomographic acquisitions over ice sheets;

7) Generating airborne prototype ice motion and ice subsurface structure products to support preparations for the user consultation meeting and final mission down-selection.

In addition to the objectives defined in the SOW, ice sounder data were acquired in support of ice motion data interpretation:

8) Generating across-flow sounding profiles at different up-/down-stream positions;

9) Generating along-flow sounding profiles at two different times, one when the flow speed is low and another one when the flow speed has increased.
2 Data acquisition campaigns

During IceSAR-2012, P-band SAR data were acquired with the airborne POLARIS system, which was originally developed as a nadir looking ice sounder [6] but recently upgraded with a SAR capability [30]. In this section POLARIS and its observation modes are briefly introduced. The test sites and the flight patterns over these test sites are presented, and an overview of the radar data is provided. Finally the in-situ data are addressed.

2.1 Radar system and observation modes

The POLARIS radar can operate in either sounding mode, with the antenna beam pointing to nadir, or in SAR mode, with the beam steered to the right or left of the flight track. Independent of the beam direction, the radar can be configured to work in either polarimetric (1 aperture, full polarimetry) or multi-aperture (4 apertures, single-polarization) configuration. The beam direction can be changed manually in in-flight, whereas switching between polarimetric/multi-aperture configurations must be done on the ground.

In SAR mode, the flight altitude is nominally 4 km above the surface, although this may be reduced in areas of high surface elevation due to air traffic restrictions. The range of look angles covered is from approximately 20º to 45º, corresponding to a swath of 2.5 km in ground range at the nominal altitude.

In sounding mode, the nominal flight altitude is 600 m above the surface.

For all flights, the small (4-element) POLARIS antenna was used, see Figure 2.1. Most data were acquired in the polarimetric SAR mode. Tomography data were acquired in multi-aperture SAR mode at HH polarization, and sounding data were acquired for objectives 8 and 9.

The radar was flown on the Norlandair TF-POF Twin Otter aircraft on which POLARIS has been certified and flown in the past. In order to maintain and reproduce stable flight tracks, a system called EMAP4, developed at the DTU Space Geodynamics division, was used. The system uses GPS to calculate and present in real-time to the pilots the current deviations from a desired track, as well as steering information to return to the track. Furthermore, when operating at the high altitude required in the SAR mode, the aircraft’s own radar altimeter cannot be used, and the EMAP4 program displays the current estimated altitude over the terrain, based on GPS altitude and the GTOPO30 digital elevation model (DEM). This feature was employed on the longer data acquisitions where the surface elevation changed significantly (e.g. along the K-transect). For acquisitions of smaller areas (e.g. the tomography at SHR), a constant GPS altitude was employed.

Navigation data were acquired with three Javad GPS receivers, providing 1Hz kinematic GPS data, and a Honeywell H764G EGI (Inertial Navigation Unit with embedded GPS) providing 50 Hz inertial data. On flights that took off and landed in SFJ, a GPS reference station was placed on the ground to support kinematic processing. On transit flights, no reference stations were available.

![Figure 2.1 POLARIS SAR.]
2.2 Test sites

Most of the activities focus on the K-transect on the Russell glacier in South-west Greenland, near Kangerlussuaq, at 67° North – just north of the Arctic Circle. Additional data were acquired during the transit from/to Kulusuk, and though this transit does not pass the dry snow zone it provides percolation zone data from higher elevations.

The K-transect is one of the best studied areas of the Greenland ice sheet, partly due to the relatively simple logistical conditions of an international airport close-by. The K-transect was established in 1990 by the IMAU at the Utrecht University and currently comprises eight locations with GPS measurements as shown in Figure 2.2. The K-transect stretches approximately 150 km inland from the edge of the ice sheet, and it crosses the equilibrium line. It passes through the ablation zone, the wet snow zone, and ends in the percolation zone. A 2.5 km wide strip centred about a straight line between SHR and S10 was mapped during the IceSAR-2012 campaigns.

Figure 2.2 K-transect with GPS stations [31].

Two 5 km by 5 km areas at SHR and S10 were mapped particularly intensively. At SHR, a significant ice speed-up has previously been observed in early June. S10 represents a different ice zone, the percolation zone, thus contributing to the assessment of the impact of the geophysical conditions. The corners of a box covering the SHR-S10 strip are listed in Table 1.

<table>
<thead>
<tr>
<th>Waypoint/site</th>
<th>Latitude</th>
<th>Longitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>ANW (K-transect box)</td>
<td>67° 07.519’ N</td>
<td>49° 59.764’ W</td>
</tr>
<tr>
<td>ASW (K-transect box)</td>
<td>67° 04.590’ N</td>
<td>50° 00.234’ W</td>
</tr>
<tr>
<td>BSE (K-transect box)</td>
<td>66° 58.392’ N</td>
<td>46° 57.917’ W</td>
</tr>
<tr>
<td>BNE (K-transect box)</td>
<td>67° 01.310’ N</td>
<td>46° 57.084’ W</td>
</tr>
</tbody>
</table>
2.3 Flight patterns

IceSAR-2012 includes three campaigns (April, May, and June) in order to:

- ensure temporal baselines comparable to – and exceeding – those expected for Biomass
- observe seasonal variations.

The time separation between the April and May campaigns is close to the 17 days repeat cycle of Biomass [32]. The June flights are late enough that the melt season has started, and the ice velocity has increased due to percolation of melt water. The schedule was constrained by the CryoVex campaign (for which the same aircraft is used), by a coordinated flight with the UAVSAR in June, and by the availability of the DTU personnel.

Table 2–Table 4 are traceability matrices outlining the correspondence between the data acquisition and the campaign objectives listed in the SOW [7] and in Section 1.1. The numbers in the first column refer to the list in Section 1.1. An “X” means that the data contribute to the objective by itself, whereas a “+” means that the data contribute to the objective when combined with one or more other data sets. For instance, in Table 2 “X+” means that the April K-transect data are intended to assess the coherence signature (dependence on the spatial baseline), but also to be combined with K-transect data from other campaigns in order to assess another aspect of the coherence signature (dependence on the temporal baseline).

Figure 2.3 outlines the flight patterns. The K-transect and the short crossing tracks at SHR and S10 contribute to the assessment of the radiometric signature and the coherence signature as well as to ice velocity products generated with Offset Tracking. Since the ice velocity is approximately parallel to the transect, the crossing tracks are required in order to assess interferometric techniques, with which only the range ice velocity component can be measured. To some extent the ice displacement was compensated for when the flight tracks were defined. A range component of the ice displacement adds to the spatial baselines and increases the corresponding decorrelation. This applies only to aircraft geometries, where the spatial baselines are small, whereas the ice displacement is negligible compared to typical satellite baselines. In order to obtain an altitude of ambiguity corresponding to that of Biomass, the POLARIS baselines should be 5-10 m, which is comparable with the diameter of the flight tube that can be achieved with the Twin Otter in combination with the EMAP4 system mentioned in Section 2.1.

The tomography tracks are parallel to the K-transect. In this way, the ice motion causes little decorrelation, as it can largely be compensated for by azimuth shifts during the tomographic processing.

For tomography, the cross track aperture size defines the resolution in the elevation plane, while the baselines (the spacing of the antenna elements) define the angle of ambiguity in the same plane. The larger the penetration depth (or the ice thickness), the larger the required angle of ambiguity, and the smaller the acceptable baselines. Also, when increasing the unambiguous depth, a coarser resolution results for a given number of tracks. During IceSAR-2012, two times 10 tracks were flown per campaign, i.e. 10 tracks mapping the scene from one side and another 10 tracks mapping the scene from the opposite side. In order to be sure that ambiguities are sufficiently suppressed, data were acquired with the system configured for four antenna apertures, such that data are effectively acquired from 40 tracks. The price paid is that only single pol data could be acquired.

In Table 3 “NA” means that the data acquisition failed due to an antenna configuration error. To compensate for this the tomographic flight in June was introduced.
Table 2 Traceability matrix for PolSAR, InSAR, and DInSAR data acquisitions.

<table>
<thead>
<tr>
<th>Objective/Time, site</th>
<th>April K-transect</th>
<th>April SHR, S10</th>
<th>May K-transect</th>
<th>May SHR, S10</th>
<th>May Transit W–E</th>
<th>June K-transect</th>
<th>June SHR, S10</th>
<th>June Transits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radiometric signature (1)</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coherence signature (2,4)</td>
<td>X+</td>
<td>+</td>
<td></td>
<td></td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>DInSAR technique (2, 3, 4)</td>
<td>+</td>
<td>+</td>
<td></td>
<td></td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Offset tracking technique (3)</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td></td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Ice motion product (5)</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td></td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
</tbody>
</table>

Table 3 Traceability matrix for tomography.

<table>
<thead>
<tr>
<th>Objective/Time, site</th>
<th>April SHR</th>
<th>May SHR</th>
<th>June SHR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tomographic signature, polarimetric (2)</td>
<td>NA</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Structure product, polarimetric (4)</td>
<td>NA</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Ice velocity (3,6,7)</td>
<td>NA</td>
<td>+</td>
<td>+</td>
</tr>
</tbody>
</table>
Table 4 Traceability matrix for sounding.

<table>
<thead>
<tr>
<th>Objective\Time, site</th>
<th>April Transit E–W</th>
<th>April K-transect</th>
<th>April SHR, S10</th>
<th>June K-transect</th>
<th>June SHR, S10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coast-coast profile</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Along-track profile, dry base (8,9)</td>
<td></td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Across-track profile, dry base, down-stream (8,9)</td>
<td></td>
<td></td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Across-track profile, dry base, up-stream (8,9)</td>
<td></td>
<td></td>
<td></td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Along-track profile, wet base (8,9)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Across-track profile, wet base, down-stream (8,9)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Across-track profile, wet base, up-stream (8,9)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>X</td>
</tr>
</tbody>
</table>
Figure 2.3 Flight patterns for acquisition of SAR data (green) and sounder data (cyan).
2.4 Radar data overview

IceSAR flights in Greenland were carried out on ten different days. On April 19, the radar was installed in and flown from Akureyri, Iceland (AEY) to Kangerlussuaq, Greenland (SFJ), followed by two more days of acquisitions. The radar was uninstalled in SFJ, and reinstalled there in May. Three May flights were carried out, the third of which was the transit back to AEY. In June, the radar was installed in AEY and flown in support of the UAVSAR campaign in Iceland, twice on June 8, and on the morning of June 9, followed by the transit to SFJ the same day. This was followed by three more days of acquisitions, the final one being the transit back to AEY. On the final leg, over Iceland, sounding data in support of the UAVSAR campaign were also acquired. The flight dates (in Greenland) are summarized in Table 2.5.

To identify specific sites and acquisition times, an acquisition naming scheme has been adopted, with the following format: `<Scene><DOY><a-z>`, where the `<Scene>` identifies the geographical site, `<DOY>` is the day of year of the acquisition, and `<a-z>` distinguishes between different acquisitions on the same day. Thus KTRot129b would be the second (b) acquisition of the KTRot scene on May 8<sup>b</sup> (Day-of-year 129).

The main scene is the KTRot scene, which follows the K-transect in the East-West direction as shown in Figure 2.4. At each end of the transect, the radar beam direction (left/right) was switched in order to image the scene under the same incidence angle range on the east- and westbound tracks. Two subsets of this scene, at the SHR and S10 GPS sites, have also been defined, named SHRot and S10ot. They are not shown in Figure 2.4, but they are centred on the SHR and S10 sites, aligned with the KTRot scene, and limited to 5 km along-track. The <i>ot</i> modifier indicates that for these scenes, the ice velocity can primarily be extracted using offset tracking rather than interferometry, as the main ice velocity component is in the along-track (East-West) direction. To investigate interferometry, data were also acquired from two 5 km long crossing (North-South) tracks at SHR and S10, defining the SHRotf and S10ot scenes shown in Figure 2.4. The SHRot and S10ot scenes are not shown, but are centered on the SHR and S10 sites, and limited to 5 km along-track.

On transit flights to and from the Norlandair base in AEY, the opportunity arose to acquire SAR data over the central ice sheet, in order to investigate coherence, backscatter and polarimetric signature in this region. This was done once in May, and twice in June, at two sites, CIS and EIS, shown in Figure 2.5.

To enable a radiometric and geometric calibration of the SAR instrument, a corner reflector was placed in Kangerlussuaq at on the river bank, and acquisitions were carried out in May and June at this site, called SFJcr (see Figure 2.4). The left-looking beam was used in May, and the right-looking beam in June.

Tomography data acquisition was attempted on April 21, but failed due to an erroneous configuration of the antenna beam feeding cables in HH polarization. The flight was repeated, using the correct configuration, on May 7, and on June 11. The tomography sites coincide with SHRot, but were imaged (using a left-looking beam) in a race-track pattern from both westbound tracks (north of the scene, SHRtomN) and eastbound tracks (south of the scene, SHRtomS).

In April and June, sounding data were also acquired along the K-transect and at the SHR and S10 sites. Two 5 km North-South profiles through the center of the SHRif and S10if sites were defined and called SHRsnd and S10snd. The East-West profile is the KTRsnd profile, following the center of the KTRot scene. Finally, the entire profile from Kulusuk to S10 was sounded during the April transit flight, called ISsnd.

An overview of the number of acquisitions at each site, and on each date, is given in Table 2.6. Note that some of the KTRot acquisitions lack data at the beginning/end, as the track was sometimes left prematurely to line up for the SHRif and S10if acquisitions in time.
Table 2.5 Overview of flight days in Greenland during the IceSAR-2012 campaign. AEY=Akureyri, Iceland, SFJ=Kangerlussuaq, Greenland

<table>
<thead>
<tr>
<th>Flight Day</th>
<th>Objective/Description</th>
<th>Modes used</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>April 19</td>
<td>Transit from AEY to SFJ Sounding of icesheet, K-transect and crossing tracks at SHR/S10</td>
<td>Sounding Quad-Pol</td>
<td></td>
</tr>
<tr>
<td>April 20</td>
<td>SAR imaging of K-transect and crossing tracks at SHR/S10</td>
<td>SAR Quad-Pol</td>
<td></td>
</tr>
<tr>
<td>April 21</td>
<td>SAR tomography of SHR site</td>
<td>SAR Multi-aperture, HH</td>
<td>Failed due to antenna configuration error</td>
</tr>
<tr>
<td>May 7</td>
<td>SAR tomography of SHR site</td>
<td>SAR Multi-aperture, HH</td>
<td>Repeat of the April 21 flight, correct config</td>
</tr>
<tr>
<td>May 8</td>
<td>SAR imaging of K-transect and crossing tracks at SHR/S10 SFJ corner reflector calibration</td>
<td>SAR Quad-Pol</td>
<td>Flight shortened by equipment failure</td>
</tr>
<tr>
<td>May 9</td>
<td>Transit from SFJ to AEY SAR imaging of K-transect and central icesheet</td>
<td>SAR Quad-Pol</td>
<td></td>
</tr>
<tr>
<td>June 9</td>
<td>Transit from AEY to SFJ SAR imaging of icesheet sites Sounding of K-transect</td>
<td>Sounding Quad-Pol</td>
<td>SAR Quad-Pol</td>
</tr>
<tr>
<td>June 10</td>
<td>SAR imaging of K-transect and crossing tracks at SHR/S10 SFJ corner reflector calibration</td>
<td>SAR Quad-Pol</td>
<td></td>
</tr>
<tr>
<td>June 11</td>
<td>SAR tomography of SHR site</td>
<td>SAR Multi-aperture, HH</td>
<td></td>
</tr>
<tr>
<td>June 12</td>
<td>Transit from SFJ to AEY SAR imaging of K-transect and central icesheet</td>
<td>SAR Quad-Pol</td>
<td></td>
</tr>
</tbody>
</table>
Figure 2.4 SAR Scenes on the K-transect, and the SFJ corner reflector calibration site.

Figure 2.5 SAR scenes on the K-transect, and on the central and eastern icesheet (CIS/EIS).
Table 2.6 Overview of data acquisitions. The April 21 acquisition failed, indicated by asterisk. Numbers in brackets indicate the corresponding day of the year. Numbers in parentheses indicate the number of acquisitions (out of the total) that are incomplete.

<table>
<thead>
<tr>
<th>Scene Name</th>
<th>Mode</th>
<th>April</th>
<th>May</th>
<th>June</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>19</td>
<td>20</td>
<td>21</td>
<td>7</td>
</tr>
<tr>
<td>SFJcr</td>
<td>SAR QuadPol</td>
<td>110</td>
<td>111</td>
<td>112</td>
<td>128</td>
</tr>
<tr>
<td>SHRrot</td>
<td>SAR QuadPol</td>
<td>4</td>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>SHRif</td>
<td>SAR QuadPol</td>
<td>2</td>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>SHRsnd</td>
<td>Sounder QuadPol</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SHRtomN</td>
<td>SAR Multi-apt</td>
<td>*</td>
<td>10</td>
<td></td>
<td>10</td>
</tr>
<tr>
<td>SHRtomS</td>
<td>SAR Multi-apt</td>
<td>*</td>
<td>10</td>
<td></td>
<td>9</td>
</tr>
<tr>
<td>S10ot</td>
<td>SAR QuadPol</td>
<td>4</td>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>S10if</td>
<td>SAR QuadPol</td>
<td>2</td>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>S10snd</td>
<td>Sounder QuadPol</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>KTRot</td>
<td>SAR QuadPol</td>
<td>4(1)</td>
<td></td>
<td></td>
<td>2(1)</td>
</tr>
<tr>
<td>KTRsnd</td>
<td>Sounder QuadPol</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CIS</td>
<td>SAR QuadPol</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>EIS</td>
<td>SAR QuadPol</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>ISSnd</td>
<td>Sounder QuadPol</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Corner reflector calibration
* SHR east-west for offset tracking; subset of KTRot
* SHR north-south for interferometry
* SHR north-south sounding profile
* SHR east-west for tomosar; coincident with SHRrot
* SHR east-west for tomosar; coincident with SHRrot
* S10 east-west for offset tracking; subset of KTRot
* S10 north-south for interferometry
* S10 north-south sounding profile
* K-transact east-west for offset tracking
* K-transact east-west sounding profile
* Central icesheet, coherence/backscatter/polarimetry
* Eastern icesheet, coherence, backscatter, polarimetry
* Icesheet from Kulusuk to S10. Opportunity acquisition.
2.5 **In-situ data**

In the period April 2012 – June 2012 Ground based measurements were carried out by IMAU to support the P-band SAR operations carried out by DTU. Measurements were carried out along a transect on the Westside of the Greenland Ice Sheet at 67°N running from the margin (340 m a.s.l.) to a height of 1850 m a.s.l. approximately 150 km from the ice margin, see Figure 2.6. Emphasis of the measurements was focused at SHR and S10. SHR is a site in the ablation zone characterized by strong surface undulations and S10 is in the accumulation zone characterized by a smooth snow surface. Sites (Figure 2.7) are chosen such to test whether different surface characteristics (SHR: rough and water in the ice and S10: smooth and no water in the ice) affect the SAR measurements done by the DTU aircraft.

![Figure 2.6](image)

Figure 2.6 The K-transect sites 4-8 are situated in the ablation zone, site 9 is near the equilibrium line and site 10 in the accumulation zone. The blue squares indicate sites where weather stations are operated year round (S5, S6, S9).

The measurement period was chosen such that the change in velocity, which takes place in the start of the ablation zone are captured somewhere along the transect by the different measurement campaigns planned. The precise location of velocity transition at a certain time is not predictable but a rough estimate could be made in forehand. During the period April 2012 to June 2012 GPS measurement were done at all locations. In addition we did water pressure measurements at SHR. Pressure was recorded in a hot water drilled borehole on hourly basis [33]. A time-lapse camera (two pictures a day) was used to monitor the position of the corner reflector with respect to the surface. After initial set up of the reflectors at SHR they have been lowered once just before the third campaign. Pictures are available in the data archive of the project.
2.5.1 Data processing GPS data

Hourly measurements of positions are made with L1-band GPS sensors mounted on aluminum poles [34]. Hourly positions are recorded which are averaged over 168 hours after removal of incidental outliers, to obtain mean positions. From these positions 168-hourly intervals are taken to calculate velocities from the displacement. Data are all equally weighted, a detailed description of the data processing is presented by Den Ouden et al. [35].

2.5.2 Velocity results

A summary of the velocity profiles over time for the 6 highest sites is shown in Figure 2.8. Clearly the spring acceleration in the velocity is captured between campaign 2 and 3 for the three lowest stations. For the three higher sites no clear acceleration took place before the 10th of June. The acceleration is later in the season the higher one gets on the ice sheet as can be noted by studying the velocity pattern of the three lowest sites.

Another way to represent the velocity pattern along the transect is to plot the data as a function of distance along the transect for the three different campaigns.

2.5.3 Water pressure measurements

The velocity changes along the transect are determined by changes in the water pressure in relation to the drainage capacity of the hydraulic system in the ice which changes during the course of the ablation season. In Figure 2.10 we present data of the water pressure and the ice velocity at SHR. If the pressure is near 57 bar it reaches the overburden pressure. Once the melt starts early May pressure increase, drainage capacity increases as well, but early June the increase in ablation is so fast that the drainage capacity can not increase fast enough anymore and water pressure reaches the overburden pressure which leads to the so called early spring velocity acceleration.
Figure 2.8 Velocities at the six highest sites along the K-transect during the measurement campaigns from April 15th – June 10th. The arrows indicate the dates of the flight campaigns. Vertical and horizontal scales are taken to be identical for the different sites.
Figure 2.9 The velocity pattern along the transect during the different measurement campaigns. The stars denote the long-term average indicating that during the first two campaigns conditions are like the average conditions whereas the spring acceleration for the three lowest sites took place between campaign 2 and 3.

Figure 2.10 Water pressure measurements in relation to velocity measurements during the three measurement campaigns as indicated by the arrow. Water pressure on the right axis, velocity on the left axis. During campaign 3 water level is close to overburden pressure implying a water table 60 meters below the surface.
3 Data pre-processing

3.1 Navigation data

The kinematic GPS data were processed by the DTU Space Geodynamics division, using the online PPP (Precise Point Positioning) service provided by Natural Resources Canada (www.nrcan.gc.ca) for the transit flights, and GraNav software for the other flights, where local reference stations could be set up. For each scene of interest, a polynomial fit of the difference between GPS and inertial data was carried out and subtracted from the inertial data, to eliminate long-term trends in the inertial data and provide the high time resolution of the inertial data.

3.2 Level 0c processing

Raw radar data were initially split into scenes and processed to level 0c using the standard POLARIS level 0c processor, carrying out range compression, equalization, internal calibration and interpolation and transformation of navigation data to the radar data times and coordinate system. This processing is identical for sounding and SAR data, and described in the POLARIS User Data Products document [36].

For tomography, navigation data were transformed and provided for each receive aperture center, as well as for the full aperture center. The received radar data from each patch were compensated for the one-way SAR cable delay differences, and associated phase, so that the signals from each patch antenna port have no (intended) delay/phase shift relative to each other. This leaves the receive beamforming to the tomographic processing.

3.3 Level 1c processing - SAR focusing

A time-domain backprojection SAR processor was developed for the IceSAR project. The SAR processor takes level 0c POLARIS data, acquired by either a left- or right-looking beam, and performs SAR focusing to a predefined output grid in ground range geometry. This output grid is based on an external digital elevation model, retrieved from the Byrd Polar Research Institute GIMP DEM [37][38]. A laser DEM of the K-transect was acquired by the NASA LVIS sensor, but this unfortunately did not cover the entire swath. All acquisitions of the same site (e.g. KTRot) were focused to the same grid, so that, assuming perfect navigation data, focused data will already be coregistered and in ground range geometry. The focused data are radiometrically calibrated (see Section 3.4) so that the amplitude of the focused image is an estimate of the radar backscatter coefficient $\sigma^0$.

3.3.1 Output grid definition

For each of the SAR scenes in Table 2.6 (KTRot, SHRot, SHRif, S10ot, S10if, CIS, EIS), a local $(s,c,h)$-coordinate system [39] was defined. $(s,c,h)$-coordinates are curvilinear coordinates defined on a sphere that locally approximates the reference ellipsoid, with $s$ the along-track coordinate, $c$ the across-track coordinate, and $h$ the altitude above the reference sphere. The origin of the coordinate system is set at the midpoint of the nominal flight track, and the radius of the approximating sphere is chosen as the radius of curvature of the WGS-84 reference ellipsoid in the along-track direction, evaluated at the origin. For each site, an equidistantly sampled grid in $s$ and $c$ was then defined. For all sites, a 3 m $c$-spacing was used, whereas a 1 m $s$-spacing was used for the longer KTRot, CIS and EIS scenes, and a 0.5 m spacing was used for the smaller sites. The GIMP DEM elevation was then transformed and interpolated to each $(s,c)$ grid point, to provide the corresponding $h$-elevation at each grid point. The output grid is stored in a file, and used as input to the SAR processor. In order to coregister data acquired from left- and right-looking beams, a convention was adopted to always define the $(s,c,h)$-system and grid assuming a left-looking geometry. This has the advantage of the $c$-coordinate always being positive. To focus data acquired with a right-looking beam to this grid, the grid is first flipped (in
the $s$-direction), and the SAR data are focused to the flipped grid. Then the focused data are flipped in the $s$-direction, to coregister the data to the original grid.

The output grids used to focus the data are delivered with the data, in NetCDF form. The supplied files also hold the WGS84 latitude, longitude, and ellipsoid altitude for each grid point.

The $(s,c,h)$-coordinates can be converted to geocentric spherical WGS84 ECEF-coordinates by

$$\begin{bmatrix} \tilde{x} \\ \tilde{y} \\ \tilde{z} \end{bmatrix}_{\text{ECEF}} = \mathbf{M} \begin{bmatrix} x' \\ y' \\ z' \end{bmatrix} + \mathbf{o}$$

where the 3x3 transformation matrix $\mathbf{M}$, the 3x1 translation vector, $\mathbf{o}$, and the reference sphere radius, $r_o$, are provided with the grid. The intermediate $(x', y', z')$-coordinates represent rectangular coordinates in a geocentric system based on the reference sphere of the $(s,c,h)$-system, and can be used to calculate the range between two points in $(s,c,h)$-coordinates. Care should be taken to use at least double-precision floating point arithmetic for such calculations.

### 3.3.2 SAR focusing algorithm

The SAR focusing algorithm takes as input a level 0c (range compressed) radar data file (and associated annotation and navigation data files), an output grid file (see Section 3.3.1), and number specifying the desired azimuth resolution. The azimuth resolution should be coarser than or equal to the $s$-spacing of the grid. The following procedure is then used to focus the data:

For each output grid point $(s_m, c_o)$:
1. Look up grid elevation, $h_o$.
2. Interpolate sensor $(s_r, c_r, h_r)$-position at $s_r = s_m$. This point is used to define the phase reference.
3. Calculate broadside range, $r_s$, and aperture length, $L_s = r_b \lambda / (2 \rho_s)$.
4. For each input line in aperture, i.e. for all $-\frac{L_s}{2} < s_r - s_o < \frac{L_s}{2}$:
   a. Calculate range, $r$, from sensor to $(s_m, c_o, h_o)$.
   b. Calculate look angle and look up cross-track antenna pattern.
   c. Calculate azimuth weight (Hamming, inverse antenna gain and range attenuation).
   d. Calculate phase correction to the phase reference point, $\phi = \left(\frac{4\pi}{\lambda}\right)(r - r_b)$.
   e. Interpolate radar data at $r$, phase correct, multiply by azimuth weight and calibration constant, and add to output pixel.

Although focused data are registered to the output grid, the phase is referenced to the sensor position, when the sensor is broadside of the target. Thus when forming interferograms from two images, the interferometric phase is not flattened. Although for smaller scenes, one could define a common reference track to reference all acquisitions to, this is not straightforward for long scenes, where the surface elevation (and correspondingly the sensor altitude) changes significantly along the track. The sensor positions, in $(s,c,h)$-coordinates interpolated to each output line, are provided along with the data.

The focusing is split in two parts, a MATLAB program that calculates auxiliary information and sets up processing parameters, and a stand-alone executable file that utilizes an NVIDIA Graphics Processing Unit (GPU) to implement the main focusing loop in a highly parallel implementation. With the GTX560Ti GPU employed here, the program can focus 200,000 pixels/second at 0.5 m azimuth resolution (corresponding to a 9000-line aperture).
3.4 Calibration

In level 0c processing, transfer function equalization, and a relative calibration (delay, gain, and phase) is carried out between the different polarimetric channels and/or subapertures of the POLARIS system. During the IceSAR-2012 campaign, a trihedral reflector was placed at a fixed, known position in Kangerlussuaq to allow a further external calibration of the POLARIS system in SAR mode, and to enable focused data to be radiometrically calibrated to represent radar backscatter coefficients. This calibration is implemented as part of the level 1c processing. Two further reflectors were placed at the SHR site on the ice, to be used in the tomographic processing. The calibration described in this section is based only on the Kangerlussuaq reflector, as the best estimate of position and orientation was available at this fixed location.

The trihedral reflector is illustrated in Figure 3.1. The short sides are 2000 mm long, and the bottom edge was aligned along a 60° degree bearing, and tilted 20° from the local level, making the incidence angle of maximum reflection 35°, corresponding to the standard SAR mode midswath incidence. The position of the apex point was measured by kinematic GPS (after the reflector was taken down) to be (lat,lon,height) = (67.004778°, -50.707213°, 65.59 m). The height is above the WGS84 ellipsoid.

![Figure 3.1 Calibration trihedral reflector on the Kangerlussuaq River bank.](image)

A flight track was defined that put the reflector at midswath with the standard SAR mode parameters. Two acquisitions were carried out, one on May 8, SFJcr129a, with the left-looking beam, and one on June 10, SFJcr162a, with the right looking beam.

3.4.1 Radiometric and polarimetric calibration

The output grid used to focus the calibration data was not based on a DEM, but on a flat grid representing a constant surface elevation equal to the 65.59 m measured for the corner reflector. A 1 m resolution was used, and no external calibration constant was applied in the focusing, but corrections were made for range attenuation and cross-track antenna pattern. The calibration constant for each copol channel (HH and VV) was calculated by finding the reflector in the focused SAR image, extracting and upsampling an area around the reflector. Then the power in the mainlobe was integrated. The average backscatter coefficient of the surrounding clutter was estimated, multiplied by the mainlobe area, and subtracted from the mainlobe energy. The radar cross section of the trihedral was calculated based on the formulas in [40], and averaged over all aperture angles. The calibration
constant was then found by dividing the calculated radar cross section by the clutter-adjusted mainlobe energy.

The approach above was used for the co-polar channels. To obtain a full polarimetric calibration, the average cross-polar ratio (VH/HV) in a flat, distributed area of the image was measured, and by imposing the polarimetric scattering matrix relations $S_{HH} = S_{VV}$ (for the corner reflector) and $S_{HV} = S_{VH}$ (for the distributed target) and using the approach described in [41], a full polarimetric calibration could be calculated. The calibration revealed a transmit imbalance (H/V) of 0.1 dB/-2.8°, and a receive imbalance (H/V) of -0.5 dB/1.6° (Phase angles were extracted at the reflector mainlobe peak for the copolar channel). This is consistent with values found in an earlier sounding campaign, using extended ice scenes for a relative calibration [42]. In that study, a transmit imbalance -0.1 dB and receive imbalance -0.6 dB were found, albeit with the large, 8-element antenna. The amplitude imbalances were incorporated in the external calibration applied to IceSAR data, but the (small) phase imbalances were not included.

A focused, polarimetric image of the SFJcr site is shown in Figure 3.2, indicating the corner reflector and the distributed target site used for calibration.

![Polarimetrc SAR image of the Kangerlussuaq calibration site](image)

Figure 3.2 Polarimetrc SAR image of the Kangerlussuaq calibration site. The red arrow indicates the position of the trihedral reflector, and the magenta rectangle indicates the distributed area used for cross-polar calibration.

### 3.4.2 Focusing quality and geometric calibration

The focusing quality was examined by inspecting the interpolated corner reflector echoes extracted from the SFJcr site, see Figure 3.3 and Figure 3.4. In this case, a 0.5 m grid and azimuth resolution (before weighting) was used, to test the wide-aperture capability of the processor. The results are shown in Table 3.1.

In range, an 85 MHz pulse is used, and Hamming weighting is employed to reduce sidelobes. Since the image is focused to ground range, the expected resolution at the reflector’s 34° incidence angle is 4.1 m, which agrees with the measured resolution. The expected, 3dB azimuth resolution after weighting is around 0.8 m, which also agrees with observations. The observed azimuth displacement is within 0.5 m is seen from Table 3.1, whereas a larger offset of around -3.7 m is seen in ground range. The azimuth displacement is likely due to navigation data imperfections, whereas a systematic offset may be present.
in the ground range shift. However, the difference in ground range displacements could be due to imperfect navigation data.

Figure 3.3 Left looking beam corner reflector response (dB) in ground range (top) and azimuth (bottom).
Figure 3.4 Right looking beam corner reflector response (dB) in ground range (top) and azimuth (bottom).

Table 3.1 Geometric calibration results

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Left-looking beam</th>
<th>Right-looking beam</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 dB res (ground range)</td>
<td>4.1 m</td>
<td>4.0 m</td>
</tr>
<tr>
<td>3 dB res (azimuth)</td>
<td>0.9 m</td>
<td>0.8 m</td>
</tr>
<tr>
<td>Ground range displacement</td>
<td>-3.8 m</td>
<td>-3.6 m</td>
</tr>
<tr>
<td>Azimuth displacement</td>
<td>0.2 m</td>
<td>-0.4 m</td>
</tr>
</tbody>
</table>
4 P-band ice signatures

4.1 Radiometric signature

4.1.1 K-transect backscatter over time

In Figure 4.1 is shown the estimated HH backscatter coefficient ($\sigma^0$) for the entire K-transect at three different dates (April, May, June) during the campaign. Note that part of the near range samples are missing in the April image, as a too large range delay was used for the April acquisitions.

It is seen that April and May acquisitions differ from SHR to S78 while the May and June acquisitions are quite similar in this area. From S78 to S10 also the April and May acquisitions are similar, while from S78 up to just before S10 (from $s = -20$ km to 50 km), the June data show a significantly higher backscatter level. Around S10, the three acquisitions show similar levels of backscatter. This could indicate that from SHR to S78, surface melt began between April and May, whereas from S78 to S10 the melt did not begin until after the May acquisition. At S10 even the June data do not suggest any melt. The $\sigma^0$-values, averaged over part of the swath (from $c = 2000$ to 3500) are shown in Figure 4.2, which supports the above observations.

In Figure 4.3, polarimetric versions of the Figure 4.1 images are shown. Not surprisingly, the crosspolar contribution is strongest between SHR and S6, where crevasses and other surface features can result in multiple reflections from tilted surfaces.

Figure 4.1 HH backscatter coefficient ($\sigma^0$) for the K-transect at different acquisition times.
Figure 4.2 Midswath averaged HH $\sigma^0$ for the acquisitions in Figure 4.1

Figure 4.3 K-transect polarimetric $\sigma^0$ SAR images, HV=red, HH=green, VV=blue. Dynamic range is from -40 dB to 0 dB.

4.1.2 Polarimetric signatures at selected sites

At selected sites, representing different types of ice, average backscatter versus incidence angle was extracted from the SAR data. For the (homogeneous) CIS site, averaging was done over the entire scene (32 km). For the selected GPS sites along the K-transect (SHR, S78, S10), the averaging was done over a 5 km area centered on the corresponding GPS site position. Polarimetric SAR images of the area over which averaging was done is shown for the SHR site in Figure 4.4. The backscatter profiles are shown for all the examined sites in Figure 4.5-Figure 4.8
Figure 4.4 SHRot polarimetric SAR images at three acquisition dates
Technical Assistance during the 2012 ICESAR Validation Campaign

Figure 4.5 SHR average backscatter versus incidence angle.

Figure 4.6 S78 average backscatter versus incidence angle.
Figure 4.7 S10 average backscatter versus incidence angle.
Figure 4.8 Central Ice sheet (CIS) average backscatter versus incidence angle. No SAR data were acquired at this site in April.

4.2 Interferometric signature

The primary quantity characterizing the interferometric signature is the interferometric coherence, $\gamma$. This depends, among other things, on the temporal baseline, the spatial baseline, the time of acquisition and the type of ice. For each examined site, all possible combinations of acquisitions were examined, giving temporal baselines ranging from 0 to 53 days (April 20 to June 12). The interferometric coherence was for each pair estimated by the following procedure:

1. The phase of one image was referenced to the track of the other image (using the navigation data and the same DEM used in focusing). This phase adjustment removes the topographic contribution to the interferometric phase when the images are combined.

2. To calculate the coherence, the images should be coregistered. However due to ice motion, navigation data inaccuracy, and DEM imperfections, this is not the case. The coherence was estimated by carrying out a complex offset-tracking between the two images. This is a procedure where, on a subsampled grid in range and azimuth, search windows are extracted from the images and cross-correlated to find the shift that maximizes the normalized correlation coefficient. The maximum correlation coefficient can be interpreted as the interferometric coherence. The window size used was 48x48 m (16 samples x 48 lines), identical to the grid spacing.

Some example coherence plots are shown in Figure 4.10. It is seen that even for 0-day baselines, some areas exhibit decorrelation. Especially for the April data, where there was no surface melt along the K-transect, little temporal decorrelation is expected for the 0-day baselines, and yet areas of complete decorrelation are seen. The critical baseline (assuming surface scattering) is 200 m in near range ($\theta=20^\circ$) and 650 m in far range ($\theta=45^\circ$), much less than the typical deviations from the desired flight track seen during the campaign. In the presence of subsurface scattering, however, the critical spatial
baseline can become much smaller than that, so that even small (10 m to 20 m) deviations from the flight track can cause spatial decorrelation. To examine the impact of temporal and spatial decorrelation, the dependence of the interferometric coherence on incidence angle, $\theta$, and height-to-phase conversion factor, $k_z$ was found by calculating $k_z$ maps for all combinations of acquisitions. Then for each combination of acquisition dates, the coherence of all pairs spanning these dates was extracted, and binned according to their $k_z$ and $\theta$ values (100 bins and 25 bins, respectively). The bins were then averaged over all samples to produce maps of coherence versus $k_z$ and $\theta$. $k_z$ is directly proportional to the perpendicular baseline. The ratio of the perpendicular baseline to the critical baseline (for surface scattering) is illustrated in Figure 4.9 for the nominal IceSAR geometry and the values of $k_z$ and $\theta$ encountered. The coherence versus $k_z$ and $\theta$ plots are shown in Figure 4.11-Figure 4.14 for the sites SHR, S78, S10, and CIS, respectively.

![Figure 4.9 Ratio of perpendicular and critical baseline for the IceSAR geometry, assuming surface scattering.](image-url)
Figure 4.10 Interferometric coherence of example K-transect combinations.
Figure 4.11 SHR, HH interferometric coherence as function of incidence angle ($\theta$), and $k_z$.

Figure 4.12 S78 HH interferometric coherence as function of incidence angle ($\theta$), and $k_z$. 
Figure 4.13 S10 HH interferometric coherence as function of incidence angle ($\theta$), and $k_z$.

Figure 4.14 CIS HH interferometric coherence as function of incidence angle ($\theta$), and $k_z$. 
5 Ice displacement mapping

5.1 Offset tracking

Offset tracking techniques for retrieval of ice velocities was run on all the combinations of K-transect pairs available. Two types of techniques were applied, both based on maximizing the normalized cross-correlation between corresponding search windows in each image:

1. Correlation of complex images. This technique requires coherence between the tracked images, but allows offset-tracking in homogeneous areas with no features.
2. Correlation of intensity images. This technique requires either (a) features in the intensity images, which can be correlated and/or (b) interferometric coherence between the images, which allows tracking also on the speckle pattern. In the latter case, complex tracking should be preferred, as this can exploit the phase information as well [43].

Feature tracking typically requires much larger windows than complex/speckle tracking and typically fails in homogeneous area, where there is little texture.

In the following, intensity cross-correlation was carried out using 64x192 pixel windows (192x192 m projected on ground), whereas complex cross-correlation was carried out using 16x48 (48x48 m projected on ground) windows. For comparison, in the Greenland Ice Mapping Project under NASA’s MEaSUREs program, Ian Joughin uses up to 192x192 pixels for amplitude cross-correlation and approximately 24x24 pixels for complex cross-correlation [43].

For the output grid a 20x50 subsampling of the original grid was used in case of intensity cross-correlation, whereas a 16x48 subsampling was used for complex tracking. In both s- and c- lags from -48 m to 48 m were correlated, and the peak correlation was found. Then the correlation field around the peak was upsampled, and a second order fit to the cross-correlation peak was carried out, from which the s- and c- shift could be determined.

5.1.1 Error characterization

When deriving ice velocities from displacements (measured with offset tracking or interferometry), it is important to be aware that several error sources can give rise to observed displacements (misregistrations) between two SAR images not related to actual scene changes. In case of airborne mapping the main error sources are navigation data errors (due to GPS/INS accuracy or uncompensated delays between radar and navigation data timestamps), and DEM errors. Even with perfect navigation data, an error in the DEM used during focusing can cause misregistrations, which depend both on the elevation error and the baseline variation. Thus measured displacements can vary significantly for two different pairs, even though the scene is unchanged and the same DEM has been used in the focusing.

The slant range misregistration, \( \delta_{r,\text{topo}} \), is given by:

\[
\delta_{r,\text{topo}} = -\frac{b_{\text{perp}}}{r_0 \sin \theta} \Delta h
\]

where \( b_{\text{perp}} \) is the baseline component perpendicular to the line-of-sight direction, given by look angle \( \theta \), \( r_0 \) is slant range, and \( \Delta h \) is the DEM error. Note that with the ground range geometry used here (see Section 3.3), offset-tracking will output shifts in ground range, which are larger than the slant range shifts by a factor 1/sin\( \theta \). The range displacement measured with a space-based P-band SAR would have the same sensitivity to DEM errors as POLARIS has, provided the \( b_{\text{perp}}/r_0 \) ratio (or equivalently \( k_z \)) is the same.

The azimuth misregistration due to DEM errors are

\[
\delta_{x,\text{topo}} = \frac{1}{\sin \theta} \frac{\partial b_{\text{perp}}}{\partial x} \Delta h
\]
which is seen to depend on the perpendicular baseline velocity. Azimuth displacements due to DEM errors are mainly seen in airborne geometries, where the baseline can vary significantly along the track.

To examine the typical impact of DEM errors for the IceSAR data, the LVIS laser DEM of the K-transect was used as a reference DEM, and $\Delta h$ was calculated as the difference between the LVIS DEM and the GIMP DEM used in focusing. A 0-day pair from April, where little ice motion is expected, was offset-tracked (using intensity cross-correlation) to find a displacement field. The expected displacement field from DEM errors was calculated using the two equations above. This can only be done for a limited swath, due to the low coverage of the LVIS data, as otherwise, the LVIS data should of course have been used in the focusing. The comparison is shown in Figure 5.1, where it is seen that the simulated misregistrations indeed correlate with similar-sized measured displacements. Near S10 (around 60 km), the LVIS DEM agrees well with the GIMP DEM (meaning small expected misregistrations), and still large measured displacements are seen. This could be due to penetration of the P-band radar signal at S10 (supported by the observations in Section 4.2 and Figure 4.13), leading to an effective elevation below the surface, while the laser-based LVIS instrument tracks only the ice surface. Remaining errors can probably be attributed to navigation data inaccuracies. These observations suggest that expected errors on the displacement fields, due to DEM and navigation errors, are on the order of +/- 1 m for the airborne POLARIS system. The velocity errors decrease linearly with the temporal baseline for a given displacement error, but the displacement error in turn increases with the temporal baseline due to decorrelation.

![Comparison of measured and simulated shifts due to DEM errors. A 0-day baseline April pair was used. The DEM error is defined as the difference between the GIMP DEM used in the focusing and the LVIS DEM. Note that the colour scales for range and azimuth shifts differ.](image-url)
The range displacement errors increase with the realized \( \frac{b_{perp}}{r_0} \) ratio, and it should be noted that for a large part of the long K-transect flights the ratio exceeds that of Biomass. Consequently, both the range and azimuth displacement errors in Figure 5.1 (greatly) exceed those expected for a space-based system with the same resolution, signal-to-noise ratio etc. as POLARIS.

5.1.2 Measurements

The results of intensity offset tracking are shown in Figure 5.2 (ground range displacement) and Figure 5.3 (azimuth displacement) for a number of combinations (two April-May, two May-June and four April-June pairs). Figure 5.4 shows the same ice displacements in a different rendering.

The results of complex tracking for the same combinations are seen in Figure 5.5 and Figure 5.6. The numbers in the title of each sub-plot indicate the day of year of the data that are combined. In the white areas the quality parameters of the cross-correlation did not meet their threshold, and no displacement estimate is obtained.

The intensity tracking results are consistent, in that different pairs with the same temporal baseline produce the same offsets. For the same temporal baseline, the same spatial coverage is achieved from -60 km to 40 km, however in the last part of the image (near S10), the coverage is seen to vary for different combinations with similar temporal baseline. This is probably because at S10 it is the speckle pattern that is tracked, and due to subsurface penetration of the radar signal (see Figure 4.13) the coherence depends heavily on the spatial baseline actually flown for the individual combination.

The complex tracking is seen to work well for the April-May pairs from -20 km to -50 km, whereas near S10 (65 km) it fails. This is due to the available spatial baselines rather than temporal decorrelation, however, as complex tracking produces valid results in this area for larger baselines. The decreased coverage up to -20 km is consistent with the observations of Figure 4.1, which indicate that in May, surface melting has started up to S78, which is located around \( s = -20 \) km.

5.1.3 Comparison of offset-tracking and in-situ GPS measurements

For all available measurements, the azimuth displacements were extracted at the location of the IMAU GPS receivers (see Section 2.5), and the tracked offsets were compared to the GPS measurements, with the results shown in Figure 5.7 for azimuth intensity tracking. For SHR and S9, there is good agreement (within +/-1 m) for all temporal baselines, consistent with the expected errors due to imperfect DEM and navigation data (see Section 5.1.1). At S10, this is the case for both the April-May (18 days) and April-June (51 days) combinations. The May-June measurement is 2 m off, which is probably due to a large baseline coupling with a DEM error for the single available measurement here.

The ground range intensity tracking measurements are compared in Figure 5.8. Note that the range displacements are much smaller than the azimuth displacements, which means that larger relative errors are to be expected. At SHR, there is again good agreement, within +/-0.5 m, and for the other GPS sites, the overall displacements are so small (1-2 m) that they are comparable to the navigation/DEM errors.

The corresponding complex tracking results are shown in Figure 5.9 and Figure 5.10. There are not as many results available due the lower coverage (see e.g. Figure 5.6), but the existing results are similar to those of intensity tracking. Note the good agreement between of the azimuth shift at S10 for the 51-day (April-June) baseline.
Figure 5.2 Ground range displacement [m] from intensity tracking (April-May, May-June, April-June).
Figure 5.3 Azimuth displacement [m] from intensity tracking (April-May, May-June, April-June).
Figure 5.4 Ice displacement from intensity tracking. The displacement arrows show the true direction of the ice, ignoring the different c- and s-scales of the background polarimetric images.
Figure 5.5 Ground range displacement [m] from complex tracking (April-May, May-June, April-June)
Figure 5.6 Azimuth displacement [m] from complex tracking (April-May, May-June, April-June)
Figure 5.7 Comparison of intensity offset tracking and GPS measured azimuth displacements. Errorbars indicate min/max displacements when more than one measurement were available.

Figure 5.8 Comparison of intensity offset tracking and GPS measured ground range displacements.
Figure 5.9 Comparison of complex offset tracking and GPS measured azimuth displacements.

Figure 5.10 Comparison of complex offset tracking and GPS measured ground range displacements.
5.2 Interferometry

In space-based SAR interferometry, coregistration is often implemented by estimating range and azimuth shifts at the nodes of a sparse grid, fitting a low order shift model (e.g. 0th order model) to these shifts, and resampling the slave image according to this model. However, the IceSAR-2012 data are characterized by

1. Curvilinear flight tracks
2. High spatial resolution
3. Large temporal baselines

Since the POLARIS level-1 SAR processor focuses data pairs to the same ground range grid using a DEM, they are in principle coregistered and geometrically corrected for topographic effects. However, as described in Section 5.1.1, the curvilinear flight tracks in combination with DEM errors result in erroneous shifts and since these shifts are not the same for the two images of an interferometric pair coregistration errors result. The coregistration errors vary over the scene, and they are significant compared to the fine spatial resolution. This complicates all airborne SAR interferometry, but the large temporal baselines constitute an additional challenge when ice velocities are measured with differential SAR interferometry (DInSAR) because the (spatially varying) ice displacements occurring between the acquisitions may greatly exceed the spatial resolution. Consequently, airborne DInSAR typically requires a more advanced coregistration approach than space-based DInSAR.

DInSAR processing has been applied to IceSAR data acquired at SHR and S10, where tracks were flown perpendicular to the K-transect in order to have a significant ice motion component in the range direction. At SHR the coherence is too low for DInSAR for all temporal baselines: April-May, May-June and April-June. The good results obtained with intensity offset tracking at SHR (Figure 5.7 and Figure 5.8) are presumably due to large-scale surface structures (feature tracking), but apparently the surface weathering, e.g. due to melt events, results in excessive changes of the wavelength-scale surface structure. DInSAR requires higher coherence than offset tracking and stability on a scale comparable with the wavelength.

Figure 5.11 shows that DInSAR can be successfully applied to data acquired at S10. The fringes represent ice displacement, and accordingly the fringe rate is lower for the April-May baseline than for the April-June baseline. The interferograms are flattened, i.e. the topographic contribution to the interferometric phase has been eliminated by subtracting a phase term computed from the GIMP DEM and the spatial baseline vectors. The flattening is a separate step because the POLARIS level-1 SAR processor references the phase to the actual track (cf. Section 3.3.2), not a common reference track. The fringe quality is very fine both for the April-May baseline and for the April-June baseline. A little phase noise is seen in two areas at the bottom of the April-May interferogram and in particular in the left part of the May-June interferogram, where the corresponding coherence images have low values. Generally, the coherence images match the corresponding $k_\ell$ images. For instance, the red regions with small $k_\ell$ values in Figure 5.12 coincide with the high-coherence regions in the April-June coherence in Figure 5.11. The low-coherence feature seen in the upper left corner in all six subplots in Figure 5.11 is not related to $k_\ell$. It must be attributed to changes occurring between the data acquisitions.
Technical Assistance during the 2012 ICESAR Validation Campaign

Figure 5.11 Interferometric phase (left) and coherence (right) of data acquired at S10.

Figure 5.12 $k_z$ image of data acquired at S10 (April-June baseline).
5.3 BIOMASS simulation

In order to assess the suitability of Biomass for ice velocity mapping the POLARIS data acquisition was considering Biomass parameters like incidence angles, $k_z$ values, and temporal baselines as mentioned in Section 2.3. Subsequently, selected POLARIS data have been degraded such as to emulate Biomass data. The range resolution has been degraded to that of Biomass by reducing the bandwidth to 6 MHz. Also the azimuth resolution has been degraded by reducing the azimuth bandwidth. The resulting azimuth resolution is about 50/4 m, as Biomass is designed for an azimuth resolution of 50 m at an equivalent number of looks of 4 [3]. The degraded POLARIS data have an azimuth pixel spacing of 9 m, but a spatial weight is applied for sidelobe suppression such that the effective resolution is approximately the same as the Biomass one-look resolution.

The Biomass performance has been simulated with POLARIS data acquired at SHR and S10 in April, May and June. Data acquired from flight tracks crossing the K-transect (the SHRif and S10if acquisitions defined in Section 0) have been used in order to ensure that the ice displacement has a significant range component. In this way both offset tracking and interferometry can be properly assessed using the same data.

Table 5.1 outlines the applicability of the offset tracking and DInSAR techniques, both at the full POLARIS resolution and at the degraded Biomass resolution. Both techniques work at S10, whereas at SHR, offset tracking fails when the resolution is degraded, and DInSAR fails irrespective of the resolution.

<table>
<thead>
<tr>
<th>Sensor</th>
<th>POLARIS</th>
<th>Biomass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site</td>
<td>SHR</td>
<td>S10</td>
</tr>
<tr>
<td>Offset Tracking</td>
<td>Applicable</td>
<td>Applicable</td>
</tr>
<tr>
<td>DInSAR</td>
<td>Not applicable (melt etc.)</td>
<td>Applicable</td>
</tr>
</tbody>
</table>

Figure 5.13 illustrates why offset tracking works when applied to the full resolution POLARIS data, but fails when applied to the coarse resolution data from SHR. The crevasses are clearly visible in the full resolution POLARIS images (3x0.5 m pixel spacing), and the pattern looks much the same in April and May, so it seems reasonable that a cross-correlation of intensity windows results in a distinct peak. On the other hand the spatial resolution of the simulated Biomass images (36x9 m pixel spacing) is so coarse that the crevasses cannot be resolved. Since the April and May data look very different, it is understandable that the cross-correlation does not result in a distinct peak. For the intensity cross-correlation the window size is 64x192 pixels, i.e. much larger than the Biomass windows shown in Figure 5.13. The large windows reduce the noise of the normalized cross-correlations, but nevertheless peaks cannot be reliably detected. Finally, the lack of a cross-correlation peak shows that the data pairs that are combined are not coherent, because otherwise the speckle pattern would have ensured a peak as illustrated by the S10 data.

Figure 5.14 shows two offset tracking examples based on simulated Biomass data from the S10 scene. In both cases April and May data are combined, but $k_z$ varies over the scene. In the example to the left, windows are extracted where $k_z = 0.05$ m$^{-1}$, and the (interpolated) normalized cross-correlation function has a distinct and unambiguous peak. In the example to the right $k_z$ is somewhat larger and a spurious peak shows up, so the peak position could still be determined correctly, but the quality measures might not meet the thresholds defined for the amplitude of the normalized cross-correlation peak and the ratio of the peak amplitude to the average amplitude of its surroundings.

Table 5.1 Applicability of Offset tracking and DInSAR.
Figure 5.15 illustrates why offset tracking can be successfully applied to both full resolution POLARIS data and coarse resolution Biomass data from S10. Basically no ice features are visible in the radar data from S10. What is seen in Figure 5.15 is speckle, and the similarity of the speckle patterns in April and May indicates that the scene is stable on a scale comparable with the wavelength. The speckle pattern depends on the resolution, but speckle is seen at any resolution, unlike the ice features at SHR. Consequently, speckle tracking does not depend on high resolution, but it does require coherence though not as much as DInSAR, e.g. Ian Joughin uses a coherence threshold of 0.07 for speckle tracking with a window size of 192x192 pixels [43].

![Figure 5.15](image1.png)

Figure 5.13 Comparison of POLARIS (top) and simulated Biomass (bottom) amplitude images centered on SHR. The images cover the same area.

![Figure 5.14](image2.png)

Figure 5.14 Normalized intensity cross-correlation computed from simulated Biomass data extracted from two locations within the S10 scene.
Figure 5.15 Comparison of POLARIS (top) and Biomass (bottom) amplitude images centered on S10. The April and May images cover the same area, but the full resolution POLARIS images cover a much smaller area than the Biomass images, because of the different pixel spacing (3x0.5 m for POLARIS and 36x9 m for BIOMASS).

DInSAR processing of simulated Biomass data from SHR and S10 has been attempted. It fails at SHR, both when combining April data with May data and when combining April data with June data. In view of the unsuccessful offset tracking of simulated Biomass data from SHR, this is not a surprise. At S10, however, DInSAR works fine as illustrated by the interferograms in Figure 5.16. These interferograms should be compared with the full-resolution interferograms in Figure 5.11. Again the fringes represent ice displacement, as the interferograms have been flattened by subtracting the topographic contribution.

Figure 5.16 Interferograms generated from simulated Biomass data acquired at S10. Temporal baselines: 18 days from April to May (left) and 51 days from April to June (right).
and accordingly the fringe rate is lower for the April-May baseline than for the April-June baseline. For the 51 days baseline the fringes are somewhat noisy, e.g. there are a few examples where neighbouring fringes merge, but phase unwrapping would not be a problem. DInSAR requires a higher coherence than offset tracking, so it is encouraging that DInSAR works fine over a very long temporal baseline, which includes part of the warm season.

From the S10 interferograms generated with simulated Biomass data the ice displacement has been estimated, and in Figure 5.17 it is plotted versus the displacement measured with GPS. The agreement between the SAR and GPS measurements is very good. An operational DInSAR processor would typically apply phase unwrapping and estimate an absolute phase from a ground control point (GCP) with known position and velocity. Instead, with the prototype processor at hand an additional phase term is applied to flatten the interferogram, assuming a constant displacement of the entire scene, and from this phase the displacement is computed. The error bars, which are almost hidden behind the symbols in Figure 5.17, represent the standard deviation as estimated from the pixels surrounding the position of the GPS receiver.

![Figure 5.17 Ice displacement at S10 estimated from simulated Biomass data and plotted versus the displacement measured with GPS.](image-url)
7 Tomography

7.1 Introduction

The purpose of the tomographic analysis here presented is the assessment of the capability of P-band SAR to map the volumetric structure of ice sheets through the exploitation of multi-baseline and, when available, multi-polarimetric surveys.

In addition to its primary objectives, the BIOMASS mission has the potential to provide ice sheet motion products and, thanks to the use of longer wavelength, also subsurface structure products. These products would be of great scientific interest as they would allow to improve the knowledge of the physics of glaciers and monitor their changes at a large scale over time.

For these reasons, the dataset acquired by POLARIS in the framework of IceSAR 2012 campaign represents an important opportunity to investigate the potential benefits of longer wavelength over existing shorter wavelength missions as for ice sheet monitoring.

The tomographic processing of POLARIS data has been carried out with a particular focus on the following tasks:

- 3D volume reconstruction through single pass tomographic focusing based on navigation data
- Incoherent combination of multiple passes (based on navigation data)
- Tomographic focusing: coherent combination of multiple passes, involving:
  - Multi-baseline phase calibration and quality assessment
  - Joint tomographic focusing of multiple passes
- Surface picking (best effort) – either at ice/air interface and within the ice layer.
- Assessment of penetration depth
- Polarimetric Tomography analysis
- Differential Tomography analysis to map motions as a function of depth. Involving:
  - Generation of synthetic data obtained by injecting simulated motions
  - Analysis of real data (conditional on actual penetration depth)
7.2 SAR Tomography: basic principles

The idea behind the concept of TomSAR is rather simple. Consider a scenario where several SAR sensors, flown along parallel tracks, image a scene from different points of view, as depicted in the left panel of Figure 1. Such a system offers the possibility to gather the backscattered echoes not only along the azimuth direction, but also along the cross-range direction, defined by the axis orthogonal to the Line Of Sight (LOS) and to the orbital track. Accordingly, the backscattered echoes can be focused not only in the slant range, azimuth plane, but in the whole 3D space [19], [12].

It follows that, if the carrier frequency is such that the penetration in the scattering volume is guaranteed, the vertical profile of the scatterers is retrieved by separating their contributions in multiple layers. Therefore, the exploitation of multi-baseline acquisitions allows to create a fully 3D imaging system, where the size of the 3D resolution cell is determined by pulse bandwidth along the slant range direction, and by the lengths of the synthetic apertures in the azimuth and cross range directions, see Figure 1.

Figure 1: left panel: a tomographic SAR system. Right panel: cross range, slant range extent of the TomSAR resolution cell.
7.3 Description of the data

The data used for the tomographic analysis were gathered by lying POLARIS (reconfigured with side-looking capability) at the SHR site located in the South-West part of Greenland (67°N).

In addition to SHR also the S10 site was considered, even though data relative to this site were not intended to be used for tomographic analysis, in that it is composed by only three sparse baselines. Though, as the S10 data-set is fully polarimetric, information about the vertical structure can be retrieved by using polarimetric/tomographic analysis techniques to recover vertical resolution.

The two sites belong to different areas of the ice sheet: the SHR site (-50°E, average elevation approximately 700 m) is in the ablation zone of the glacier, whereas the S10 site (-47°E, average elevation approximately 1850 m) is located in the accumulation area, in particular in the percolation zone. This implies a notable difference in the physical structure of the ice between the two sites. The ablation zone is characterized by the presence of meltwater and features like streams and lakes. The percolation zone is characterized by localized percolations from the surface during summer melt without becoming entirely wet. The subsequent refreezing of the percolating meltwater forms ice pipes and lenses.

Data available for SHR site are constituted by 2 sets acquired respectively on May 7 and on June 11, 2012. Each set is constituted by 10 surveys with South-West look direction and 10 surveys with North-East look direction. One acquisition missing is reported in the North-East June data-set. All surveys were acquired in HH polarization and four receiving channels (one for each patch of the POLARIS antenna) are available for each survey. The data available for S10 site are constituted by a set of 4 North-East looking fully-polarimetric surveys, acquired on April 20, 2012.

Data were provided from DTU in Level 0c format within navigational data and ancillary information for processing. The nominal parameters of the acquisition system are briefly summarized in Table 1.

<table>
<thead>
<tr>
<th>POLARIS</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Carrier Frequency</td>
<td>$f_0$</td>
</tr>
<tr>
<td>Carrier Wavelength</td>
<td>$\lambda$</td>
</tr>
<tr>
<td>Sampling Frequency</td>
<td>$f_s$</td>
</tr>
<tr>
<td>Slant Range Resolution</td>
<td>$d_r$</td>
</tr>
<tr>
<td>Look Angles</td>
<td>$\theta$</td>
</tr>
<tr>
<td>Flight Height</td>
<td>$H$</td>
</tr>
<tr>
<td>Horizontal Baseline Span</td>
<td>$A$</td>
</tr>
<tr>
<td></td>
<td>435 [Mhz]</td>
</tr>
<tr>
<td></td>
<td>0.69 [m]</td>
</tr>
<tr>
<td></td>
<td>125 [MHz]</td>
</tr>
<tr>
<td></td>
<td>1.8 [m]</td>
</tr>
<tr>
<td></td>
<td>20° - 45°</td>
</tr>
<tr>
<td></td>
<td>4000 [m]</td>
</tr>
<tr>
<td></td>
<td>20 [m]</td>
</tr>
</tbody>
</table>

Table 1: Parameters of POLARIS acquisition system.
7.4 Data focusing

7.4.1 Pre-processing

A relevant zero Doppler component was observed in the raw data frequency spectrum of SHR data, that could be due to ringing phenomena arising from the aircraft hull or wings. Such a component has been cancelled out by applying a notch-filter, as reported in Figure 2.

![Figure 2 - SHR NE looking, raw data Doppler Spectrum before (left) and after (right) zero Doppler filtering.](image)

Data from all SHR passes collected along the SW looking tracks have also been observed to exhibit a highly squinted Doppler centroid, as visible in Figure 3. This phenomenon could possibly be attributed to a crabbing motion of the aircraft under the action of a constant wind.

![Figure 3 - SHR SW looking, raw data Doppler Spectrum before (left) and after (right) zero Doppler filtering.](image)

7.4.2 Azimuth focusing with time domain back-projection

Raw data have been focused using a time domain back-projection algorithm, in order to obtain an azimuth resolution of 5 m. The algorithm takes as inputs raw data as well as the information about
platform position at each pulse provided by navigational data, so as to cope with platform deviations off the nominal straight line. Moreover if accurate topography information is available, data are automatically coregistered, geocoded and phase flattened.

In Figure 4 an example of the focused area at SHR site is shown.

![Figure 4 - SHR (May) site, SLC intensity.](image-url)
7.5 Single pass tomography at SHR

SAR tomography is used to retrieve the 3D distribution of the complex reflectivity of the imaged medium based on multi-baseline surveys. The rationale of this technique is easily understood by considering that the availability of multi-baseline observations allow the formation of a further synthetic aperture that is orthogonal to the flight path, i.e.: across range. Accordingly, the gathered radar echoes can be focused not only in the range-azimuth plane, but in the whole 3D space, with a vertical resolution related to the total baseline aperture in the vertical direction [12], [19].

One key advantage of this technique is that it allows to obtain 3D information about the imaged scene largely in the absence of a-priori assumption about the scene itself. In this sense SAR tomography constitutes a major tool for validating, developing and tuning physical models of radar scattering, as witnessed by the recent developments achieved in the analysis of forested areas.

7.5.1 Baseline planning

A critical condition for SAR tomography is that the average baseline spacing within the data stack should guarantee the height of ambiguity to be larger than the thickness of the imaged volume. If this condition is not met the imaging is wrapped along elevation, preventing the interpretation of the results. Accordingly, a fundamental constraint to obtain a correct 3D reconstruction is that either the ice thickness or the wave penetration depth is smaller than the height of ambiguity within the ice layer.

Assuming a typical airborne geometry, and letting the flight height be 3500 m above the ice/air interface, a height of ambiguity of 150 m is obtained at 30° by flying horizontal baselines about 6 m apart from each other or vertical baselines about 3.5 m apart from each other. Smaller baselines would be required in the case where wave penetration is deeper. Details are reported in the Technical proposal. It is also to be considered that flight trajectories might happen to depart significantly from the planned lines due to the action of wind. This translates into more strict requirements about baseline spacing and number of passes, so as to augment the probability of gathering data along flight lines close to the planned ones.

As neither the effective wave penetration nor the impact of wind on the planned flight lines are known a priori, the safest choice for carrying out tomographic analysis is to take advantage of POLARIS’s capability to acquire data at four closely spaced antennas simultaneously. This choice allows for a vertical resolution on the order of 500-800 m. Yet, it guarantees nearly ambiguity-free imaging. Accordingly, tomographic focusing from single pass data provides the most robust solution for the assessment of penetration depth, and eventually bedrock detection.

High resolution tomographic imaging can then be obtained by jointly processing multi-antenna acquisitions from multiple passes. In order to do this, however, it is important to keep in mind that tomographic focusing requires knowledge of platform position to within a sub-wavelength accuracy (i.e: few centimeters) [14], which is usually beyond the accuracy provided by navigational data. This information can be retrieved from InSAR techniques, provided coherence is preserved between different passes.

In order to ensure coherence between any two quadruples it was then decided to overlap one of the four antennas from each pass, that is to let the distance between two passes be on the order of 1 m or less, than the expected POLARIS orbital tube under perturbed conditions. Accordingly, the decision was made to repeat the same flight lines by flying along an oval-like racetrack. This choice would: i) maximize the acquisition time with respect to the overall flight time; ii) provide two independent experiments for cross-validation purposes; iii) provide unambiguous imaging in case of significant wave penetration.
However, this approach is feasible conditional on the presence of a detectable surface, either at the ice/air interface or within the ice layer, whose position relatively to the SAR sensors can be accurately measured using InSAR techniques. In the case where surface scattering from the ice/air interface is visible, residual motion compensation can be carried out with great accuracy using prior knowledge of terrain topography (from LIDAR data, if available). The cases where terrain topography is not known or the detected surface is within the ice layer are more delicate. However, multi-pass InSAR provide equations enough to recover both phase offsets due to platform position and surface topography [9], [10], [11]. Conversely, the case where the scene is dominated by extended volume scattering would result in the complete loss of coherence between acquisitions from different passes, preventing the application of InSAR to recover sensor and surface position. In this case tomographic focusing could be carried out based on navigational data only, most likely producing inaccurate results.

7.5.2 Results

The two panels in Figure 5 reports two tomographic sections (also referred to as tomogram) focused in the ground range-height plane. The left panel was obtained by considering a single patch, which provides no vertical resolution, whereas the right panel was produced by combining all the four patches.

The combination of the four patches provides vertical resolution, witnessing correct processing and data. Yet, it is immediate to see that scattering contribution appears to be localized mostly at the surface (approximately 700 m), which implies that the effective thickness of the scattering layer is much lower than the vertical resolution obtained by processing a single quadruple.

![Figure 5](image)

Figure 5- left panel: ground range-height focusing from a single patch (no vertical resolution capabilities). Right panel: ground range – height focusing from four patches.

This result was observed for every flight and over the whole illuminated scene, as widely discussed in the remainder. It then follow single pass tomography is not suited to investigate the vertical structure at this test site, as it does not provide enough resolution to distinguish contributions from different depths. In the remainder the SHR data-set will be investigated by processing multiple passes, so as to increase vertical resolution by collecting larger baselines.
7.6 Interferometric analysis

This section reports a quick look interferometric analysis of each scene.

For the SHR site results are reported relatively to both looking directions, i.e.: South-West (SW) and North-East (NE).

In the first place, NE looking data have been observed to exhibit relevant losses of coherence due to lower signal-to-noise ratio in far range. A comparison between SW and NE looking data is reported in Figure 6.

![Image of Figure 6: Amplitude (upper panels, log scale) and coherence (lower panels) for the two SHR datasets.]

7.6.1 SHR May

The analysis has been carried out on eight passes focused at the supposed air/ice interface. Coherence is estimated on a 62 m x 62 m window in order to have an available number of independent looks higher than 100. The interferometric coherence magnitude and phase for two different interferometric pairs are shown in Figure 7 and Figure 8 respectively. Coherence magnitude is observed to stay overall quite high, showing poor dependence on spatial baselines. The observed interferometric fringes are almost entirely due to aircraft motion, as it will be discussed in the remainder. It is also relevant to note that coherence values are slightly lower at large temporal baselines, as visible by comparing the two figures below, implying some temporal decorrelation.
Figure 7 - Coherence (upper panel) and corresponding interferogram (lower panel), SHR May data. Time lag with respect to master acquisition: approx 20 minutes.

Figure 8 - Coherence (upper panel) and corresponding interferogram (lower panel), SHR May data. Time lag with respect to master acquisition: approx 120 minutes.
Results for all baselines are summarized in Figure 9, which reports coherence magnitudes in all baseline as obtained from real data (lower left) or by simulating an exponential vertical profile with characteristic penetration $z = 50$ m. In most areas the observed coherence is higher than the simulated values, indicating that the signal is mostly scattered from the surface. Coherence is observed to get slightly lower as the temporal lag increases (images are sorted by acquisition time), which indicates the data-set is partly affected by temporal decorrelation.

![Interferometric coherence magnitudes at SHR (May 2012). Lower left panels are relative to real data. Upper right panels were obtained by simulating an exponential vertical profile with characteristic penetration $z = 50$ m. Images are sorted by acquisition time.](image)

Figure 9: Interferometric coherence magnitudes at SHR (May 2012). Lower left panels are relative to real data. Upper right panels were obtained by simulating an exponential vertical profile with characteristic penetration $z = 50$ m. Images are sorted by acquisition time.
7.6.2 SHR June

The analysis has been carried out with the same procedure applied to data acquired in May. Data are focused using the same reference grid as for May data. The interferometric coherence magnitude and phase for two different interferometric pairs are shown in Figure 10 and Figure 11. As for May data, coherence magnitude is observed to stay overall quite high, independently of spatial and temporal baselines. Coherence appears to be even higher than that of May data, in accordance with the fact that in June the melting season takes place.

![Figure 10](image)

Figure 10 - Coherence (upper panel) and corresponding interferogram (lower panel), SHR June data. Time lag with respect to master acquisition: approx 20 minutes.
Figure 11 - Coherence (upper panel) and corresponding interferogram (lower panel), SHR June data. Time lag with respect to master acquisition: approx 120 minutes.
The analysis at S10 has been carried out on the four available passes focused at the supposed air/ice interface. Coherence is estimated on a 82 m x 82 m window. The interferometric coherence magnitude and phase for two different interferometric pairs are shown in Figure 14 and Figure 15. Coherence magnitude is observed to be significantly lower than that of SHR data. Figure 12 reports coherence magnitudes in all baseline as obtained from real data (lower left) or by simulating an exponential vertical profile with characteristic penetration $z = 50$ m. Differently from SHR, coherence are here observed to strongly depend on the vertical wavenumber, resulting in similar maps as those obtained from synthetic data. This observation is consistent with the fact that baselines at S10 are larger than at SHR, which increases sensitivity to wave penetration, and also shows that penetration phenomena are observed at this site.

Figure 12: Interferometric coherence magnitudes at S10. Lower left panels are relative to real data. Upper right panels were obtained by simulating an exponential vertical profile with characteristic penetration $z = 50$ m.

Figure 13 details the analysis by simulating a penetration depth of 100 m, for the interferometric pair shown in Figure 15. Again, a good agreement can be observed between the two images, supporting the hypothesis of penetration of the radar signal into the ice volume.
Figure 13 – Simulated coherence for the interferometric pair of Figure 15 in case of volumetric scattering. Gaussian extinction profile with characteristic penetration of z = 100 m is assumed.

Figure 14 - Coherence (upper panel) and corresponding interferogram (lower panel), S10 data. Time lag with respect to master acquisition: approx 80 minutes.
Figure 15- Coherence (upper panel) and corresponding interferogram (lower panel), S10 data. Time lag with respect to master acquisition: approx 200 minutes.
7.7 Algebraic analysis of the covariance matrix of the data

In order to discuss the overall interferometric correlation among all focused passes, an analysis of the eigenvalue spectrum of the covariance matrix of the data has here presented for each one of the illuminated scenes.

An indication of the decorrelation undergone by the underlying scattering mechanisms can be provided by evaluating the effective algebraic rank of the matrix formed by taking the interferometric coherence in all passes at each location in the ground range-azimuth focusing plane.

If only a single eigenvalue is (significantly) larger than zero, then the underlying scattering mechanism is maximally coherent, i.e. coherences are high in all interferograms. This is the case of non decorrelating targets, such as point or superficial scatterers. The opposite case is where all eigenvalues tend to be the same magnitude, which corresponds to a completely decorrelated target (or noise). Intermediate cases indicate decorrelation phenomena, which could be due either to temporal or volumetric decorrelation.

In Figure 16 simulated maps are reported for the case of superficial scattering and volumetric scattering at the SHR and S10 sites. For the volumetric case a Gaussian extinction is assumed, with a characteristic penetration depth of 50 m in the case of SHR and 100 m in the case of S10.

It is worth noting that the scattering mechanism is the same at all locations in all maps shown in Figure 16, the variation of the algebraic rank being due to the variation of the vertical wavenumber.
7.7.1 SHR May

The rank map reported in Figure 17 is intended to provide a quick assessment of the scene decorrelation level by showing at each pixel the number of eigenvalues larger than 10% of the highest eigenvalue. Accordingly, areas with rank 1 correspond to coherent targets (superficial or point-like), whereas areas with rank 8 correspond complete decorrelation (noise). It is immediate to see that nearly the whole scene is characterized by rank values ranging from 1 to 3, which is consistent with the presence of shallow penetration (50 m or less) in few areas.

It is here worth remarking that the rank analysis is not intended to distinguish among different decorrelation sources (like volumetric and temporal). Though, it allows to appreciate whether decorrelation is occurring or not. Accordingly, the observed low rank values over large part of the scene indicate that the signal is mostly contributed by a scattering mechanism that is loosely affected by temporal and volumetric decorrelation.

Figure 16 – Simulated rank maps for superficial (upper panel) and volumetric scattering in case of SHR geometry (middle panel) and S10 geometry (lower panel).
7.7.2 SHR June

The rank map shown in Figure 18 confirms the results found for May data. In this case the rank map appears to be even more homogeneously distributed towards low values.

![Figure 18 - Map of the rank for SHR June data. Rank 1 means coherent scattering mechanism (surface), higher rank means increasing decorrelation.](image)

7.7.3 S10

The rank map shown in Figure 19 has overall higher values than that of SHR data. Highest rank points at the sides of the area are due to the widening separation of the flight tracks and consequent increasing spatial decorrelation. Comparing the rank map of Figure 19 with the simulated map of Figure 16 (lower panel) a good agreement can be found as in the case of coherence, again supporting the hypothesis of deeper penetration than at SHR.
Figure 19 - Map of the rank for S10 data. Rank 1 means coherent scattering mechanism (surface), higher rank means increasing decorrelation.
7.8 Multi-pass tomographic processing

Processing multiple flight lines allow to form a 2D synthetic antenna, and accordingly to focus the signal in the 3D space. The fundamental advantage over processing single quadruples is that collecting different flight lines allows to form a significantly large baseline span, resulting in finer vertical resolution.

Though, there are two issues related to multi-pass processing that need be taken into account.

1. The actual flight paths along which the sensor is flown unavoidably depart from the ideal straight lines assumed in the baseline design phase, depending on aircraft stability, wind and weather conditions. The resulting deviation is usually on the order of few meters.

2. Aircraft trajectories are known to within the accuracy provided by the navigational system, which is usually on the order of centimetres to tenths of centimetres.

The fact that aircraft trajectories depart from the planned ones results in a non-uniform sampling of the virtual antenna along the elevation direction. This factor hinders the application of standard focusing algorithm employed in along track focusing, which would result in strong grating lobes. A remedy to this is provided by dedicated processing methods such as adaptive filtering [20], Compressive Sensing [22], or other inversion procedures. These methods also provide super-resolution capabilities, that is the capability to resolve targets more closely spaced than system resolution.

Navigational system errors about the trajectories on the order of 1/10 wavelength (or larger) also result in side-lobes and defocusing in elevation, which hinders the interpretation of the results. To a first order approximation these errors appear as slow varying phase screens affecting the interferogram phases. Such phase screens have to be estimated and removed before applying any tomographic processing. This procedure is usually referred to as phase calibration [14].
7.8.1 Phase calibration

The problem of Phase calibration of airborne data for tomographic applications was tackled in many works in the last years, that differ from each other based on how phase screens are estimated and parameterized.

A possible approach is to phase calibrate the data by removing the interferometric phases associated with ground scattering, which are estimated based on detected stable point targets within the data-stacks [14], or by isolating ground-only contributions via a polarimetric decomposition technique [10]. This approach allows a consistent reconstruction of volumetric scattering above the ground. Yet, terrain topography remains unknown unless dedicated InSAR procedures are employed. A similar approach is found in [25], with the difference that the residual phase screens are obtained via entropy minimization. A different perspective is found in [26]. In that paper a procedure is proposed for the estimation of the along-track derivatives of motion errors in a single-baseline interferogram, which are afterwards integrated along track and used to correct the data.

In this work we employed a phase calibration tailored for airborne tomography, based on recent developments on this subject [13]. Such an approach parameterizes the interferogram phases in all available interferogram by means of the following parameters:

- Phase center height (one parameter per pixel)
- Ground-range slave sensor position (N-1 parameters per azimuth line)
- Height slave sensor position (N-1 parameters per azimuth line)

where N is the total number of overpasses.

Solving for the parameters above yields surface topography (intended as phase center height) and platform position for each slave image. The latter information is used to compute the phase screens required to correct the interferogram phases.

This information is derived by processing all available interferometric pairs at the same time, according to a two step procedure. In the first step the Phase Linking algorithm [15] is used to retrieve the optical paths from each sensor position to the phase center at each range, azimuth location. The estimated optical paths are then processed in the complex domain by alternating the estimation of phase center height and platform position.

In the remainder of this section results are presented obtained by processing data acquired at SHR in May 2012.

Figure 20 shows the phase of one interferometric pair (top panel) and the synthetic phases obtained according to the estimated motion and topographic contributions (middle panel). This result clearly shows that the observed phases are mostly due to residual platform motion. The topographic contribution can be observed by evaluating the phase residual (bottom panel).

Figure 21 generalizes this result to all available interferograms. The lower left panels show the phase residual obtained by taking the difference between the interferogram phases and the synthetic phase screens due to the estimated motion and topographic contributions. In all cases the residual are close to zero, witnessing the effectiveness of this approach. Figure 22 provides a figure of merit that quantifies phase calibration quality. The figure of merit was obtained as the coherent average of all phase residuals, so that a result equal to 1 indicate a perfect noise-free calibration. A comparable phase calibration quality was observed for all the other data-sets gathered at SHR (May - North East looking, June – North East and South West looking).
Figure 20 – Top panel: estimated phase in one interferometric pair. Middle panel: estimated phase due to platform position. Bottom panel: phase residual.

The impact of phase calibration on the tomographic imaging is shown in Figure 23, that reports a calibrated (top) and non-calibrated (bottom) tomogram, that is a representation of the focused signal backscattered power over a height azimuth or height range section. The calibrated tomogram appears to be very well focused, no side-lobe phenomena being observed. On the contrary, the absence of phase calibration results in a total loss of information about the vertical structure of the backscattered power, due to strong defocusing phenomena visible in the bottom panel of Figure 23.

Finally, the estimated phase center height is rendered in Figure 24 (data from May 2012) and Figure 25 (data from June 2012).

It is worth pointing out that residual low frequency undulations can appear in the estimated phase center height, as visible considering the differences between results from May and June. This residual disturbance could be fixed through multi-squint techniques, see [26]. This point has not been considered in this work as the analysis is focused on accurate tomographic imaging (rather than on absolute topographic retrieval). The impact of the aforementioned topographic oscillations on the tomographic focusing merely reduces to translating the whole tomographic profiles up and down along height. Moreover, such a translation is extremely low pass in the range, azimuth plane. Accordingly, the aforementioned undulations only affect topography estimation, whereas the quality of the tomographic focusing is fully preserved.
Figure 21: Top right panels: Interferogram phases in all available baselines. Bottom left panels: phase residuals after removing the estimated contributions due to platform position and surface topography. Data: SHR, May 2012.

Figure 22: Fit quality over the imaged scene. Data: SHR, May 2012.
Figure 23 – Top panel: Capon tomogram obtained after phase calibrating the data set. Bottom panel: uncalibrated tomogram. Data: SHR, May 2012.

Figure 24: Estimated phase center height. Data: SHR, May 2012.
Figure 25: Estimated phase center height. Data: SHR, June 2012.
7.8.2 Processing methods for elevation focusing

A common problem of airborne multi-pass campaign is that the resulting baseline set is: i) not uniformly sampled (sparse distribution); ii) strongly varying along and across track.

This features result in the presence of unwanted side-lobes phenomena and also strong spatial variation of the achievable vertical resolution, see Figure 26 and Figure 27.

These issues can be overcome by posing tomographic focusing as a spectral estimation problem, so as to reuse processing techniques such as Capon filtering, MUSIC, Compressive Sensing, and many others [20], [22]. Another nice feature of these processing methods is that they provide super-resolution capabilities, that is the capability to resolve targets more closely spaced than the vertical resolution provided by the available baseline set.

In this work we will largely employ the Capon estimator. The reason for this choice is that it is particularly suited for investigating natural media, as it produces super-resolution capabilities and grating lobes reduction without the need for a-priori information about the targets other than horizontal homogeneity.

The benefit of this approach is easily understood by examining Figure 26, where it is immediate to see that Fourier tomogram (also referred to as beamforming) is affected by relevant sidelobe phenomena that completely disappear in the Capon tomogram.

Moreover, for the data-sets acquired at SHR the vertical resolution ranges from 50 to over 200 m over the whole imaged scene, see Figure 27. This results in the signal from pure surface scattering to spread over a quite large height span, making it a hard task to detect wave penetration on the order of tenths of meters based on Fourier tomograms.

The main drawback associated with the Capon Spectral Estimator is the poor radiometric accuracy, especially in presence of a low baseline aperture. In this sense, conventional Fourier analysis (beamforming) is more accurate. A formal treatment of these arguments is found in [28], where both the Fourier and Capon estimators are discussed as special cases of a generalized spectral estimation technique. In particular, it is shown that spatial resolution and radiometric accuracy cannot be achieved at the same time, at least in absence of precise a-priori information. Accordingly, the employment of the Capon Spectral Estimator has to be considered as a compromise. Indeed it results in non accurate backscattered power values, but it permits to appreciate details that would not be accessible otherwise with the available baseline set.
Technical Assistance during the 2012 ICESAR Validation Campaign

Figure 26: top panel: Capon Tomogram. Middle panel: Fourier Tomogram. Bottom panel: Synthetic tomogram corresponding to ideal surface-only scattering.

Figure 27: Fourier tomography vertical resolution. Data: SHR, May 2012.
7.8.3 **Tomogram representation**

The tomograms shown so far have been presented in a fixed system of coordinates where \( x \) is the average flight direction, \( y \) is the ground range, and \( z \) is height. This representation allows to appreciate the dynamics of the topographic variation. Yet, it tends to hide signal variation occurring at smaller scales (say on the order of less than 50 m), such as shallow wave penetration phenomena. For this reason we will hereinafter consider the so called **flattened tomograms**, that is tomograms obtained by referring the height coordinate to the estimated phase center height at each \( y,x \) location, see Figure 28. Another advantage of this approach is that is allows to immediately refer the \( z \)-coordinate to a certain height above or a certain depth beneath the phase center height.

One open question is, of course, whether phase center height is found at or slightly beneath the surface, as it may happen in case of relevant penetration. This question will be better discussed in the remainder.
Figure 28: top panel: Capon Tomogram. Middle panel: Capon Tomogram after phase center height compensation. Bottom panel: zoom in.
7.9 Tomographic profiles

This section is devoted to discussing the scattering properties at the investigated sites based on tomographic vertical profiles.

7.9.1 SHR May

In Figure 29 a tomographic section is shown. Vertical wavenumbers are computed referring to radar waves propagating in air. The upper panel represents the map of the rank with the azimuth position of the corresponding tomographic line highlighted in red. The tomograms have been obtained via Fourier transform (i.e. beamforming, middle panel), which is analogous to focusing the signal in the height direction, and via Capon spectral estimation (bottom panel), which provides vertical super-resolution capabilities. It is immediate to see that on vast portions of the imaged scene the surface is clearly visible, whereas only few signal contribution is observed from the ice volume beneath, in full accordance with the results previously shown. It can be noted that in points corresponding to higher rank on the map (upper panel) there appears to be some shallow penetration. Considering that the signal beneath the surface is not focused correctly since the change of velocity due to the change of medium has not been taken into account, the penetration depth could be realistically considered on the order of 20 m. In Figure 30 a Fourier Tomogram of a range line is shown along with its impulse response. In Figure 31 a simulated tomogram obtained assuming the same acquisition geometry of Figure 29 and a penetration of 50 m is shown for comparison.

![Figure 29](image)

Figure 29 – Map of the rank for SHR May data (upper panel), Beamforming (middle panel) and Capon tomogram corresponding to the azimuth cut indicated with a red line (lower panel).
7.9.2 SHR June

Results are similar to the ones found for May data. A tomographic section is shown for example in Figure 32.
7.9.3 S10

Tomographic imaging at S10 is affected by relevant sidelobe phenomena and strong resolution variations, that cannot be eliminated as in the SHR case through super-resolution processing. This is of course due to the fact that the four available flight lines were not intended for tomographic processing. A possible way to improve the quality of the results is to jointly process multi-baseline and multi-polarimetric data, so as to highlight the eventual presence of volume scattering by exploiting polarization differences through Polarimetric SAR Tomography methods. This analysis will be discussed in section 7.11.

In Figure 33 a tomographic section from a central part of the area is shown. The tomographic profile has been obtained from the four available HH surveys. The vertical distribution of the signal is quite symmetric, though a slight asymmetry towards subsurface can be observed. There seems to be penetration of the radar signal into the ice volume up to an extent of approximately -100 m. The limited availability of only four passes and the distribution of the vertical wavenumbers do not allow a high resolution imaging in the vertical (ground range-elevation) plane, as it can be observed in Figure 34. Improvement of the resolution is obtained through Algebraic Synthesis exploiting also polarimetric diversity, as it will be explained in the remainder.
Technical Assistance during the 2012 ICESAR Validation Campaign

Figure 33 – Map of the rank for S10 data (upper panel), Beamforming (middle panel) and Capon tomogram corresponding to the azimuth cut indicated with a red line (lower panel).

Figure 34 – An example of tomogram obtained with Beamforming (lower panel) and corresponding impulse response (upper panel), S10 data. Values are scaled from 0 (blue) to 1 (red). It can be observed how the signal response suffers from the presence of high sidelobes near the main peak.
7.10 Differential tomographic analysis at SHR

Differential SAR tomography can be thought of as a straightforward extension of conventional SAR tomography from three to four dimensions, i.e.: target position in the 3D space and target velocity along the radar line of sight (LOS) [21]. This extension is made by possible by acquiring the data not only from different look angles, implying 3D resolution capabilities, but also at different times. It then follows that not only target position can be retrieved, but also its velocity, clearly provided the target has undergone a significant motion within the observation period. Differential SAR tomography could then be used, for example, to reveal if scatterers within the ice volume (if present) undergo a different motion compared to the surface.

As discussed above the analyzed SHR scene appears to be mostly characterized by superficial scattering (with respect to the vertical resolution), with the exception of few areas that were indicated as being affected by relevant decorrelation phenomena (see the rank maps in Figure 17 and Figure 18). The aim of this section is to investigate whether the observed decorrelation is to be attributed to temporal or volumetric phenomena. Before showing experimental results it is worth pointing out that differential SAR tomography effectiveness is strictly connected to the distribution of the normal baselines with respect to the acquisition time. The best case is found when the normal baselines are random with respect to the acquisition times, which provides the best separation between target depth and velocity. On the contrary, the case where spatial and temporal baselines are aligned with each other results in an ambiguity between target velocity and position.

In the frame of an airborne campaign flight trajectories are unavoidably perturbed with respect to the planned one, resulting in the spatial and temporal baselines distribution to change along track. For May data a well conditioned case is found for example in the part of the imaged scene corresponding to along track positions around \( x \approx -260 \) m, as in this area baselines are scattered with respect to acquisition times, see Figure 36.

The four panels in Figure 35 show the outcomes of differential SAR tomography analyses for four different targets within this area (May data), i.e.: a rank 1 target; a rank 3 target in the proximity of the first one; two (synthetic) ideal point like targets acquired with the same spatial and temporal baselines as the other two (real) targets. The top and bottom panels in the right column have been obtained by assuming ideal point targets. Those panels have been displayed in order to show the actual Impulse Response of differential SAR tomography focusing, which is determined by the spatial and temporal baseline distribution. The phase has been calibrated based on the rank 1 point.

The top and bottom panels in the left column of Figure 35 show the results relative to the rank 1 and rank 3 (real) targets. In the first place it is possible to note that the peak in the height/velocity plane is found at the same position for both targets, i.e.: no relevant difference is observed concerning target positions and velocities. This indicates that the same scattering mechanism, which is associated to the surface level, is found at both locations. In the case of the rank 3 point contributions from beneath the surface are observed to be strongest than in the rank 1 case, which indicates some penetration into the ice volume is occurring.

It is also worth noting that in the rank 3 case the signal is also appears to be spread along the velocity direction. The same conclusion can be drawn by observing Figure 37, which reports the zero height profile of the differential tomograms in Figure 35. This indicates that higher rank areas are also characterized by temporal decorrelation, as discussed in the previous sections.

Finally, for completeness we report in Figure 38 a case that is not favourable to differential SAR tomography, corresponding to along track positions around \( x \approx -3880 \) m. In this case spatial and temporal baselines are nearly parallel, resulting in ambiguity between target position and velocity.
Figure 35 – Differential tomograms for a point with rank one (upper panels) and a point with rank three (lower panels), along with impulse responses. Log scale.

Figure 36 – Vertical wavenumbers vs. acquisition times for the rank 1 point analyzed in Figure 35.
Figure 37 – Zero height section of the tomograms from Figure 35. The blue and red lines are relative to the rank 1 and rank 3 points, respectively.
7.11 Algebraic Synthesis from multibaseline full-pol S10 data

Although the difficulties of imaging the volume at S10, it can be seen from Figure 39 that polarimetric diversity can be exploited to highlight different features within the vertical direction.

Comparing the tomogram related the combination of co-polar channels (second panel) with the one related to the cross-polar channel (fourth panel), it can be noted how the first one seems to be more related to a superficial layer, while the second appears distributed below the surface for almost 100 m. This fits very well the idea the HV is mostly contributed by volume scattering, whereas the HHVV term is contributed by surface scattering [29].

Figure 38 – Differential tomograms for a point at coordinates (-3882, 3518), and the corresponding impulse response. Log scale. Bottom panel: vertical wavenumbers vs. acquisition times for the considered point.
The observed diversity between tomograms at different polarizations suggests the possibility to infer further information about the scattering mechanisms contributing to the signal by jointly processing multiple polarizations and multiple baselines. A formal framework to accomplish this task is provided by the Algebraic Synthesis technique [10]. Such a technique offers the possibility to decompose the data second order moments into different scattering mechanisms, and form a separate tomogram for each of these, extending with continuity the concepts within PolInSAR [23] to the multi-baseline case.

In Figure 40 reports an image of the reconstruction accuracy obtained by assuming two scattering mechanism. It can be seen how more than 80% of the information is retained, which shows that a two-layered model is well suited to representing the scene at S10.

A result of the decomposition is shown in Figure 41, reporting two tomograms relative to the two scattering mechanisms yielded by the Algebraic Synthesis technique. Both images are perturbed by sidelobes, due to the non-favourable baseline distribution. Yet, the first and the second scattering mechanism clearly present the features of surface and volume scattering, respectively.

It can be noted that the result obtained is analogous to results found in literature for forest scenarios: the first scattering mechanism is strong and very localized at surface, whereas the second mechanism is distributed and localized in this case at subsurface.

Figure 42 reports a simulation of the expected response from superficial and volumetric scattering mechanisms. A volumetric Gaussian extinction at -100 m is assumed. Comparing this Figure with the results of the Algebraic Synthesis, a good agreement can be found concerning both scattering mechanisms.

These results further corroborates the hypothesis of penetration into the ice volume for S10 data. The observed is about 100 m assuming propagation in air, which scales down to about 50-60 m accounting for ice propagation velocity.
Figure 40 – Percentage of information of the data represented using two scattering mechanisms.

Figure 41 – Decomposition of the tomogram of Figure 33 lower panel into surface (upper panel) and volume (lower panel) scattering.
Figure 42 – Simulated Capon tomograms of a surface (upper panel) and a volume (lower panel). A Gaussian extinction at -100 m is assumed.
7.12 Large scale tomographic analysis

This section is dedicated to discussing the 3D scattering property of the whole illuminated scene. The analysis will be carried out based on tomographic layers, that is horizontal (x,y) sections associated with different heights (depths). As discussed above, height will be referred to the estimated phase center location. Accordingly, the section referred to as “0 m” is to be intended as the section corresponding to the phase center, whereas the section denoted as “dz m” is to be intended as the section corresponding to dz m away from the phase center.

7.12.1 SHR May

In Figure 43 the tomograms of the phase centre for the whole scene are shown. Focusing obtained with beamforming is reported in the upper panel, focusing obtained with Capon is reported in the lower panel. Values are scaled between 0 (blue) and 1 (red).

Figure 43 – Tomographic sections corresponding to the phase centre, SHR May data. Focusing obtained with Fourier (upper panel) and Capon (lower panel).
The corresponding elevations are reported in Figure 44, where low pass terms have been removed to highlight contrast. The feature in the lower left part of the image coincides with a river identifiable on Google Earth.

![SHR, May - Elevation [m]](image)

Figure 44 – Elevations corresponding to the phase centre, SHR May data. Low pass terms have been removed to highlight contrast.

In Figure 45 and Figure 46 sections corresponding to 23 m, 47 m and 70 m below and above the phase centre are reported.
Figure 45 – Sections corresponding to 23, 47 and 70 m below the strongest return.
Figure 46 – Sections corresponding to 23, 47 and 70 m above the strongest return.

It can be observed how the signal strength at lower elevations is mostly related to the main lobe of the tomograms of the strongest return. In the Fourier (beamforming) panels some apparent in-depth components that do not appear in Capon panels can be observed, see for example Figure 47 at h=70 m, ground range 1700 m and azimuth 0 m. A comparison with the tomographic section in the ground range-elevation plane of Figure 48 reveals that this components are due to the sidelobes of the response and not attributable to penetration of the signal into the ice volume. Though, signal contributions at lower elevations can be observed in the Capon tomograms.
Figure 49 – Sections at 47 m and -47 m normalized to the values correspondent to the strongest return.

In Figure 50 the sections at -47 m and 47 m obtained with Capon are reported after normalization to the values obtained in correspondence of the strongest return. It can be observed that the signal is stronger at negative height values, confirming that some in-depth components can indeed be identified, for example around the azimuth position 1000 m. This confirms the analyses presented in the former, corroborating the fact that the signal is mostly contributed by superficial scattering although shallow penetration can be observed as well.

7.12.2 SHR June

The analysis shows basically the same results found for May data. Corresponding results are shown from Figure 51 to Figure 52.
Figure 53 - Tomographic sections corresponding to the strongest return, SHR June data. Focusing obtained with Fourier (upper panel) and Capon (lower panel).

Figure 54 - Elevations corresponding to the strongest returns, SHR June data. Low pass terms removed to highlight contrasts.
Figure 55 – Sections corresponding to 23, 47 and 70 m below the strongest return.
Figure 56 – Sections corresponding to 23, 47 and 70 m above the strongest return.

Figure 57 - Sections at 47 m and -47 m normalized to the values correspondent to the strongest return.
7.12.3 S10

In Figure 58 the Capon tomogram of the strongest return is shown for the HH polarization.

![Figure 58 - Capon tomogram of the strongest return, S10 data.](image)

The corresponding elevations are reported in Figure 59.

![Figure 60 - Elevations corresponding to the strongest returns, S10 data. Low pass terms removed to highlight contrasts.](image)

In Figure 61 two antipodal sections normalized with respect to the values obtained in correspondence of the strongest return is shown.
Figure 61 – Capon tomograms of sections at 33 m and at -33 m, normalized to the values corresponding to the strongest returns.

Compared to SHR data, in this case a clear interpretation of the results is hindered from the bad quality of the impulse response, which is affected by sidelobes.

Accordingly, a more proper discussion of the scattering mechanisms at S10 can be provided by analyzing vertical tomographic profiles.
It is observed in Figure 62 how the signal response is heavily influenced by the presence of sidelobes all over the space. As already mentioned, the reason for this is that flights at S10 site were not planned for tomographic acquisitions. Nonetheless, asymmetry of the response towards subsurface can be observed at some points, suggesting penetration into the volume.

A comparison with results from the Algebraic Synthesis technique is shown in Figure 63, Figure 64, Figure 64.
Co-polar coherences and ground to volume ratios are shown in Figure 66 and Figure 67. From Figure 68 it can be observed that co-polar coherence is strong in both HH data and ground mechanism and lower in volumetric mechanism. This is consistent with polarimetric behaviour of the two physical mechanisms assumed. In Figure 69 ground to volume ratios for the three polarimetric channels are represented in logarithmic scale. The ratio is positive for co-polar channels and negative for cross-polar channel, again consistently with the physics of the assumed scattering mechanisms.
Figure 70 – Co-polar coherence for HH data (upper panel), ground (middle panel) and volumetric scattering mechanism (lower panel).
Figure 71 – Ground to volume ratios for the three polarimetric channels.
7.13 Surface height and penetration depth

The aim of this section is to provide a quantitative evaluation of wave penetration based on the 3D reconstruction obtained by SAR tomography.

Two points need to be taken care of to this aim. One is the effect of vertical resolution, which is strongly varying along and across track, see Figure 72. As previously shown the employment of the Capon spectrum greatly helps compensate for this phenomenon. Though, even assuming a super-resolution factor on the order of 4 or 5, and perfect side-lobe rejection as well, it is not trivial to produce a realistic assessment of the “thickness” of the signal at SHR in presence of a Fourier vertical resolution exceeding 100 m in most parts of the imaged scene. The other that deserves attention is that so far tomographic sections have been represented with respect to the phase center height, which is in general not guaranteed to correspond to the air/ice interface.

![Resolution map](image)

Figure 72: Fourier tomography vertical resolution. Data: SHR, May 2012.

7.13.1 Results from May 2012

Five tomographic sections (dz = -80, -40, 0, 40, 50 m w.r.t. phase center height) are shown in Figure 73. Scattering contributions are visible at -40 m, witnessing wave penetration in some areas. Though, results are somehow replicated at +40 m, indicating that this phenomenon is also related to the finite resolution of the tomographic processor. This conclusion is corroborated by observing the clear correlation between the resolution map in Figure 72 and the observed scattering at +40 m.

In order to better investigate wave penetration a full tomographic analysis has been performed by employing the MUSIC spectral estimator, [20], [28]. Such an estimator provides greatly enhanced resolution capabilities w.r.t. the Capon estimator. Yet, the resulting spectrum is not to be intended as an estimation of backscattered power, but rather as a simple indication of the presence of a signal source at that location. Results are shown in Figure 74. The signal is observed to be present at -40 m, whereas the section at +40 m is only contributed by weak sidelobes very strongly correlated with the vertical resolution map. This analysis corroborates the idea of an actual wave penetration in many areas at SHR.

Another phenomenon is worth pointing out, that is the fact that peak value is not always reached in correspondence to the phase center height. In fact, a closer analysis has revealed that the peak is located above the phase center, depending on the area and also on the original resolution of the tomographic processor, see Figure 75. Such a surface offset was taken as the upper boundary of the ice
layer. In similar fashion, the MUSIC algorithm was also employed to estimate the lower boundary of the ice layer. Results are detailed for a number of tomographic profiles in Figure 76, Figure 77, Figure 78.

Figure 73: Tomographic sections with respect to phase center height. Focusing method: Capon spectrum. Data: SHR, May 2012.
Figure 74: Tomographic sections with respect to phase center height. Focusing method: MUSIC spectrum. Data: SHR, May 2012. All panels are normalized such that the peak value along z is 1 at each xy location.
Figure 75: Estimated surface offset with respect to phase center height. Data: SHR, May 2012.

Figure 76: top left panel: Tomographic section at 40 m below the phase center. Bottom panel: height, azimuth section (normalized). Top right panel: height, ground range section (normalized). The two vertical sections corresponds to the black lines in the top left panel. The white lines denote the upper and lower ice boundaries as estimated by the MUSIC algorithm. Data: SHR, May 2012.
Figure 77: top left panel: Tomographic section at 40 m below the phase center. Bottom panel: height, azimuth section (normalized). Top right panel: height, ground range section (normalized). The two vertical sections corresponds to the black lines in the top left panel. The white lines denote the upper and lower ice boundaries as estimated by the MUSIC algorithm. Data: SHR, May 2012.
These three figures provide interesting details about the scene, in that:

- The upper and lower ice boundary estimated by the MUSIC algorithm are in excellent agreement with the more radiometrically accurate Capon spectra, implying that MUSIC can be used as an effective tool to fix the spectrum boundaries.

- Relevant penetration changes are observed between neighbouring areas, i.e: between areas characterized by similar vertical resolution. This implies that the tomographic processing does provide information about the ice vertical structure, despite a vertical resolution coarser than 100 m on most part of the imaged scene.

- The resolution variation impacts mainly by producing an increase, or spread, of the apparent signal “thickness” from near to far range.

Wave penetration was firstly assessed simply by taking the difference between the upper and lower ice boundaries estimated by the MUSIC algorithm, see Figure 80 (top panel). This map is clearly related to physical properties, as a clear morphological signature is observed. Still it is also evident a strong correlation with resolution, which is reported in the middle panel to facilitate the comparison. This result is easily understood as a coarse resolution corresponds to a poor sensitivity with respect to penetration, which makes the estimator prone to interpreting each minimal coherence drop in term of penetration.

Figure 79 reports a few histograms relative to relative to results obtained by considering areas where resolution is lower than 50, 70, and 250 m. The interesting feature in these graphs is that in all cases a
bimodal distribution is observed, constituted by a peak at 0 m (i.e.: no penetration) and another that moves from about 40 to 65 m as resolution gets coarser. This suggests that results can be de-biased by calibrating the penetration estimates in areas where resolution is finer, and then correcting the other areas using some function that accounts for the local resolution. It was experimentally found the function that best decorrelates penetration and resolution is obtained by dividing by the square root of the resolution. After debiasing the estimated penetration depths give rise to a bimodal distribution over the whole imaged scene, see Figure 79 and Figure 80 (bottom panel). The average penetration depth is on the order of 40 m assuming propagation in air, which scales to about 20 m considering ice propagation velocity.

Figure 79: histogram of the estimated penetration depths. The different colours are relative to results obtained by considering areas where resolution is lower than 50, 70, and 250 m. The cyan line is relative to the penetration depth as obtained after debiasing.
Figure 80: top panel: penetration depth obtained as the difference between the upper and lower ice boundaries estimated by the MUSIC algorithm; middle panel: Fourier resolution; bottom panel: debiased penetration depth. Data: SHR, May 2012.

Finally, Figure 81 reports five tomographic section with reference to the estimated surface height, as opposed to phase center height. This result appear to bring more physical information, as it manages to break down the symmetry observed w.r.t. phase center height.
Figure 81: Tomographic sections with respect to the estimated surface height. Focusing method: Capon spectrum. Data: SHR, May 2012.
7.13.2 Results from May 2012, North-East looking

The figures within this section reports results from the May data-set acquired by flying the sensor along the North-East direction.

Tomographic sections, see Figure 83, show the same morphological features observed in the complementary May data-set, notwithstanding the totally different variation of spatial resolution, see Figure 82.

In particular, the same penetration changes between neighbouring areas are observed in both data-sets, as shown in Figure 84, Figure 85, Figure 86.

The estimated penetration depth maps are also consistent with each other, see Figure 87, Figure 88, Figure 89.

Figure 82: Fourier tomography vertical resolution. Data: SHR, May 2012, North-East looking.
Figure 83: Tomographic sections with respect to phase center height. Focusing method: Capon spectrum. Data: SHR, May 2012, North-East looking.
Figure 84: Estimated surface offset with respect to phase center height. Data: SHR, May 2012, North-East looking.

Figure 85: top left panel: Tomographic section at 40 m below the phase center. Bottom panel: height, azimuth section (normalized). Top right panel: height, ground range section (normalized). The two vertical sections corresponds to the black lines in the top left panel. The white lines denote the upper and lower ice boundaries as estimated by the MUSIC algorithm. Data: SHR, May 2012, North-East looking.
Figure 86: top left panel: Tomographic section at 40 m below the phase center. Bottom panel: height, azimuth section (normalized). Top right panel: height, ground range section (normalized). The two vertical sections corresponds to the black lines in the top left panel. The white lines denote the upper and lower ice boundaries as estimated by the MUSIC algorithm. Data: SHR, May 2012, North-East looking.

Figure 87: histogram of the estimated penetration depths. The different colours are relative to results obtained by considering areas where resolution is lower than 50, 70, and 250 m. The cyan line is relative to the penetration depth as obtained after debiasing. Data: May 2012, North-East looking.
Figure 88: top panel: penetration depth obtained as the difference between the upper and lower ice boundaries estimated by the MUSIC algorithm; middle panel: Fourier resolution; bottom panel: debiased penetration depth. Data: SHR, May 2012, North-East looking..
Figure 89: Estimated penetration depths as resulting from South-West (top) and North-East (bottom) data-sets.
7.13.3 Results from June 2012

The figures within this section reports results from the June data-set. Results are globally similar to those observed for the May data-set, concerning morphological features and the estimated penetration depths, see for example Figure 91, Figure 98.

One relevant difference is observed in some areas where the backscattered power at –40 m appears to be much less than in the May case. This phenomenon can be observed in the left part of the illuminated scene, see for example Figure 91 and especially Figure 95. This finding appears to be due to the higher melt rate experienced in June than in May. Few areas were identified by the MUSIC algorithm as being associated with deeper penetration than in May, even though this phenomenon was not apparent based on the Capon spectra (see Figure 94 and Figure 97). This point is left open for further investigations.

Figure 90: Fourier tomography vertical resolution. Data: SHR, June 2012.
Figure 91: Tomographic sections with respect to phase center height. Focusing method: Capon spectrum. Data: SHR, June 2012.
Figure 92: Estimated surface offset with respect to phase center height. Data: SHR, May 2012.

Figure 93: top left panel: Tomographic section at 40 m below the phase center. Bottom panel: height, azimuth section (normalized). Top right panel: height, ground range section (normalized). The two vertical sections corresponds to the black lines in the top left panel. The white lines denote the upper and lower ice boundaries as estimated by the MUSIC algorithm. Data: SHR, June 2012.
Figure 94: top left panel: Tomographic section at 40 m below the phase center. Bottom panel: height, azimuth section (normalized). Top right panel: height, ground range section (normalized). The two vertical sections correspond to the black lines in the top left panel. The white lines denote the upper and lower ice boundaries as estimated by the MUSIC algorithm. Data: SHR, June 2012.

Figure 95: top left panel: Tomographic section at 40 m below the phase center. Bottom panel: height, azimuth section (normalized). Top right panel: height, ground range section (normalized). The two vertical sections correspond to the black lines in the top left panel. The white lines denote the upper and lower ice boundaries as estimated by the MUSIC algorithm. Data: SHR, June 2012.
vertical sections corresponds to the black lines in the top left panel. The white lines denote the upper and lower ice boundaries as estimated by the MUSIC algorithm. Data: SHR, June 2012.

Figure 96: histogram of the estimated penetration depths. The different colours are relative to results obtained by considering areas where resolution is lower than 50, 70, and 250 m. The cyan line is relative to the penetration depth as obtained after debiasing.
Penetration depth [m] - biased

Penetration depth [m] - debiased

Figure 97: top panel: penetration depth obtained as the difference between the upper and lower ice boundaries estimated by the MUSIC algorithm; middle panel: Fourier resolution; bottom panel: debiased penetration depth. Data: SHR, June 2012.
Figure 98: Tomographic sections with respect to the estimated surface height. Focusing method: Capon spectrum. Data: SHR, June 2012.
7.14 Differential analysis May/June at SHR

A differential analysis between May and June data has been carried out for SHR, in order to verify physical consistency of the expected ice motion within one month time interval between the surveys. A coarse coregistration map of the displacement has been obtained from incoherent offset tracking applied to amplitude of a May-June SLC pair, to the average amplitude of May-June stacks and to the tomographic sections corresponding to the strongest return respectively.

![Figure 99](image)

Figure 99 - Amplitude of complex coherence before coregistering (upper panel) the May/June SLC pair and amplitude coherence after coregistering (lower panel) are shown.

In Figure 99 the coherence amplitude before coregistering the SLC pair and the amplitude coherence after coregistering are shown. It can be noted how the overall coherence before coregistration tends towards zero. This is consistent with both motion of the ice mass and melting or other changes in the scene. As expected, after coregistering coherence values have overall increased. Still, high coherence values (>0.6) are attained only in some areas, consistently with the fact that coherence losses due to temporal decorrelation phenomena cannot be recovered.

In Figure 100 the displacement maps obtained are shown, smoothing with a median filter has been applied. Comparing the three panels a very good agreement can be found. The most evident feature is an almost entirely azimuthal displacement trend from right to left, i.e., according to representation geometry, from the inner part of the ice sheet towards the coast. The result is consistent with the physical direction of the ice sheet motion. The average displacement is around 14 m, consistent with the ice sheet motion velocity reported in literature (around 140 m/y).
Technical Assistance during the 2012 ICESAR Validation Campaign

Figure 100 – Displacement maps obtained from incoherent offset tracking applied to amplitude of a May-June SLC pair (upper panel), to the average amplitude of May-June stacks (middle panel) and to the tomographic sections corresponding to the strongest return (lower panel) respectively.
7.15 Subsurface motion via 3D DInSAR (synthetic data)

This section presents the concept of 3D Differential Interferometry (3D DinSAR) as a tool to map subsurface ice motion. The analysis is carried out based on synthetic data, as the shallow penetration observed at SHR would not enable to distinguish different motions within the ice layer based on the available vertical resolution.

Traditional (2D) SAR imagery provides sensitivity to surface motion, which can be measured with great accuracy by taking the interferometric phase between two SAR images gathered at different times [27]. Phase measurements can be done on every slant range, azimuth location, enabling the reconstruction of 2D motions [27]. This concept can be extended straightforwardly to 3D SAR imagery, i.e.: tomographic products, resulting in the possibility to map 3D motions by taking the phase difference between two SAR cubes (i.e.: x,y,z focused products) gathered at different times.

The feasibility of this kind of measurement requires that scattering sources are present at a depth larger than the vertical resolution provided by the available baseline set.

An example of this analysis based on synthetic data was produced by simulating a scenario where tomographic acquisitions are gathered at two different times over a moving ice volume as thick as 1000 m. System parameters and geometry have been fixed so as to simulate POLARIS acquisitions. In particular, it is assumed that 10 quadruples per acquisition date are available. Results are shown Figure 101. The top panel of this figure reports an intensity section (ground range, depths), whereas the middle and bottom panel show the phase difference between the two dates, corresponding to the cases of a uniform ice motion and that where there is a depth gradient of one meter between the top and bottom layers. Comparing the two panels it is immediate to see that this set-up would provide great sensitivity to different kinds of subsurface motions.
Figure 101: Top panel: focused intensity in the ground range, depth plane. Middle panel: Interferometric phase between two acquisitions in case of uniform displacement of the whole ice layer. Bottom panel: Interferometric phase between two acquisitions in case of a vertical gradient in motion of the ice layer.
7 Conclusions

In the frame of IceSAR-2012 SAR data have been acquired in Greenland with the airborne POLARIS radar in order to assess P-band radiometric, polarimetric, interferometric, and tomographic signatures and to generate prototype ice motion and ice subsurface structure products in support of the Biomass candidate mission. Campaigns over the K-transect in West Greenland were conducted in April, May, and June. Reference GPS data and other in-situ data were acquired throughout the campaign period. Subsequently, the tomographic POLARIS data have been level-0 processed by DTU and handed over to PoliMi for tomographic processing and analysis, while all other POLARIS data have been level-1 processed, calibrated, and used for signature analysis and ice velocity measurements.

Along most of the K-transect, the backscatter coefficient is low, especially in April and May, where it is about -20 dB. The backscatter coefficient is higher (about -10 dB) at SHR and S10, which could be due to the abundant surface features at SHR and ice inclusions in the firn at S10. In between, the ice might have a lower backscatter because of a higher homogeneity of the soaked ice facies.

The co-pol ratio is close to 0 dB, and the cross-pol ratio is about -10 dB in near rang and -6 dB in far range. At SHR, however, the cross-pol ratio is locally somewhat higher, presumably because of the very rough surfaces.

The coherence depends very much on $k_z$, and the higher the elevation the more the coherence decreases with $k_z$. This is explained by deeper penetration at higher elevations, where the ice is colder / more dry and surface melt and percolation is less pronounced. The incidence angle dependence also decreases with the elevation, presumably because the surface to volume scattering ratio decreases with elevation.

At S10 coherence is preserved over a temporal baseline of at least 51 days, but elsewhere the June data are not coherent with the April and May data. The environmental effect seems to be more important than the length of the temporal baseline.

Two-dimensional ice velocities have been measured using offset tracking techniques along the entire K-transect and over the SHR site in the ablation zone and the S10 site in the percolation zone. At SHR, intensity offset tracking provides ice displacements in good agreement with the GPS measurements, while complex offset tracking is not successful when June data are involved. The failure of complex offset tracking at SHR is explained by the small windows and loss of coherence in June where half a meter of the ice surface had melted away. At S10, ice displacements measured with intensity offset tracking and complex offset tracking are reasonably consistent with the GPS data. Along the K-transect, however, the coverage of successful ice displacement measurements is very low when June data are involved. This is not fully understood in view of the fact that intensity offset tracking works with June data at SHR, but the ice may simply be different at S10, as suggested by its higher backscatter coefficient.

DInSAR has only been applied to data from SHR and S10, where orthogonal tracks were flown in order to have maximum displacements in the range direction. At SHR, the coherence is insufficient for DInSAR when May or June data are involved. At S10, however, the coherence is sufficient for high-quality interferometric fringes, and DInSAR provides ice displacements in good agreement with the in situ GPS measurements. This applies to temporal baselines up to at least 51 days and data acquired as late as June.

When the resolution of the POLARIS data is degraded to that of Biomass, offset tracking does no longer work at SHR because the ice features can no longer be resolved, and no distinct cross-correlation peak results. At S10, offset tracking is still successful because here the cross-correlation peak as resulting from the speckle pattern. When applied to simulated Biomass data, DInSAR fails at SHR because of lack of coherence, while it is successful at S10 and provide results that are very consistent with the in situ GPS data.
The IceSAR campaign has included repeat pass tomographic acquisitions flown in May and June 2012. Such acquisitions were planned so as to guarantee unambiguous imaging even in the case of scattering sources located several hundreds of meters below the ice/air interface. To this aim it was decided to operate POLARIS so as to acquire four phase centers simultaneously (quadruples). This choice allows for a vertical resolution on the order of 500-800 m by focusing single pass data. In order to ensure coherence between any two quadruples it was decided to overlap one of the four antennas from each pass, that is to let the distance between two passes be on the order of 1 m or less, less than the expected POLARIS orbital tube under perturbed conditions. Accordingly, the decision was made to repeat the same flight lines by flying along an oval-like racetrack. This choice would: i) maximize the acquisition time with respect to the overall flight time; ii) provide two independent experiments for cross-validation purposes; iii) provide unambiguous imaging in case of significant wave penetration.

Though, no significant penetration phenomenon was observed in the analyzed data-sets, including SHR data from May and June and S10 data. This feature made it a difficult task to infer information about the ice vertical structure, since the vertical resolution resulting from the available baseline set largely exceeds 100 m on most part of the imaged scenes. As a result, tomographic analyses were carried out based on super-resolution methods, in order to solve structural details at a scale much finer than the available vertical resolution.

Tomographic analyses revealed that:

- Relevant penetration changes are observed between neighbouring areas, i.e: between areas characterized by similar vertical resolution.
- Relevant penetration changes are observed at the same locations in data acquired with opposite looking directions or at different times (May, June).
- Differences are visible between tomographic profiles corresponding to different polarizations available at S10, in that HV scattering appears to be located more in depth than HH scattering. This made it possible to process S10 data using Algebraic Synthesis technique to decompose the data into two scattering mechanisms, which turned out to be associated to surface scattering plus scattering from the sub-surface.

These findings show that super-resolution tomographic processing has provided information about the ice vertical structure, despite a vertical resolution largely coarser than 100 m on most part of the imaged scene.

A quantitative assessment of the effective depth of scattering contributions was provided by employing further spectral estimation techniques to find the upper and bottom layer of the scattering volume.

The estimated penetration depth was found to give rise to a bimodal distribution over the whole imaged scene, corresponding to areas with no penetration and areas with an average penetration depth on the order of 40 m assuming propagation in air, which scales to about 20 m considering ice propagation velocity. Results from different lookings and different acquisition times were found in good agreement with each other.

Polarimetric tomographic analysis revealed a deeper penetration at S10 (almost 100 m in air, which scales down to 50-60 m in ice), consistently with the fact that S10 is found at the percolation zone.

No further details about the ice vertical structure could be retrieved given the available vertical resolution. In particular, it was not possible to clearly assess whether the observed contributions from beneath the ice/air interface are associated with generic volume scattering (similar to forest scattering), or if they are characterized by some relevant polarimetric or structural signature. Also, the available resolution hindered the investigation of subsurface motions, resulting in the May/June differential analysis at SHR to be limited at surface level.

These analyses would be enabled at the investigated sites by tomographic and polarimetric data characterized by a vertical resolution on the order of 15-20 m (in air), similarly to the TropiSAR campaign.
8 References


Technical Assistance during the 2012 ICESAR Validation Campaign


[38] I.M., A. Negrete, T. Scambos, T. Haran, in prep, “A high-resolution elevation model for the Greenland Ice Sheet from combined stereoscopic and photoclinometric data”


[40] A.W. Doerry and B. C. Brock, "Radar Cross Section of Triangular Trihedral Reflector with Extended Bottom Plate", Sandia National Laboratories, p.21-22


Additional airborne activity during the IceSAR2012 campaign

ESA Contract No. 4000106112/12/NL/FK

Ulrik Nielsen, Technical University of Denmark
Anders Kusk, Technical University of Denmark
Jørgen Dall, Technical University of Denmark

October 2014
Version 1
Abstract:

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: Ulrik Nielsen, Anders Kusk, Jørgen Dall

** NAME OF ESA STUDY MANAGER**

** ESA BUDGET HEADING**
# Table of contents

1 Introduction ......................................................................................................................... 4  
2 Data acquisition .................................................................................................................. 4  
  2.1 Radar system and observation modes ........................................................................... 4  
  2.2 Flights and acquisitions ............................................................................................... 5  
  2.3 In-situ GPS measurements ......................................................................................... 7  
3 Data overview .................................................................................................................... 8  
  3.1 Tomography Level 0c data from Greenland ................................................................. 8  
  3.2 Level 1c SAR data ....................................................................................................... 8  
  3.3 Level 2 interferometry ................................................................................................. 8  
    3.3.1 Level 2 data format ............................................................................................ 9  
4 Pre-processing ................................................................................................................... 11  
  4.1 Digital Elevation Model .............................................................................................. 11  
  4.2 Level-1 processing, SAR Focusing ............................................................................. 14  
5 Level-2 Processing, Interferometry ...................................................................................... 15  
  5.1 Displacement Estimation ............................................................................................ 16  
  5.2 Environmental Effects ............................................................................................... 17  
6 Summery .......................................................................................................................... 23  
7 References ......................................................................................................................... 24
1 Introduction

The IceSAR 2012 campaign was carried out in support of the Biomass Earth Explorer mission. The secondary objectives suggested for Biomass include velocity and structure of glaciers and ice sheets.

The increased penetration at P-band improves the ability to map sub-surface ice features and to quantify the near-surface ice extinction (or the equivalent penetration depth). The extinction of the electromagnetic field with depth is related to geophysical parameters of glaciological interest. An unambiguous relationship, however, does not exist, because the extinction depends on several parameters, e.g. grain size, firn density, ice inclusions, ice temperature, and water contents [1]. The penetration depth has also an impact on the temporal decorrelation, as the influence of near-surface change processes reduces with increasing penetration depth. Decorrelation is important when ice velocities are measured with differential interferometry (DInSAR) or speckle tracking.

The objective of the “additional airborne activity during the IceSAR 2012 campaign” is two-fold:

• Acquisition and pre-processing of tomographic P-band SAR from Greenland.
• Acquisition, processing, and analysis of P-band DInSAR data from Langjökull, Iceland.

Both data sets were acquired in June 2012 with the SAR configuration of the POLARIS radar [2].

Originally, tomographic POLARIS data should have been acquired over the SHR site in April and May 2012, but the April data acquisition failed and instead a June acquisition was added to an already planned DInSAR campaign. Based on data processed to level 0c by DTU Space, Politecnico di Milano (PoliMi) has undertaken the tomographic processing and analysis.

In June 2012 the UAVSAR of the Jet Propulsion Laboratory (JPL) acquired L-band DInSAR data in Iceland as part of a study carried out by California Institute of Technology (Caltech). One of the primary goals of the Caltech study is a “detailed analysis of the capabilities and limitations of using repeat pass radar to measure ice flow” (Mark Simons, personal communication, 2012). Mark Simons and his Caltech team have “found an interesting interferometric phase delay not caused by deformation that is visible when we compare HH and VV interferograms (from data taken simultaneously).” Mark thinks that “temporal changes in dielectric properties is causing apparent but erroneous velocities” and he assumes that “the longer the wavelength, the more of an issue this becomes.” Hence it is of interest to observe the phenomenon at P-band. Penetration into ice can cause a significant interferometric phase change [3][4], and the combination of volume scattering and surface scattering implies a polarization dependency.

2 Data acquisition

2.1 Radar system and observation modes

The POLARIS radar can operate in either sounding mode, with the antenna beam pointing to nadir, or in SAR mode, with the beam steered to the right or left of the flight track. Independent of the beam direction, the radar can be configured to work in either polarimetric (1 aperture, full polarimetry) or multi-aperture (4 apertures, single-polarization) configuration. The beam direction can be changed manually in flight, whereas switching between polarimetric/multi-aperture configurations must be done on the ground.

In SAR mode the smaller of the two POLARIS antennas is used, and the flight altitude is nominally 4 km above the surface, although this may be reduced in areas of high surface elevation due to air traffic restrictions. The range of look angles covered is from approximately 20° to 45°, corresponding to a swath of 2.5 km in ground range at the nominal altitude.
Tomography data in Greenland were acquired in multi-aperture SAR mode at HH polarization, and for all Iceland flights all data were acquired in the polarimetric SAR mode.

The radar was flown on the Norlandair TF-POF Twin Otter aircraft on which POLARIS has been certified and flown in the past. In order to maintain and reproduce stable flight tracks, a system called EMAP4, developed at the DTU Space Geodynamics division, was used. The system uses GPS to calculate and present in real-time to the pilots the current deviations from a desired track, as well as steering information to return to the track. Furthermore, when operating at the high altitude required in the SAR mode, the aircraft’s own radar altimeter cannot be used, and the EMAP4 program displays the current estimated altitude over the terrain, based on GPS altitude and the GTOPO30 digital elevation model (DEM). This feature was employed on the longer data acquisitions where the surface elevation changed significantly (e.g. along the K-transect). For acquisitions of smaller areas (e.g. the tomography at SHR), a constant GPS altitude was employed.

Navigation data were acquired with three Javad GPS receivers, providing 1 Hz kinematic GPS data, and a Honeywell H764G EGI (Inertial Navigation Unit with embedded GPS) providing 50 Hz inertial data. On the two first Iceland flights, which returned to Akureyri, a GPS reference station was placed on the ground in Akureyri to support kinematic processing. On the third flight, which continued on to Greenland, no reference stations were available, so these GPS data were processed using PPP (Precise Point Positioning).

2.2 Flights and acquisitions

The June tomography flight in Greenland has been addressed in detail in [5].

The Iceland flights were carried out at the beginning of the third IceSAR 2012 campaign in June. Two morning flights and one afternoon flight were carried out, see Table 2.1, all in fully polarimetric SAR mode. These covered two scenes, EWwest and JSXJSN, which were defined to cover the area of interest, shown in Figure 2.1.

Table 2.1 Overview of flight days in Iceland during the IceSAR-2012 campaign. AEY=Akureyri, KEF=Keflavik, SFJ=Kangerlussuaq

<table>
<thead>
<tr>
<th>Date</th>
<th>Objective/Description</th>
<th>Modes used</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>June 8</td>
<td>SAR imaging of Langjökull at 06:00</td>
<td>SAR Quad-Pol</td>
<td>AEY-Langjökull-AEY</td>
</tr>
<tr>
<td>June 8</td>
<td>SAR imaging of Langjökull at 18:00</td>
<td>SAR Quad-Pol</td>
<td>AEY-Langjökull-AEY</td>
</tr>
<tr>
<td>June 9</td>
<td>SAR imaging of Langjökull at 06:00</td>
<td>SAR Quad-Pol</td>
<td>AEY-Langjökull-KEF-SFJ</td>
</tr>
</tbody>
</table>

On each of the two first flights, the east-west going scene (EWwest) was mapped twice, once on the outbound leg and once on the return leg to Akureyri (requiring a recabling to change antenna look-direction), whereas the third flight continued to Kangerlussuaq via Keflavik, so only one east-west acquisition was made on that flight. The south- north scene (JSXJSN) was mapped once on each flight. An overview of all the acquisitions is presented in Figure 2.2. All times are UTC, which coincides with local time in Iceland.
Additional airborne activity during the IceSAR2012 campaign

Figure 2.1 Imaged scenes at the Langjökull Glacier, Iceland, shown as radar magnitude image overlays on a Google Earth background.

Figure 2.2 Acquisitions of the Langjökull glacier. Blue indicates the EWwest scene, red indicates the JXSJXN scene.
2.3 In-situ GPS measurements

Prior to the campaign, Caltech deployed ten GPS receivers on Langjökull. Subsequently, Caltech has processed the GPS data in kinematic mode using the GNSS-Inferred Positioning System and Orbit Analysis Simulation Software package (GIPSY) developed by JPL. The sampling spacing of the processed data is 20 min. An overview of the GPS receivers in relation to the radar scenes is seen in Figure 2.3.

![Figure 2.3 Location of GPS receivers.](image)

Five receivers are present in each scene: (L3, L4, M1, M2, M5) for the EWwest site and (L3, L4, L5, M3, M4) for the JXJSN site. However, due to a data gap at M2, no data are available from this receiver during the acquisition period of the radar data.

Analysis of the GPS data shows sinusoidal variations with a period of approximately 12.3 hours, as seen in Figure 2.4. The length of the period suggests solid earth tide as the explaining mechanism. The variations are most pronounced in the vertical direction as expected for earth tide. When comparing HH and VV interferograms from data taken simultaneously, these variations do not have any impact since different polarizations are influenced in the same way.
3 Data overview

3.1 Tomography Level 0c data from Greenland
The tomography data from Greenland were delivered along with the other IceSAR 2012 data and are in the format described in [5], 3.2.3. As requested by PoliMi, level 0c data were delivered, as the SAR focusing should not be applied prior to tomographic analysis. The inventory is in [6].

3.2 Level 1c SAR data
Fully polarimetric (HH, VV, HV and VH) focused SAR data for all eight acquisitions (see Figure 2.2), are delivered in the POLARIS SAR Level 1 NetCDF format described in [5], 3.2.3. There are thus 32 SAR files (4 polarizations per scene, 8 scenes), as well as the two grid files (EWwest and JXSJXN). File naming conventions are described in [7]. Basically, the naming is

\[ p<YYMMDD>_m<HHMMSS>_1c_<Scene_name>_f<RxPol><TxPol>0.nc \]

where \(<YYMMDD>-<HHMMSS>\) is the approximate start time of the acquisition, \(<Scene name>\) is either EWwest or JXSJXN, and RxPol/TxPol can be either “h” or “v”, for horizontal and vertical, respectively. This information is of course also available within the NetCDF file attributes.

For Iceland data, level 0 is not delivered in accordance with ESA’s request for quotation and DTU’s proposal.

3.3 Level 2 interferometry
As shown in Figure 5.1 and in Section 5.1, with the given temporal baselines, the expected displacements are so small that it does not make sense to provide displacement maps. Instead,
Additional airborne activity during the
IceSAR2012 campaign

Table 3.1 NetCDF format for POLARIS interferometric product

<table>
<thead>
<tr>
<th>dimensions:</th>
</tr>
</thead>
<tbody>
<tr>
<td>c = 333</td>
</tr>
<tr>
<td>s = 1333</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>variables:</th>
</tr>
</thead>
<tbody>
<tr>
<td>double c(c)</td>
</tr>
<tr>
<td>c:units = &quot;m&quot;</td>
</tr>
<tr>
<td>c:description = &quot;ground range pixel position&quot;</td>
</tr>
<tr>
<td>double s(s)</td>
</tr>
<tr>
<td>s:units = &quot;m&quot;</td>
</tr>
<tr>
<td>s:description = &quot;along-track pixel position&quot;</td>
</tr>
<tr>
<td>float if_phase(s, c)</td>
</tr>
<tr>
<td>if_phase:description = &quot;Unwrapped interferogram phase&quot;</td>
</tr>
<tr>
<td>if_phase:range_looks = 3.</td>
</tr>
<tr>
<td>if_phase:azimuth_looks = 18.</td>
</tr>
<tr>
<td>if_phase:units = &quot;rad&quot;</td>
</tr>
<tr>
<td>float mli(s, c)</td>
</tr>
<tr>
<td>mli:description = &quot;Multilooked intensity image &lt;</td>
</tr>
<tr>
<td>mli:range_looks = 3.</td>
</tr>
<tr>
<td>mli:azimuth_looks = 18.</td>
</tr>
<tr>
<td>float if_coherence(s, c)</td>
</tr>
<tr>
<td>if_coherence:description = &quot;Interferogram coherence&quot;</td>
</tr>
<tr>
<td>if_coherence:range_looks = 3.</td>
</tr>
<tr>
<td>if_coherence:azimuth_looks = 18.</td>
</tr>
<tr>
<td>float kz(s, c)</td>
</tr>
<tr>
<td>kz:description = &quot;Phase sensitivity to height variation&quot;</td>
</tr>
<tr>
<td>kz:units = &quot;rad/m&quot;</td>
</tr>
<tr>
<td>float kx(s, c)</td>
</tr>
<tr>
<td>kx:description = &quot;Phase sensitivity to ground range displacement&quot;</td>
</tr>
<tr>
<td>kx:units = &quot;rad/m&quot;</td>
</tr>
<tr>
<td>float lat(s, c)</td>
</tr>
<tr>
<td>lat:description = &quot;WGS84 Latitude of sample&quot;</td>
</tr>
<tr>
<td>lat:units = &quot;deg&quot;</td>
</tr>
<tr>
<td>float lon(s, c)</td>
</tr>
<tr>
<td>lon:description = &quot;WGS84 Longitude of sample&quot;</td>
</tr>
<tr>
<td>lon:units = &quot;deg&quot;</td>
</tr>
<tr>
<td>float h_ell(s, c)</td>
</tr>
<tr>
<td>h_ell:description = &quot;WGS84 ellipsoid height of sample&quot;</td>
</tr>
<tr>
<td>h_ell:units = &quot;m&quot;</td>
</tr>
</tbody>
</table>

// global attributes:
:acquisition_1_radar_frequency = 435000000.
:acquisition_1_tx_pol = "h"
:acquisition_1_rx_pol = "h"
:acquisition_1_start = "2012-06-08T05:35:58Z"
:acquisition_1_stop = "2012-06-08T05:40:35Z"
:acquisition_2_radar_frequency = 435000000.
:acquisition_2_tx_pol = "h"
:acquisition_2_rx_pol = "h"
:acquisition_2_start = "2012-06-08T06:27:26Z"
:acquisition_2_stop = "2012-06-08T06:32:23Z"
interferograms are delivered, accompanied by geocoding and data necessary for interpretation. Interferograms were made for all combinations of acquisitions. For the EWwest track, 10 combinations are possible, whereas three combinations are possible for the JXSJXN acquisitions. Interferograms were generated for both HH and VV polarization, giving 26 interferograms all in all. A multilooking of 3 x 18 (range x azimuth) was carried out, the same multilook factor being used for interferogram and coherence estimation.

### 3.3.1 Level 2 data format

The level 2 data are delivered in NetCDF files, one for each interferogram pair. The naming is:

```
<filename1>-<filename2>.nc
```

where the filename1 and filename2 are the filenames of the level 1 SLC used to form the interferogram (excluding the .nc extension)

An overview of the format is given in Table 3.1 below. The multilooked interferogram phase (unwrapped) and coherence is provided in ground range geometry, i.e. $(s,c)$-coordinates, where $s$ is along-track position and $c$ is horizontal cross-track position (ground range) [8]. The grid is a subsampled version of the grid to which the level 1 data were focused. Note that the absolute interferogram phase has not been estimated, so if attempting differential interferometry, this should be accounted for. The original wrapped phase (which is used in the analysis in section 5) can be retrieved by taking the unwrapped phase modulo $2\pi$.

To aid the interpretation of the interferograms, $k_s$ and $k_c$ maps (phase sensitivity to topography and ground range displacement, respectively) are provided on the same grid. To support geocoding, also the latitude, longitude and ellipsoid height of each pixel is provided on the same grid. Finally, a multilooked intensity image is provided, formed by multilooking the product of the two image amplitudes.
4 Pre-processing

4.1 Digital Elevation Model

An accurate DEM is needed in order to focus, coregister, and geocode the data during the level 1 processing. Furthermore, a DEM is also needed to flatten interferograms with respect to topography.

Digital elevation data are provided by Center for Remote Sensing (CRS) at the University of Iceland. The data are based on surveys in 2007 and 2012.

The survey in 2007 was conducted by the British Natural Environment Research Council (NERC) for the Department of Geography at the University of Cambridge. LiDAR data covering about 60% of the glacier was acquired during the summer with a density about 0.25 points per square meter. To get full coverage of the glacier, CRS filled in the gaps by locally shifting an existing SPOT5 DEM towards the edges of the gaps. The resulting DEM with a grid spacing of 30 m is in this way covering the glacier and the surrounding topography.

Furthermore, a DEM was processed by CRS based on data acquired in 2012 with the SPOT5 system using the High-Resolution Stereoscopic (HRS) imaging instrument. The data was acquired for a specific project with the glacier as target. This means that the sensor gain was set to low values during acquisition, and this in turn makes it difficult to extract topography outside the glacier. For this reason the coverage of the produced DEM is limited to the glacier. Furthermore, the DEM has many gaps due to the presence of clouds during acquisition. CRS has filled these gaps using the 2007 DEM, vertically shifted to minimize discontinuities, resulting in a DEM covering only the glacier with a grid spacing of 30 m. The IceSAR 2012 flight tracks and the corresponding scenes of this study are covering parts of both the glacier and the surrounding topography. Therefore the coverage of the 2012 DEM is insufficient. The coverage of the 2007 DEM, on the other hand, is sufficient, but a comparison of the two DEMs shows that the glacier has retreated from 2007 to 2012, corresponding of height differences of up to 40 m at the southern tongues.

Since the radar data in this study are acquired in 2012, application of the 2007 DEM would introduce a significant error in the processing of the SAR data. Therefore, to get an accurate DEM with sufficient coverage, the 2007 and the 2012 DEMs are again merged. First, the 2012 DEM is resampled to the same UTM 27 grid with 30 m spacing as the 2007 DEM. In this way, the 2012 DEM is used to model the glacier and the 2007 DEM to model the surrounding topography, where no change has occurred. However, the non-glaciated bedrock, caused by the retreat of the glacier, is not covered by the described merging procedure. To model this zone, the point cloud measurements on which the 2012 DEM is based, was requested from CRS. The point density at the part of the zone southwest of the glacier, which intersects the radar scenes, happened to be relatively high with only a few larger gaps. The data were therefore gridded and used to model the retreat zone. The gaps were filled by interpolation. A source map of the combined DEM is shown in Figure 4.1, and a shaded relief presentation of the DEM itself in Figure 4.2.
Figure 4.1 Overview of data sources for the combined DEM. Map projection is UTM zone 27.
Figure 4.2 Shaded relief presentation of the combined DEM. Map projection is UTM zone 27.
4.2 Level-1 Processing, SAR Focusing

A time-domain backprojection SAR processor was developed for the IceSAR project. The SAR processor takes level 0c POLARIS data, acquired by either a left- or right-looking beam, and performs SAR focusing to a predefined output grid in ground range geometry. This output grid is based on the external digital elevation model described in the previous section. All acquisitions of the same site (e.g. EWwest) were focused to the same grid, so that, assuming perfect navigation data, focused data will already be coregistered and in ground range geometry. The focused data are radiometrically calibrated so that the amplitude of the focused image is an estimate of the radar backscatter coefficient $\sigma^0$. The focusing is described in detail in [9] All Iceland data were focused to 3 m x 1 m grid spacing (range x azimuth).
5 Level-2 Processing, Interferometry

Intensity based offset tracking is used to assess the need for coregistration. Displacement maps based on the two morning acquisitions (June 8, 5AM and 6AM) at the EWwest site are shown in Figure 5.1. The resolution of the POLARIS SAR data is about 4 m by 1 m (ground range by azimuth) [10], so the figure shows that the displacements in both range and azimuth are at sub-meter/pixel level, and coregistration is therefore not performed in order to simplify the interpretation when different interferograms are compared. The interferograms are flattened with respect to the DEM, and multi-looked with a factor of 3 in range and 18 in azimuth. The interferogram based on the same two morning acquisitions are shown in Figure 5.2. It is seen to be relatively flat and not characterized by inadequate coregistration.

Figure 5.1 Displacement images from the EWwest site based on offset tracking, range (top) and azimuth (bottom). Based on the (12.06.08_05:18:12, 12.06.08_06:24:04)-acquisitions.
Additional airborne activity during the IceSAR2012 campaign

5.1 Displacement Estimation

The feasibility of estimating ice surface displacements based on interferometry is assessed. Two analyses are conducted as detailed below: 1) the local variation within interferograms is compared with the true displacement, and 2) the variation of local estimates across all interferograms is compared with the true displacement.

The horizontal across-track displacement measured with the GPS receivers is 4.5 cm for the 24 hour baseline. The displacement is calculated as the mean of the receivers at the EWwest site. This corresponds to an interferometric phase of 24 degrees at center-swath. This value is now compared to the phase noise of the interferograms. A subimage of 41x41 pixels centered at M2 in the interferograms is considered, and the standard deviation of the interferometric phase in this subimage is calculated for each interferogram. The standard deviation estimates are averaged over all interferograms is calculated to 27 degrees, which is compatible to the signal of interest. This suggests that interferometric displacement estimation is not feasibility due to the small velocity of the ice compared to the small temporal baselines.

As an additional analysis, the interferometric phase is converted into horizontal across-track displacement. The mean displacement per 24 hours based on the subimage is calculated for each interferogram. The standard deviation of this local mean displacement across all interferograms is calculated to 2.1 m. Compared to the 4.5 cm displacement measured by GPS, this further show that the displacement cannot be retrieved by interferometry for the given scenario.

Figure 5.2 Interferogram based on the (12.06.08 05:18:12, 12.06.08 06:24:04)-acquisitions.
5.2 Environmental Effects

All interferograms at the EWwest site are presented in a 5x5 matrix structure in Figure 5.4. The coherence of the HH polarisation is found in the upper triangular part of the matrix while the difference between the HH and VV interferograms are found in the lower triangular part. The same structure is used in Figure 5.5, but with the $k_z$-map in the lower triangular part, i.e. the vertical interferometric wavenumber, which represents phase sensitivity with respect to height variations. Small $k_z$-values indicate a small spatial baseline and vice versa.

The interferograms can be divided into three groups based on the temporal baseline: 1 hour, 12 hour, and 24 hour. Relatively high coherence is observed for the 1 hour baselines, which is expected. The coherence drops when the baseline is increased to 12 hours. However, for the 24 hour baselines, the coherence increases compared to the 12 hour. No correlation with variations in the spatial baseline is observed when comparing with the $k_z$-maps, which therefore suggests an underlying environmental mechanism as the explaining factor.

A region at the bottom right part of the site is seen to have low coherence even at the 1 hour baselines. The region is located at a high elevation compared to the surroundings, as seen from the DEM in Figure 5.3.

With respect to the interferometric difference images, no pronounced correlation with the temporal baseline is observed. Phase noise is less pronounced for the 1 hour baseline, but no polarimetric patterns are found to match the observations in the coherence.

Two regions with features are defined in Figure 5.2 and enlarged in Figure 5.6 and Figure 5.7. In both enlargements the time-of-day dependency of the coherence is pronounced while all the HH-VV interferograms are very similar.

Corresponding results for the JSXJSN site are shown in Figure 5.8 and Figure 5.9 where the results are seen to be in agreement with those of the EWwest.

![Figure 5.3 DEM of the EWwest site.](image-url)
Figure 5.4 Coherence of HH polarisation (upper triangular part) and difference between HH and VV interferograms (lower triangular part) at the EWwest site. The homogeneous blue areas are not covered due to a large range offset used for the first of the two Day1 PM acquisitions.
Additional airborne activity during the IceSAR2012 campaign

Figure 5.5 Coherence of HH polarisation (upper triangular part) and $k_x$-map (lower triangular part) at the EWwest site.
Additional airborne activity during the IceSAR2012 campaign.

Figure 5.6 Enlargement of region A in Figure 5.2.
Additional airborne activity during the IceSAR2012 campaign

Figure 5.7 Enlargement of region B in Figure 5.2.
Additional airborne activity during the IceSAR2012 campaign

Figure 5.8 Coherence of HH polarisation (upper triangular part) and difference between HH and VV interferograms (lower triangular part) at the JSXJSN site.

Figure 5.9 Coherence of HH polarisation (upper triangular part) and $k_x$-map (lower triangular part) at the JSXJSN site.
6 Summery

In June 2012 DTU acquired tomographic POLARIS SAR data over the SHR site in Greenland. In July 2012, upon level 0c processing, the data were delivered to ESA and to PoliMi. The results are documented in [5].

In June 2012 DTU also acquired POLARIS SAR data over the Langjökull glacier in Iceland. In order to focus, coregister and geocode the data, a DEM was needed, and it was generated by properly combining DEMs from 2007 and 2012, provided by CRS at the University of Iceland. In this way, the best properties of both DEMs are obtained, i.e. the good coverage and the most recent elevations, respectively. Upon level 0 and level 1 processing, the coregistration was checked, and interferograms were formed from all possible data combinations thereby obtaining temporal baselines of about 1 hour, 12 hours, and 24 hours. Also the k\, maps were generated, but large k\, values do not seem to explain any of the features observed in the interferograms and coherence maps.

The displacements are measured with ten ground-based GPS receivers. The measured displacements are close to zero because the glacier moves slowly and the temporal baselines are small. The interferometric phase equivalent to the GPS displacement has been computed and it turns out to be comparable to the phase noise of the actual interferograms. Furthermore, the standard deviation of the local velocity across all interferograms is much larger than the true velocity measured by GPS. This shows that the small displacements cannot be retrieved by means of interferometry, and consequently no displacement data product is delivered.

The coherence drops when the baseline is increased from 1 hour to 12 hours, but coherence is partly restored when the baseline is further increased to 24 hour. This suggests an environmental mechanism: The dielectric properties depend on the ice temperature and the contents of liquid water, and the ice is supposed to be more cold and dry at 6 AM than at 6 PM. Hence, the 1 hour interferograms and 24 hours interferograms combine two data sets acquired under similar environmental conditions, while the environmental difference is maximized in the 12 hours interferograms.

Naturally, the phase noise of the interferograms reflects the coherence level, but otherwise no clear and systematic characteristics are seen in the interferograms.

The HH and VV interferograms are very similar, i.e. the difference between the interferometric phases at HH and VV polarization is small. Unlike the displacement estimates, the differential interferograms are not affected by baseline errors, because such errors have the same impact on the HH and VV interferograms. On the other hand, the Caltech observations suggest that the dielectric changes associated with the temporal/environmental changes do not have the same impact on the HH and VV interferograms. However such a difference is not clearly detectable in the differential interferograms generated from the P-band POLARIS data.
7 References


# Table of Contents

1 INTRODUCTION .......................................................................................................................... 4

2 INTRODUCTION .......................................................................................................................... 5
   2.1 OPERATING PRINCIPLE ............................................................................................................. 5
   2.2 SENSOR CONFIGURATIONS ....................................................................................................... 5
   2.3 OPERATING MODES .................................................................................................................. 6
   2.4 DATA ACQUISITION .................................................................................................................. 6
   2.5 NAVIGATION DATA ACQUISITION ......................................................................................... 7

3 DATA PROCESSING ..................................................................................................................... 8
   3.1 SCENE EXTRACTION ............................................................................................................... 8
   3.2 LEVEL 0C PROCESSING ......................................................................................................... 8
   3.3 LEVEL 1C PROCESSING .......................................................................................................... 8
   3.4 FILENAME CONVENTIONS ..................................................................................................... 8

4 USING POLARIS DATA ............................................................................................................... 11
   4.1 MATLAB TOOLS .................................................................................................................... 11
   4.2 LEVEL 0C DATA LAYOUT ...................................................................................................... 11
   4.3 LEVEL 1C DATA LAYOUT ...................................................................................................... 13
   4.4 CALIBRATION ........................................................................................................................ 13
   4.5 EGI/GPS NAVIGATION DATA ............................................................................................... 15
   4.6 RADAR AND PROCESSING PARAMETERS FILE (CFG.M) .................................................... 16

APPENDIX A POLARIS SOUNDING MODES .................................................................................. 18
APPENDIX B MATLAB SCRIPT FOR SOUNDING DATA INGESTION ......................................... 20
APPENDIX C MATLAB SCRIPT FOR ANNOTATION INGESTION ............................................... 21
APPENDIX D MATLAB SCRIPT FOR NAV DATA INGESTION ..................................................... 22
1 Introduction

This document is provided as an aid for users of POLARIS radar ice sounding data. Section 2 describes the sensor configurations, modes of operation, and the data acquisition. Section 3 briefly describes the processing carried out on the data, as well as the filename conventions used for the output files of the POLARIS processor. Section 4 describes how to work with the POLARIS data using MATLAB. In Appendix A, the POLARIS operational modes are listed in tabular form, and Appendix B, Appendix C, and Appendix D contains MATLAB source codes, which can be used to read POLARIS sounding data, annotation, and navigation data.
2 Introduction

2.1 Operating principle

POLARIS is an airborne radar ice sounder. In operation, it transmits pulses at a frequency of 435 MHz and receives echoes from the ice sheet below the aircraft. The sensor can operate in a variety of configurations and modes, described in the following.

2.2 Sensor configurations

The POLARIS sensor can be flown with one of two antennas:

1. A small, four-element antenna, with H- and V-polarization ports available for each element.
2. A large, eight-element antenna, where the elements are combined pairwise inside the antenna structure, resulting in four “effective” elements, all with access to both H- and V-polarization.

H polarization direction is defined as the along-track direction (flight direction), V as the across-track direction.

Furthermore, the sensor can be configured on ground in one of two modes, independent of the antenna used:

1. Polarimetric mode, in which the sensor can transmit and receive both polarizations. Two subapertures, A and B, can be received with this configuration, A being the central elements, and B being the outer elements. Often, however, subapertures A and B are combined online.
2. Four-channel clutter-suppression mode (CS4), which allows reception on four subapertures, designated 1,2,3,4, going from left to right. In this mode, polarimetry is not available, so a single polarization is used for both transmit and receive, VV being typical.

A Twin Otter installation of the four-element POLARIS antenna is shown on Figure 1.
2.3 Operating modes

The POLARIS sensor can operate in a variety of modes:

- **Basic mode**
  - In basic mode, the same pulse length, bandwidth, receiver gain, and range window is employed for each transmitted pulse. This mode may be combined with polarimetry and/or clutter suppression.

- **Shallow/Deep sounding (SDS)**
  - In SDS modes, the sensor alternately transmits short, high-bandwidth pulses and long, low bandwidth pulses. The short pulses are designed to sound the surface and the upper part of the ice sheet, whereas the long pulses are designed to sound the bedrock and lower part of the ice. Different receiver gains and range windows are employed for the shallow and deep channels; the range windows are usually designed to overlap.

- **Polarimetry**
  - In polarimetric modes, alternating polarizations are transmitted to obtain polarimetric signatures of the ice. In Quad-polarization mode, both H and V polarizations are received for each transmitted polarization (i.e. HH, HV, VH, and VV are available). In DualCo mode, only the co-polar signals (HH and VV) are recorded.

- **Clutter suppression (CS)**
  - In CS modes, several antenna subapertures are used on receive, whereas transmission is still on all antenna elements. For CS2 modes, two subapertures (designated A and B) are received: A refers to the central elements, whereas B refers to the outer elements. For CS4 modes, the antenna elements are divided into four equally large subapertures, designated 1, 2, 3, 4, going from left to right. The small POLARIS antenna has 4 elements, so in this case, the CS4 subapertures are one element each; the large antenna has 8 elements combined pairwise inside the antenna structure, so here, the CS4 subapertures each consist of two elements.

These operating modes can be combined, with Quad_SDS (quad-pol, shallow/deep sounding) being the typical mode. However, there are some restrictions due to the POLARIS hardware:

- Polarimetry and CS4 modes cannot be combined – a single transmit/receive polarization is always used in CS4-modes, typically VV.
- CS2, quad-pol and SDS cannot all be employed at the same time. However, DualCo_SDS_CS2 mode or Quad_CS2 mode can be used.

An overview of the different operating modes is given in Appendix A.

2.4 Data acquisition

During a data acquisition flight, the POLARIS sensor is typically turned on and off several times in order to change operational modes and perform calibrations in between acquisitions. This means the data from a specific flight are split into a number of “maps”, each map containing a contiguous stream of sounding data acquired with fixed operational mode and sounding parameters.

A transmit pulse repetition frequency (PRF) of up to 20 kHz can be employed, 10 kHz being typical for a Quad_SDS acquisition. Depending on the operating mode, a transmit sequence of up to 4 steps is cyclically repeated. For each step, the transmit polarization, pulse length, and bandwidth can be varied, in order to support polarimetry and shallow/deep sounding modes mentioned. Up to four channels can be received in parallel at each step of the sequence, and different receiver gains and range windows can
be used for each received channel. Each received channel is identified by a depth range (shallow/deep/full), receive polarization (H/V), transmit polarization (H/V) and the subaperture used on receive (1, 2, 3, 4, A, B, or 0, 0 indicating all four apertures combined on receive). In Table 1, an example of an operational mode (the Quad_SDS mode) is shown, with four transmit sequence steps, and eight received channels. It can be seen that the transmit polarization changes for every pulse, whereas the depth range changes on every second step. This means that channels with different transmit polarizations are offset by $1/\text{PRF}_{\text{TX}}$, and channels with different depth ranges are offset by $2/\text{PRF}_{\text{TX}}$. Channels with different polarization and depth range are separated by $3/\text{PRF}_{\text{TX}}$. This is a minor offset with the high transmit PRF typically employed, and for level 1c products, these offsets are corrected, so that all channels are coregistered.

Table 1 Quad_SDS mode data acquisition sequence with 4 transmit steps

<table>
<thead>
<tr>
<th>Stored Channel</th>
<th>dhh0</th>
<th>dvh0</th>
<th>dhv0</th>
<th>dvv0</th>
<th>shh0</th>
<th>svh0</th>
<th>shv0</th>
<th>svv0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rx Pol</td>
<td>H</td>
<td>V</td>
<td>H</td>
<td>V</td>
<td>H</td>
<td>V</td>
<td>H</td>
<td>V</td>
</tr>
<tr>
<td>Rx Gain</td>
<td>High</td>
<td>High</td>
<td>High</td>
<td>High</td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td>Rx Delay</td>
<td>Large</td>
<td>Large</td>
<td>Large</td>
<td>Large</td>
<td>Small</td>
<td>Small</td>
<td>Small</td>
<td>Small</td>
</tr>
<tr>
<td>Tx Pulse</td>
<td>Long/Long BW</td>
<td>Long/Long BW</td>
<td>Short/High BW</td>
<td>Short/High BW</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tx Pol</td>
<td>H</td>
<td>V</td>
<td>H</td>
<td>V</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

In order to reduce the data storage requirements, each received channel is coherently pre-summed online (i.e. several echoes are added before storage to hard disk), so the PRF of the stored data is reduced significantly compared to the transmitted PRF. The stored data PRF, $\text{PRF}_{\text{RX}}$, is

$$\text{PRF}_{\text{RX}} = \frac{\text{PRF}_{\text{TX}}}{\text{L}_{\text{TX}} \cdot N_{\text{PS}}}$$

where $\text{PRF}_{\text{TX}}$ is the transmit PRF, $\text{L}_{\text{TX}}$ is the transmit sequence length, and $N_{\text{PS}}$ is the presuming factor. In POLARIS annotation files, the parameter named $\text{PRF}$ is always the stored data PRF for the given data file, whereas the transmit PRF is denoted $\text{TxPRF}$.

2.5 Navigation data acquisition

The POLARIS system utilizes a Honeywell H764G EGI for collecting navigation data. This is a combined inertial/GPS system, the EGI acronym meaning Embedded GPS in an Inertial Navigation System. The GPS in the EGI does not provide differential/kinematic GPS solutions, so absolute precision accuracy is that of standard non-differential GPS, i.e. several meters. When available, more accurate kinematic GPS data can be used to refine the POLARIS navigation data.
3 Data processing

3.1 Scene extraction
In the offline processing, maps are further split into one or more segments called “scenes”. A scene represents a geographical site, and can extend over part of a map, an entire map and even several maps. The latter is a special case, and only arises when an unplanned stop of the radar during an acquisition is necessary, i.e. due to problems with the equipment. In this case there will be a discontinuity between files with the same scene name but different map numbers. If the same scene is overflown several times by design (e.g. in order to use different sounding modes) different scene names will be used.

3.2 Level 0c processing
The Level 0c processor does the following:

- Relative calibration (gain, amplitude, phase and spectral equalization) of the received channels using data from the internal calibration loop in the radar.
- Detection and blanking of saturated samples (caused by partial surface echoes) in the deep channel data.
- Pulse compression of the received echoes, with weighting for sidelobe suppression.
- Interpolation of navigation data to coincide with radar echo timestamps.

3.3 Level 1c processing
The level 1c processor takes level 0c data as input and does the following:

- Synthetic aperture (SAR) focusing in the along-track direction, in order to increase along-track resolution and decrease along-track surface clutter.
- Resampling from a temporal grid to a spatial, geo-coded grid, accounting for ice refraction using a constant index of refraction.
- Along-track coregistration of polarimetric and shallow/deep channels.

3.4 Filename conventions
POLARIS data are organized by map date, map number, and scene name, and all POLARIS sounding data files are named according to the following scheme (see also Figure 2):

```
p<Map Date>_m<Map Number>_s(Scene name)_<Level>_c<Channel>
```

where

- `<Map Date>` is the date at the start of the map in YYMMDD format, e.g. 080514 for May 14th, 2008
- `<Map Number>` is defined as the approximate UTC time of day at the start of the map, in <HHMMSS> format, e.g. 183228.
- `<Scene name>` is a descriptive name for the extracted scene, typically based on waypoints or geographical site names.
<Level>
is the processing level applied to the data, e.g. 1c for Doppler processed, geocoded user data

<Channel>
is the receive channel specifier.

The sounding data file is a matrix of complex single-precision floating point samples, with no headers or annotation in the file itself. Several annotation files are provided for each sounding data file. They all start with the sounding data filename, followed by an underscore and the annotation identifier:

- **_cfg.m:** MATLAB-readable ASCII file containing the radar setup information, data layout and processing information. This file is necessary in order to use the sounding data file
- **_nav:** Binary file containing navigation data (position and orientation of the sensor) for each echo line in the sounding data file
- **_fvs:** ASCII file containing the (zero-based) index of the first valid sample for each line in case the processor has zeroed out samples due to surface echo saturation.
Figure 2 POLARIS sounding data filename components
4 Using POLARIS Data

4.1 MATLAB Tools
Tools for reading in POLARIS data and annotation are provided. Three functions are necessary:

- `read_polaris` for reading data and annotation, see Appendix B
- `read_cfg` for reading the data annotation file only, see Appendix C
- `read_nav` for reading the navigation data file, see Appendix D

Since sounding data files can be large (several gigabytes), the `read_nav` and `read_polaris` functions can read a subset of the data lines, specified by an offset line (0-based) and the number of lines to read. Sounding data are stored in a binary matrix in range line order, in complex IEEE single precision (32-bit) floating point, little-endian format. Complex samples are stored as two consecutive floats, real part followed by imaginary part. There are no headers in the sounding data, all auxiliary information is stored in the `_cfg.m` and `_nav` files.

4.2 Level 0c data layout
The level 0c data file layout is illustrated in Figure 3. Sampling in both range and along-track (azimuth) direction is equidistant in time, such that sample number \( k \) represents an echo delay, \( \tau \), of:

\[
\tau = RxDelay + \frac{k - 1}{F_s}
\]

where `RxDelay` is the delay of the first sample, \( F_s \) is the sampling frequency of the data file in the range direction. The number of samples in each line is given by the `Nra` parameter.

In the along-track direction, the sampling distance depends on the instantaneous horizontal aircraft velocity. This can be calculated from the navigation data by combining the East and North velocity components and dividing by the data PRF (the PRF is the along-track sampling frequency):

\[
\Delta_x = \frac{\sqrt{u_e^2 + u_n^2}}{PRF}
\]

Channels in the same dataset with different transmit polarizations or depth ranges are not completely co-registered along-track, as they are offset in time by up to \( 3/PRF_{rx} \). Since the transmit PRF is typically 10 kHz or higher and the sensor velocity is generally less than 100 m/s, the spatial offset is less than 30 cm.

The absolute position of the sensor for each line is provided in the navigation data file as WGS-84 latitude, longitude, and ellipsoidal altitude. Sensor orientation is also provided, as heading, pitch, and roll angles. For recent level 0c datasets (2011 and onwards), the delay of the surface echo in the shallow channel is tracked by the processor and used to calculate the altitude of the radar over the surface. This altitude is provided in the `dif` parameter in the navigation data file. For older datasets, this has not been done, and in this case the `dif` parameter is constant for the entire dataset and represents the intended altitude over the surface for the acquisition.

In some situations, the range window, pulse length, and gain settings used in the deep channel are such that the trailing part of the surface echo saturates the receiver analog-to-digital converters. The affected samples will be at the top part of the deep channel image, and needs to be zeroed out prior to pulse compression. When this zeroing has been carried out for a sounding data file, an `_fvs` file is generated. This is an ASCII file, with each line holding the (zero-based) index of the first valid sample in the corresponding sounding data line. An example shallow/deep level 0c radargram set is shown on Figure 4.
Figure 3 Level 0c data file layout (one channel). Samples are complex baseband format. Quantities in italic refer to radar setup parameters available in the _cfg.m file accompanying the binary data file.

Figure 4 Example level 0c data from the Antarctic, log amplitude color-coded. Bedrock echo is visible in both shallow (top) and deep (bottom) channels, and double-bounced surface echo is seen in the shallow channel between the surface and bedrock echoes. Some samples at the top of the deep channel have been zeroed out due to surface echo saturation.
4.3  Level 1c data layout

The level 1c data format is illustrated in Figure 5. The level 1c processor focuses data to a geocoded grid. The output track follows the actual flight track, but resampled to constant spacing in the instantaneous along-track direction. All channels (polarimetric/shallow/deep) are coregistered to the same track. The resampled position (lat/lon) of the sensor for each line can be read from the level 1c navigation data file. In range direction, the processor accounts for refraction by assuming a constant refractivity of the ice.

The level 1c output data are thus sampled equidistantly in WGS-84 ellipsoid altitude (termed elevation in the following). All lines in a level 1c file are defined for the same elevation range, the first sample starting at an offset \( Z_{\text{off}} \), the following samples decreasing in elevation. The elevation spacing parameter \( Z_{\text{Spacing}} \) is negative to reflect this, so sample number \( k \) represents an elevation, \( Z \), of

\[
Z = Z_{\text{off}} + (k - 1) \cdot Z_{\text{Spacing}}
\]

For many scenes, the elevation of the ice changes significantly along the track (e.g. when flying from the coast inland over the Greenland ice sheet) and the aircraft changes altitude to accommodate this, typically keeping a constant altitude of 610 m (1000 ft) above the ice. Thus for each line, the available radar data cover only a subset of the total elevation range. Zero-samples are inserted as needed at the start and end of each line to represent elevations not covered by the radar data. An example of a level 1c radargram (full depth range) is shown on Figure 6.

4.4  Calibration

During level 0c processing, the channels in a dataset are calibrated relative to each other, using in-flight measurements from the internal calibration loop in the radar, recorded prior to and after each map. This way, internal gain, delay and phase differences in the radar can be corrected. All polarizations and/or sub-apertures in the same depth range (shallow/deep/full) are calibrated so that the gain, delay and phase are equal to those of a reference channel chosen during the processing. The reference channel echoes are not corrected, but the \( RxDelay \) parameter of all channels is adjusted to that measured for the reference channel. To compare the echo intensities at different depth ranges, a system gain parameter, \( G_{\text{sys}} \) parameter (in dB) is provided for each file in a data set. This is also derived from calibration data, and represents the gain introduced by the radar system and processing. By dividing the echo intensity \( (I=\text{re}^2+\text{im}^2) \) by the system gain (i.e. \( 10^{G_{\text{sys}}/10} \)), shallow and deep channel received power can be compared. If using dB-representation of the intensity (i.e. \( I_{\text{db}} = 10\log_{10}(\text{re}^2+\text{im}^2) \)), the \( G_{\text{sys}} \) parameter should just be subtracted.
Figure 5 Level 1c data file layout (one channel). Samples are complex baseband format, stored in order of decreasing ellipsoid height (NB!), to reflect the acquisition geometry. Quantities in italic refer to radar setup parameters available in the \_cfg.m file accompanying the binary data file.

Figure 6 Example level 1c-processed POLARIS data (log amplitude color-coded) from the Antarctic, showing surface echo (1), basal echo (2), double-bounced surface echo (3), and double-bounced basal echo (4). Some samples at the bottom have been zeroed out, due to lack of range window coverage at these elevations.
4.5 EGI/GPS Navigation data

The nav file contains navigation data and, if available, surface height estimates for the sounding file it accompanies. The file format is binary, little-endian, and consists of 128-byte records, one for each corresponding line in the sounding data file. The data structure (C-style) is given below. The provided MATLAB read_nav function (see Appendix D) returns a MATLAB struct array with the same field names.

```c
struct TNavRecord {
    int utc_src;            // UTC source
    int date;               // UTC date, given as YYYYMMDD
    double time;            // UTC time of day [s]
    double lat;             // WGS84 geodetic latitude [rad]
    double lon;             // WGS84 longitude [rad]
    double alt;             // WGS84 height above ellipsoid (HAE) [m]
    double dif;             // Best estimate of altitude over terrain [m]
    double ve;              // East velocity [m/s]
    double vn;              // North velocity [m/s]
    double vu;              // Up velocity [m/s]
    double hdg;             // Heading [rad]
    double pit;             // Pitch [rad] positive nose up
    double rol;             // Roll [rad] positive right roll
    int nav_src;            // Source of navigation data
    int dif_src;            // Source of altitude over terrain estimate
    char reserved[24];      // Reserved for future use
}; // 128-byte nav record
```

For the utc_src parameter, the following values are presently possible:

```
utc_src = 1 : EGI
```

Additional types may be added later.

For the nav_src parameter, the following values are presently possible:

```
nav_src = 1 : EGI Blended inertial and GPS
nav_src = 2 : EGI Pure inertial
nav_src = 3 : EGI Foreground GPS
nav_src = 4 : EGI INS fitted to EGI GPS (post proc)
nav_src = 5 : EGI INS fitted to External Kinematic GPS
```

Additional types may be added later.

For the dif_src parameter, the following values are presently possible:

```
dif_src = 1 : Geoid height from EGI
dif_src = 2 : Nominal altitude over surface (manually entered)
dif_src = 3 : Laser altimeter
dif_src = 4 : Polaris sounding data
```
4.6 Radar and processing parameters file (*cfg.m*)

The *cfg* files contain the parameters for the radar data and the processing applied for the relevant data product. They are ASCII-files with a format executable as a MATLAB script. When executed in MATLAB, e.g. `run(‘p080514_m183228_all_la_cfg’),` a struct-array with the name *ch* is created in the current workspace. A better option is to use the provided `read_cfg` or `read_polaris` functions which provide the struct array as a return variable. Table 2 and Table 3 list the records available in the annotation files for level 0c and 1c data.

Table 2 POLARIS annotation file (*cfg.m*) fields output by the level 0c processor

<table>
<thead>
<tr>
<th><strong>Table 2</strong></th>
<th><strong>Level 0c parameters</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>MapNr</strong></td>
<td>Map number</td>
</tr>
<tr>
<td><strong>Mode</strong></td>
<td>Mode name, string in single quotes, e.g ‘DualCo_SDS’</td>
</tr>
<tr>
<td><strong>Setup</strong></td>
<td>Setup name</td>
</tr>
<tr>
<td><strong>Antenna</strong></td>
<td>Antenna used, currently either small (4 elements) or large (8 elements)</td>
</tr>
<tr>
<td><strong>RxConf</strong></td>
<td>Sensor configuration, string with 8 characters, 2 per hardware channel indicating polarization and aperture nr.</td>
</tr>
<tr>
<td><strong>TxPRF</strong></td>
<td>Transmit PRF</td>
</tr>
<tr>
<td><strong>RefHeight</strong></td>
<td>Nominal altitude over terrain for mode [m]</td>
</tr>
<tr>
<td><strong>Fc</strong></td>
<td>Center frequency of transmitted signal</td>
</tr>
<tr>
<td><strong>Fs</strong></td>
<td>Sampling frequency of data in file</td>
</tr>
<tr>
<td><strong>Fif</strong></td>
<td>IF frequency of data in file (0 for complex baseband)</td>
</tr>
<tr>
<td><strong>DataFormat</strong></td>
<td>Data format, 1=real 32-bit float, 2=complex 32-bit float</td>
</tr>
<tr>
<td><strong>PRF</strong></td>
<td>Effective received PRF of data file after pre-summing</td>
</tr>
<tr>
<td><strong>RxCh</strong></td>
<td>Receiver hardware channel (1, 2, 3, 4, 5 = 1+2, 6 = 3+4)</td>
</tr>
<tr>
<td><strong>B</strong></td>
<td>Transmitted pulse bandwidth [Hz]</td>
</tr>
<tr>
<td><strong>T</strong></td>
<td>Transmitted pulse duration [s]</td>
</tr>
<tr>
<td><strong>Tukey</strong></td>
<td>Transmitted pulse Tukey tapering factor (0.0-1.0)</td>
</tr>
<tr>
<td><strong>Nra</strong></td>
<td>Samples pr. Line</td>
</tr>
<tr>
<td><strong>RxDelay</strong></td>
<td>Receiver range delay, relative to Tx pulse [s]</td>
</tr>
<tr>
<td><strong>RxGainCode</strong></td>
<td>Receiver VGA gain code (0-255)</td>
</tr>
<tr>
<td><strong>NomRxGain</strong></td>
<td>Nominal VGA Voltage gain [V/V]</td>
</tr>
<tr>
<td><strong>PresumFactor</strong></td>
<td>Online presummer decimation factor = Presum DC gain</td>
</tr>
<tr>
<td><strong>PrefiltFactor</strong></td>
<td>Online prefilter decimation factor (currently always 1)</td>
</tr>
<tr>
<td><strong>PrefiltGain</strong></td>
<td>Prefilter DC gain (currently always 1)</td>
</tr>
<tr>
<td><strong>UTCStart</strong></td>
<td>UTC time of day [s] of first line</td>
</tr>
<tr>
<td><strong>UTCStop</strong></td>
<td>UTC time of day [s] of last line</td>
</tr>
<tr>
<td><strong>Weight</strong></td>
<td>Weighting applied in pulse compression to suppress sidelobes</td>
</tr>
<tr>
<td><strong>AzOff</strong></td>
<td>Offset of first line in file relative to level 0a data file</td>
</tr>
<tr>
<td><strong>Naz</strong></td>
<td>Number of lines in the file</td>
</tr>
<tr>
<td><strong>EqPoly</strong></td>
<td>Polynomial coefficients used for equalization</td>
</tr>
<tr>
<td><strong>EqMu</strong></td>
<td>Polynomial fit parameters for MATLAB <em>polyfit</em> function</td>
</tr>
<tr>
<td><strong>DoEq</strong></td>
<td>Indicates whether equalization has been carried out (0/1)</td>
</tr>
<tr>
<td><strong>DelayCorrection</strong></td>
<td>Applied calibration delay correction [s]</td>
</tr>
<tr>
<td><strong>GainCorrection</strong></td>
<td>Applied calibration gain correction [dB]</td>
</tr>
<tr>
<td><strong>PhaseCorrection</strong></td>
<td>Applied calibration phase correction [rad]</td>
</tr>
<tr>
<td><strong>ExtDelay</strong></td>
<td>External delay calibration [s] – included in DelayCorrection</td>
</tr>
<tr>
<td><strong>ExtGain</strong></td>
<td>External gain calibration [dB] – included in GainCorrection</td>
</tr>
<tr>
<td><strong>ExtPhase</strong></td>
<td>External phase cal. [deg] – included in PhaseCorrection</td>
</tr>
<tr>
<td><strong>TimeRes</strong></td>
<td>Time resolution [deg] measured from calibration impulse resp.</td>
</tr>
<tr>
<td><strong>GSys</strong></td>
<td>System gain determined from calibration [dB]</td>
</tr>
</tbody>
</table>
Table 3 POLARIS annotation file (_cfg.m) additional fields output by the level 1c processor

<table>
<thead>
<tr>
<th></th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zoff</td>
<td>Elevation of first output sample (WGS84 ellipsoid height)</td>
</tr>
<tr>
<td>NZ</td>
<td>Number of elevation samples per line (identical to Nra)</td>
</tr>
<tr>
<td>ZSpacing</td>
<td>Elevation sample spacing [m]</td>
</tr>
<tr>
<td>AzEnd</td>
<td>Last sample used from level0c input file</td>
</tr>
<tr>
<td>MaxApertureLen</td>
<td>Maximum number of level 0c lines used in aperture</td>
</tr>
<tr>
<td>Nice</td>
<td>Refractive index of ice used in focusing</td>
</tr>
<tr>
<td>AzRes</td>
<td>Best focused azimuth resolution [m]</td>
</tr>
<tr>
<td>AzSpacing</td>
<td>Line spacing of level 1c data [m]</td>
</tr>
<tr>
<td>RefChannel</td>
<td>Reference channel for surface tracking / track generation</td>
</tr>
</tbody>
</table>
Appendix A POLARIS Sounding Modes

The POLARIS operating modes are listed below. The acronyms used in the Mode ID column are:
- **HH**: Horizontal transmit polarization, Horizontal receive polarization
- **VV**: Vertical transmit polarization, Vertical receive polarization
- **DualCo**: Dual Co-polarization, i.e. HH and VV
- **Quad**: Quadruple polarization, i.e. HH, VV, HV, and VH
- **SDS**: Shallow/Deep Sounding
- **CS2**: Clutter Suppression with two channels (A,B)
- **CS4**: Clutter Suppression with four channels (1,2,3,4)

In the table, multiple lines having the same Mode ID indicates a setup that changes on a pulse-by-pulse basis.

<table>
<thead>
<tr>
<th>Mode ID</th>
<th>Depth Range</th>
<th>Tx Pol (H/V)</th>
<th>Recorded Channels</th>
</tr>
</thead>
<tbody>
<tr>
<td>HH</td>
<td>Full</td>
<td>H</td>
<td>fh0</td>
</tr>
<tr>
<td>VV</td>
<td>Full</td>
<td>V</td>
<td>fvv0</td>
</tr>
<tr>
<td>DualCo</td>
<td>Full</td>
<td>H</td>
<td>fh0</td>
</tr>
<tr>
<td></td>
<td>Full</td>
<td>V</td>
<td>fvv0</td>
</tr>
<tr>
<td>Quad</td>
<td>Full</td>
<td>H</td>
<td>fh0, fvh0</td>
</tr>
<tr>
<td></td>
<td>Full</td>
<td>V</td>
<td>fvv0, fhv0</td>
</tr>
<tr>
<td>HH_SDS</td>
<td>Deep</td>
<td>H</td>
<td>dhh0</td>
</tr>
<tr>
<td></td>
<td>Shallow</td>
<td>H</td>
<td>shh0</td>
</tr>
<tr>
<td>VV_SDS</td>
<td>Deep</td>
<td>V</td>
<td>dvv0</td>
</tr>
<tr>
<td></td>
<td>Shallow</td>
<td>V</td>
<td>svv0</td>
</tr>
<tr>
<td>DualCo_SDS</td>
<td>Deep</td>
<td>H</td>
<td>dhh0</td>
</tr>
<tr>
<td></td>
<td>Deep</td>
<td>V</td>
<td>dvv0</td>
</tr>
<tr>
<td></td>
<td>Shallow</td>
<td>H</td>
<td>shh0</td>
</tr>
<tr>
<td></td>
<td>Shallow</td>
<td>V</td>
<td>svv0</td>
</tr>
<tr>
<td>Quad_SDS</td>
<td>Deep</td>
<td>H</td>
<td>dhh0, dvh0</td>
</tr>
<tr>
<td></td>
<td>Deep</td>
<td>V</td>
<td>dvv0, dvh0</td>
</tr>
<tr>
<td></td>
<td>Shallow</td>
<td>H</td>
<td>shh0, svh0</td>
</tr>
<tr>
<td></td>
<td>Shallow</td>
<td>V</td>
<td>svv0, shv0</td>
</tr>
<tr>
<td>HH_CS2</td>
<td>Full</td>
<td>H</td>
<td>fhha, fhhb</td>
</tr>
<tr>
<td>VV_CS2</td>
<td>Full</td>
<td>V</td>
<td>fvva, fvvb</td>
</tr>
<tr>
<td>DualCo_CS2</td>
<td>Full</td>
<td>H</td>
<td>fhha, fhhb</td>
</tr>
<tr>
<td>Mode ID</td>
<td>Depth Range</td>
<td>Tx Pol (H/V)</td>
<td>Recorded Channels</td>
</tr>
<tr>
<td>------------------</td>
<td>-------------</td>
<td>--------------</td>
<td>-------------------</td>
</tr>
<tr>
<td></td>
<td>Full</td>
<td>V</td>
<td>fvva, fvvb</td>
</tr>
<tr>
<td>Quad_CS2</td>
<td>Full</td>
<td>H</td>
<td>fhha, fhbb, fhva, fhvb</td>
</tr>
<tr>
<td></td>
<td>Full</td>
<td>V</td>
<td>fvva, fvvb, fhva, fhvb</td>
</tr>
<tr>
<td>HH_SDS_CS2</td>
<td>Deep</td>
<td>H</td>
<td>dhha, dhbb</td>
</tr>
<tr>
<td></td>
<td>Shallow</td>
<td>H</td>
<td>shha, shhb</td>
</tr>
<tr>
<td>VV_SDS CS2</td>
<td>Deep</td>
<td>V</td>
<td>dvva, dvvb</td>
</tr>
<tr>
<td></td>
<td>Shallow</td>
<td>V</td>
<td>svva, svvb</td>
</tr>
<tr>
<td>DualCo_SDS_CS2</td>
<td>Deep</td>
<td>H</td>
<td>dhha, dhbb</td>
</tr>
<tr>
<td></td>
<td>Deep</td>
<td>V</td>
<td>dvva, dvvb</td>
</tr>
<tr>
<td></td>
<td>Shallow</td>
<td>H</td>
<td>shha, shhb</td>
</tr>
<tr>
<td></td>
<td>Shallow</td>
<td>V</td>
<td>svva, svvb</td>
</tr>
<tr>
<td>Mix_SDS_CS2</td>
<td>Deep</td>
<td>H</td>
<td>dhh0, dvh0</td>
</tr>
<tr>
<td></td>
<td>Deep</td>
<td>V</td>
<td>dvv0, dhv0</td>
</tr>
<tr>
<td></td>
<td>Shallow</td>
<td>H</td>
<td>shha, shhb</td>
</tr>
<tr>
<td></td>
<td>Shallow</td>
<td>V</td>
<td>svva, svvb</td>
</tr>
<tr>
<td>HH_CS4</td>
<td>Full</td>
<td>H</td>
<td>fhh1, fhh2, fhh3, fhh4</td>
</tr>
<tr>
<td>VV_CS4</td>
<td>Full</td>
<td>V</td>
<td>fvv1, fvv2, fvv3, fvv4</td>
</tr>
<tr>
<td>HH_SDS_CS4</td>
<td>Deep</td>
<td>H</td>
<td>dhh1, dhh2, dhh3, dhh4</td>
</tr>
<tr>
<td></td>
<td>Shallow</td>
<td>H</td>
<td>shh1, shh2, shh3, shh4</td>
</tr>
<tr>
<td>VV_SDS_CS4</td>
<td>Deep</td>
<td>V</td>
<td>dvv1, dvv2, dvv3, dvv4</td>
</tr>
<tr>
<td></td>
<td>Shallow</td>
<td>V</td>
<td>svv1, svv2, svv3, svv4</td>
</tr>
</tbody>
</table>
Appendix B MATLAB Script for Sounding Data Ingestion

```matlab
function [data,p] = read_polaris(fn,az_start, az_num);
% [data,p] = read_polaris(fn,az_start, az_num)
% Read a polaris data and configuration file to memory
% Output:
% data - Polaris data matrix (ra x az)
% p - Structure containing data parameters read from _cfg.m file
% Input:
% fn - Data filename
% az_start (optional) - line offset in data file (default = 0)
% az_num (optional) - number of lines to read from offset (default = all)
% ~Anders Kusk, 2008

if ~exist('az_start','var'),
    az_start = 0;
end;
if ~exist('az_num','var'),
    az_num = Inf;
end;

p = read_cfg([fn '_cfg'],'ch');
 fid = fopen(fn,'r');
 if (p.DataFormat == 1),  % Real data
    fseek(fid,az_start*p.Nra*4,'bof');
    data=fread(fid,[p.Nra az_num],'float=>float');
    fclose(fid);
 elseif (p.DataFormat == 2), % Complex Data
    fseek(fid,az_start*p.Nra*8,'bof');
    data = fread(fid,[2*p.Nra az_num],'float=>float');
    fclose(fid);
    data = complex(data(1:2:end,:),data(2:2:end,:));
 else
    error('Unsupported dataformat');
end;
```
Appendix C MATLAB Script for Annotation Ingestion

function [cfg] = read_cfg(fn,cfg_type)
% [cfg] = read_cfg(fn,cfg_type)
% Script to read an annotation file into a structure
% Output
%   cfg      = Structure containing annotation data
% Input
%   fn       = cfg filename (without .m extension)
%   cfg_type = Type of config data to read
%   For POLARIS sounding data this should be 'ch'
run(fn);
cfg = eval(cfg_type);
Appendix D MATLAB Script for Nav Data Ingestion

```matlab
function [nav]=read_nav(filename,ofs,nr)
    % [nav]=readnav(filename,ofs,nr)
    %
    % Read Polaris navigation data file (_nav)
    %
    % Output:
    %   nav - structure containing navigation data
    % Input:
    %   fn - filename
    %   ofs - offset to first line (default=0)
    %   nr - nr of samples to read (default=All)
    % Anders Kusk, 2008

    if (~exist('ofs','var') || isempty(ofs))
        ofs = 0;
    end;
    if (~exist('nr','var') || isempty(nr))
        nr = Inf;
    end;

    fid=fopen(filename,'r');
    fseek(fid,ofs*128,'bof');
    [B,count]=fread(fid,[2,nr],'2*int',120);
    fseek(fid,ofs*128+8,'bof');
    [A,count]=fread(fid,[11,nr],'11*double',128-11*8);
    fseek(fid,ofs*128+96,'bof');
    [C,count]=fread(fid,[4,nr],'4*int',112);
    fclose(fid);

    utc_src = B(1,:);
    dateval = B(2,:);
    nav_src = C(1,:);
    dif_src = C(2,:);
    year = floor(dateval/10000);
    month = mod(floor(dateval/100),100);
    day = mod(dateval,100);
    t=A(1,:);
    lat=A(2,:); lon=A(3,:); alt=A(4,:);
    dif=A(5,:);
    ve=A(6,:); vn=A(7,:); vu=A(8,:);
    hdg=A(9,:); pit=A(10,:); rol=A(11,:);

    nav=struct('utc_src', utc_src, ...
        'year', year, 'month', month, ...
        'day', day, 't', t, ...
        'lat',lat, 'lon',lon, ...
        'alt',alt, 'dif',dif, ...
        've',ve,'vn',vn, ...
        'vu',vu, 'hdg',hdg, ...
        'pit',pit,'rol',rol, ...
        'nav_src', nav_src, 'dif_src', dif_src);
```
www.space.dtu.dk
National Space Institute
Technical University of Denmark
Ørsteds Plads
Building 348
DK-2800 Kgs. Lyngby
Denmark
Tel: (+45) 45 25 38 00
Fax: (+45) 45 93 16 34
E-mail: info@space.dtu.dk
ICESAR 2012
Campaign Data Inventory

ESA Contract No. 4000106112/12/NL/FK

Anders Kusk, Technical University of Denmark
Jørgen Dall, Technical University of Denmark

June 6, 2013
Version 1.1
### ESA STUDY CONTRACT REPORT

<table>
<thead>
<tr>
<th>ESA CONTRACT No</th>
<th>SUBJECT</th>
<th>CONTRACTOR:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>IceSAR 2012 Campaign Data Inventory</td>
<td>Technical University of Denmark</td>
</tr>
<tr>
<td><strong>STAR CODE</strong></td>
<td>No of volumes: 1</td>
<td>Politecnico di Milano</td>
</tr>
<tr>
<td></td>
<td>ThisisVolumeNo: 1</td>
<td>Utrecht University</td>
</tr>
<tr>
<td></td>
<td>Contractor's Ref.</td>
<td>FR_v1</td>
</tr>
</tbody>
</table>

#### ABSTRACT:

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: Anders Kusk, Jørgen Dall

** NAME OF ESA STUDY MANAGER **

** ESA BUDGET HEADING **
1 Data acquisition campaign

1.1 Radar data

During IceSAR-2012, P-band SAR data were acquired with the airborne POLARIS system, which was originally developed as a nadir looking ice sounder [1] but recently upgraded with a SAR capability [2]. In this section POLARIS and its observation modes are briefly introduced. The test sites and the flight patterns over these test sites are presented, and an overview of the radar data is provided. Finally the in-situ data are addressed. The results of the campaign are described in [3].

1.2 Radar system and observation modes

The POLARIS radar can operate in either sounding mode, with the antenna beam pointing to nadir, or in SAR mode, with the beam steered to the right or left of the flight track. Independent of the beam direction, the radar can be configured to work in either polarimetric (1 aperture, full polarimetry) or multi-aperture (4 apertures, single-polarization) configuration. The beam direction can be changed manually in in-flight, whereas switching between polarimetric/multi-aperture configurations must be done on the ground.

In SAR mode, the flight altitude is nominally 4 km above the surface, although this may be reduced in areas of high surface elevation due to air traffic restrictions. The range of look angles covered is from approximately 20° to 45°, corresponding to a swath of 2.5 km in ground range at the nominal altitude.

In sounding mode, the nominal flight altitude is 600 m above the surface.
For all flights, the small (4-element) POLARIS antenna was used, see Figure 1.1. Most data were acquired in the polarimetric SAR mode. Tomography data were acquired in multi-aperture SAR mode at HH polarization, and sounding data were acquired for objectives 8 and 9.

The radar was flown on the Norlandair TF-POF Twin Otter aircraft on which POLARIS has been certified and flown in the past. In order to maintain and reproduce stable flight tracks, a system called EMAP4, developed at the DTU Space Geodynamics division, was used. The system uses GPS to calculate and present in real-time to the pilots the current deviations from a desired track, as well as steering information to return to the track. Furthermore, when operating at the high altitude required in the SAR mode, the aircraft’s own radar altimeter cannot be used, and the EMAP4 program displays the current estimated altitude over the terrain, based on GPS altitude and the GTOPO30 digital elevation model (DEM). This feature was employed on the longer data acquisitions where the surface elevation changed significantly (e.g. along the K-transect). For acquisitions of smaller areas (e.g. the tomography at SHR), a constant GPS altitude was employed.

Navigation data were acquired with three Javad GPS receivers, providing 1Hz kinematic GPS data, and a Honeywell H764G EGI (Inertial Navigation Unit with embedded GPS) providing 50 Hz inertial data. On flights that took off and landed in SFJ, a GPS reference station was placed on the ground to support kinematic processing. On transit flights, no reference stations were available.

Figure 1.1 POLARIS SAR.

1.3 Flight days

IceSAR flights in Greenland were carried out on ten different days. On April 19, the radar was installed in and flown from Akureyri, Iceland (AEY) to Kangerlussuaq, Greenland (SFJ), followed by two more days of acquisitions. The radar was uninstalled in SFJ, and reinstalled there in May. Three May flights were carried out, the third of which was the transit back to AEY. In June, the radar was installed in AEY and flown in support of the UAVSAR campaign in Iceland (data not processed yet), twice on June 8, and on the morning of June 9, followed by the transit to SFJ the same day. This was followed by three more days of acquisitions, the final one being the transit back to AEY. On the final leg, over Iceland, sounding data in support of the UAVSAR campaign were also acquired (data not processed yet). The flight dates (in Greenland) are summarized in Table 1.1.
Table 1.1 Overview of flight days in Greenland during the IceSAR-2012 campaign. AEY=Akureyri, Iceland, SFJ=Kangerlussuaq, Greenland

<table>
<thead>
<tr>
<th>Flight Day</th>
<th>Objective/Description</th>
<th>Modes used</th>
<th>Notes</th>
</tr>
</thead>
</table>
| April 19   | Transit from AEY to SFJ  
Sounding of icesheet, K-transect and crossing tracks at SHR/S10 | Sounding Quad-Pol   |                                          |
| April 20   | SAR imaging of K-transect and crossing tracks at SHR/S10                              | SAR Quad-Pol        |                                          |
| April 21   | SAR tomography of SHR site                                                             | SAR Multi-aperture, HH| Failed due to antenna configuration error|
| May 7      | SAR tomography of SHR site                                                             | SAR Multi-aperture, HH| Repeat of the April 21 flight, correct config|
| May 8      | SAR imaging of K-transect and crossing tracks at SHR/S10  
SFJ corner reflector calibration | SAR Quad-Pol        | Flight shortened by equipment failure     |
| May 9      | Transit from SFJ to AEY  
SAR imaging of K-transect and central icesheet                                        | SAR Quad-Pol        |                                          |
| June 9     | Transit from AEY to SFJ  
SAR imaging of icesheet sites  
Sounding of K-transect                                           | Sounding Quad-Pol   |                                          |
| June 10    | SAR imaging of K-transect and crossing tracks at SHR/S10  
SFJ corner reflector calibration | SAR Quad-Pol        |                                          |
| June 11    | SAR tomography of SHR site                                                             | SAR Multi-aperture, HH|                                          |
| June 12    | Transit from SFJ to AEY  
SAR imaging of K-transect and central icesheet                                        | SAR Quad-Pol        |                                          |
2 Data overview

To identify specific sites and acquisition times, an acquisition naming scheme has been adopted, with the following format: <Scene><DOY><a-z>, where the <Scene> identifies the geographical site, <DOY> is the day of year of the acquisition, and <a-z> distinguishes between different acquisitions on the same day. Thus KTRot129b would be the second (b) acquisition of the KTRot scene on May 8th (Day-of-year 129).

The main scene is the KTRot scene, which follows the K-transect in the East-West direction as shown in Figure 2.1. At each end of the transect, the radar beam direction (left/right) was switched in order to image the scene under the same incidence angle range on the east- and westbound tracks. Two subsets of this scene, at the SHR and S10 GPS sites, have also been defined, named SHRot and S10ot. They are not shown in Figure 2.1, but they are centred on the SHR and S10 sites, aligned with the KTRot scene, and limited to 5 km along-track. The ot modifier indicates that for these scenes, the ice velocity can primarily be extracted using offset tracking rather than interferometry, as the main ice velocity component is in the along-track (East-West) direction. To investigate interferometry, data were also acquired from two 5 km long crossing (North-South) tracks at SHR and S10, defining the SHRif and S10if scenes shown in Figure 2.1. The SHRot and S10ot scenes are not shown, but are centered on the SHR and S10 sites, and limited to 5 km along-track.

On transit flights to and from the Norlandair base in AEY, the opportunity arose to acquire SAR data over the central ice-sheet, in order to investigate coherence, backscatter and polarimetric signature in this region. This was done once in May, and twice in June, at two sites, CIS and EIS, shown in Figure 2.2.

To enable a radiometric and geometric calibration of the SAR instrument, a corner reflector was placed in Kangerlussuaq at on the river bank, and acquisitions were carried out in May and June at this site, called SFJcr (see Figure 2.1). The left-looking beam was used in May, and the right-looking beam in June.

Tomography data acquisition was attempted on April 21, but failed due to an erroneous configuration of the antenna beam feeding cables in HH polarization. The flight was repeated, using the correct configuration, on May 7, and on June 11. The tomography sites coincide with SHRot, but were imaged (using a left-looking beam) in a race-track pattern from both westbound tracks (north of the scene, SHRtomN) and eastbound tracks (south of the scene, SHRtomS).

In April and June, sounding data were also acquired along the K-transect and at the SHR and S10 sites. Two 5 km North-South profiles through the center of the SHRif and S10if sites were defined and called SHRsnd and S10snd. The East-West profile is the KTRsnd profile, following the center of the KTRot scene. Finally, the entire profile from Kulusuk to S10 was sounded during the April transit flight, called ISsnd. An overview of the number of acquisitions at each site, and on each date, is given in Table 2.1. Note that some of the KTRot acquisitions lack data at the beginning/end, as the track was sometimes left prematurely to line up for the SHRif and S10if acquisitions in time.
Figure 2.1 SAR Scenes on the K-transect, and the SFJ corner reflector calibration site.

Figure 2.2 SAR scenes on the K-transect, and on the central and eastern icesheet (CIS/EIS).
Table 2.1 Overview of data available. The April 21 acquisition failed, indicated by asterisk. Numbers in brackets indicate the corresponding day of the year. Numbers in parentheses indicate the number of acquisitions (out of the total) that are incomplete.

<table>
<thead>
<tr>
<th>Scene Name</th>
<th>Mode</th>
<th>April</th>
<th>May</th>
<th>June</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>19</td>
<td>20</td>
<td>21</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SFJcr</td>
<td>SAR QuadPol</td>
<td>110</td>
<td>111</td>
<td>112</td>
<td>Corner reflector calibration</td>
</tr>
<tr>
<td>SHRrot</td>
<td>SAR QuadPol</td>
<td>4</td>
<td></td>
<td>1</td>
<td>SHR east-west for offset tracking; subset of KTRot</td>
</tr>
<tr>
<td>SHRif</td>
<td>SAR QuadPol</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>SHR north-south for interferometry</td>
</tr>
<tr>
<td>SHRsnd</td>
<td>Sounder QuadPol</td>
<td>1</td>
<td></td>
<td>1</td>
<td>SHR north-south sounding profile</td>
</tr>
<tr>
<td>SHRtomN</td>
<td>SAR Multi-apt</td>
<td>* 10</td>
<td></td>
<td>10</td>
<td>SHR east-west for tomosar; coincident with SHRrot</td>
</tr>
<tr>
<td>SHRtomS</td>
<td>SAR Multi-apt</td>
<td>* 10</td>
<td></td>
<td>9</td>
<td>SHR west-east for tomosar; coincident with SHRrot</td>
</tr>
<tr>
<td>S10ot</td>
<td>SAR QuadPol</td>
<td>4</td>
<td>1</td>
<td>2</td>
<td>S10 east-west for offset tracking; subset of KTRot</td>
</tr>
<tr>
<td>S10if</td>
<td>SAR QuadPol</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>S10 north-south for interferometry</td>
</tr>
<tr>
<td>S10snd</td>
<td>Sounder QuadPol</td>
<td>1</td>
<td></td>
<td>1</td>
<td>S10 north-south sounding profile</td>
</tr>
<tr>
<td>KTRot</td>
<td>SAR QuadPol</td>
<td>4(1)</td>
<td></td>
<td>2(1)</td>
<td>K-transect east-west for offset tracking</td>
</tr>
<tr>
<td>KTRsnd</td>
<td>Sounder QuadPol</td>
<td>1</td>
<td></td>
<td>1</td>
<td>K-transect east-west sounding profile</td>
</tr>
<tr>
<td>CIS</td>
<td>SAR QuadPol</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>Central icesheet, coherence/backscatter/polarimetry</td>
</tr>
<tr>
<td>EIS</td>
<td>SAR QuadPol</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>Eastern icesheet, coherence, backscatter, polarimetry</td>
</tr>
<tr>
<td>ISSnd</td>
<td>Sounder QuadPol</td>
<td>1</td>
<td></td>
<td></td>
<td>Icesheet from Kulusuk to S10. Opportunity acquisition.</td>
</tr>
</tbody>
</table>
3 Data delivery

3.1.1 Folder structure

A netCDF format for level 1c data has been developed and used for the first time in this delivery (see section 4). For each channel in an acquisition (polarimetric/shallow/deep), a netCDF file is delivered, containing the complex baseband data matrix, as well as annotation and navigation data. A slightly different format is used for SAR and sounding data, as the processing is quite different. A netCDF file containing the output grid used for SAR focusing (including elevation, latitude, and longitude for each pixel) is also provided.

The files are delivered in these main folders:

- **Level1_SAR**  
  - One subfolder for each scene (see section 2), containing all acquisitions

- **Level1_Sounding**  
  - One subfolder for each scene (see section 2), containing all acquisitions

- **Level0_Tomography**  
  - One subfolder for each of the two days of tomography acquisition in MATLAB-compatible format (classic POLARIS format).

- **Level2_ice_velocities**  
  - (NB experimental) Three netCDF files with offset-tracking derived ice velocities for the K-transect (**KTRot**) scene, one based on April-May acquisitions, one based on April-June acquisitions, and one based on May-June acquisitions.

- **InSitu**  
  - IMAU In-Situ GPS positions covering the entire period of the IceSAR 2012 campaign.
4 Data formats

4.1 Level 0 tomography data

The supplied level 0 data (tomography acquisitions only) are in classical POLARIS format, see [4]. Each acquisition (or scene) comes with a number of files:

- 4 radar data files (one for each patch, 1-4), binary complex float, no header.
- 4 ascii (matlab-readable) configuration files (_cfg.m) with parameters and data layout for each channel.
- 5 binary navigation data (_nav) files, holding the trajectory/attitude of each receive patch phase center, and one for the full aperture phase center used on transmit.
- Other files (_prc and _cal), with some auxiliary processing information.

With respect to SAR beamforming, on transmit, the beam has already been formed by the SAR cables, but the received signal from each patch is compensated in the processor for the one-way cable delay, and associated phase, so that the signal from each patch antenna port have no (intended) delay/phase shift relative to each other.

The antenna patterns for the individual patches is delivered, as well as the transmit aperture pattern (incl. the effect of phase steering and transmit amplitude tapering). The format is as below:

look_angle(deg) gain(dB) phase(deg)

Look angle for the antenna patterns is defined as negative when looking left (all the tomography data were acquired in left looking mode).

Phase reference is with respect to the individual patch phase centers, and for the transmit aperture, the full aperture phase center.

4.2 Level 1 sounding data format

The new netCDF sounding data format is is shown on Table 4.1.

The level 1c sounding data processor focuses data to a geocoded grid. The output track follows the actual flight track, but resampled to constant spacing in the instantaneous along-track direction. All channels (polarimetric/shallow/deep) are coregistered to the same track. The resampled position (lat_radar/lon_radar/h_ell_radar) of the sensor for each line is supplied with the data.

In range direction, the processor accounts for refraction by assuming a constant refractivity, *nice* of the ice. The level 1c output data are thus sampled equidistantly in WGS-84 ellipsoid altitude *h_ell*. All lines in a level 1c file are defined for the same elevation range. For many scenes, the elevation of the ice changes significantly along the track (e.g. when flying from the coast inland over the Greenland ice sheet) and the aircraft changes altitude to accommodate this, typically keeping a constant altitude of 610 m (1000 ft) above the ice. Thus for each line, the available radar data cover only a subset of the total elevation range. Zero-samples are inserted as needed at the start and end of each line to represent elevations not covered by the radar data.
Table 4.1 netCDF layout for sounding data

```c
netcdf p120419_m173023_KTRsnd110a_1c_dhh0 {

dimensions:
    x = 87671 ;
    h_ell = 450 ;
    ri = 2 ;

variables:
    double x(x) ;
        x:units = "m" ;
        x:description = "position of output line along instantaneous track" ;
    double t_radar(x) ;
        t_radar:units = "s" ;
        t_radar:description = "along-track radar time of day at output line" ;
    double lat_radar(x) ;
        lat_radar:units = "degrees" ;
        lat_radar:description = "radar/output line WGS84 latitude" ;
    double lon_radar(x) ;
        lon_radar:units = "degrees" ;
        lon_radar:description = "radar/output line WGS84 longitude" ;
    double h_ell_radar(x) ;
        h_ell_radar:units = "m" ;
        h_ell_radar:description = "radar WGS84 ellipsoid height at output line" ;
    double h_ell(h_ell) ;
        h_ell:units = "m" ;
        h_ell:description = "pixel WGS84 ellipsoid height" ;
    int ri(ri) ;
        ri:description = "real (0) and imaginary (1) part dimension" ;
    float data(x, h_ell, ri) ;
        data:description = "relative complex reflectivity estimate (deep/shallow calibration only)" ;
        data:date = 20120419 ;
        data:mapNr = 173023 ;
        data:scene = "KTRsnd110a" ;
        data:level = "1c" ;
        data:rxPol = "h" ;
        data:txPol = "h" ;
        data:subApt = "0" ;
        data:fc = 435000000. ;
        data:mode = "Quad_SDS" ;
        data:setup = "SDS_610m" ;
        data:antenna = "Small" ;
        data:beam = "Nadir" ;
        data:rxConf = "hbhavavbh0v0" ;
        data:refHeight = 61.0 ;
        data:gsys = 94.1597137451172 ;
        data:azRes = 1.5 ;
        data:nice = 1.77 ;
        data:firstValidLine = 0 ;
        data:lastValidLine = 87670 ;
}
```

4.3 Level 1 SAR output grid format

For each of the SAR scenes in Table 2.1 (KTRot, SHRrot, SHRif, S10ot, S10if, CIS, EIS), a local (s,c,h)-coordinate system[5] was defined. (s,c,h)-coordinates are curvilinear coordinates defined on a sphere that locally approximates the reference ellipsoid, with s the along-track coordinate, c the across-track coordinate, and h the altitude above the reference sphere. The origin of the coordinate system is set at the midpoint of the nominal flight track, and the radius of the approximating sphere is chosen as the radius of curvature of the WGS-84 reference ellipsoid in the along-track direction, evaluated at the origin. For each site, an equidistantly sampled grid in s and c was then defined. For all sites, a 3 m c-spacing was used, whereas a 1 m s-spacing was used for the longer KTRot, CIS and EIS scenes, and a 0.5 m spacing was used for the smaller sites. The GIMP DEM elevation was then transformed and interpolated to each (s,c) grid point, to provide the corresponding h-elevation at each grid point. The output grid is stored in a file, and used as input to the SAR processor. In order to coregister data acquired from left- and right-looking beams, a convention was adopted to always define the (s,c,h)-system and grid assuming a left-looking geometry. This has the advantage of the c-coordinate always being positive. To focus data acquired with a right-looking beam to this grid, the grid is first flipped (in the s-direction), and the SAR data are focused to the flipped grid. Then the focused data are flipped in the s-direction, to coregister the data to the original grid.

The (s,c,h)-coordinates can be converted to geocentric WGS84 ECEF-coordinates by

\[
\begin{bmatrix}
x \\
y \\
z_{ECEF}
\end{bmatrix}
= M
\begin{bmatrix}
x' \\
y' \\
z'
\end{bmatrix}
+ o
= M
\begin{bmatrix}
(h + r_a)\cos(c/r_a)\cos(s/r_a) \\
(h + r_a)\cos(c/r_a)\sin(s/r_a) \\
(h + r_a)\sin(c/r_a)
\end{bmatrix}
+ o
\]

where the 3x3 transformation matrix \( M \), the 3x1 translation vector, \( o \), and the reference sphere radius, \( r_a \), are provided with the grid. The intermediate \((x', y', z')\)-coordinates represent rectangular coordinates in a geocentric system based on the reference sphere of the (s,c,h)-system, and can be used to calculate the range between two points in (s,c,h)-coordinates. Care should be taken to use at least double-precision floating point arithmetic for such calculations.

The output grids used to focus the data are delivered with the data, in netCDF form, see Table 4.2. The supplied files also hold the WGS84 latitude, longitude, and ellipsoid altitude for each grid point, as well as the \( M \) matrix and \( o \)-vector described above.
Table 4.2 netCDF layout for SAR output grid file

```plaintext
cdf XRot_grd {
    dimensions:
        c = 1000;
        s = 135000;
    variables:
        double c(c);
        c:units = "m";
        double s(s);
        s:units = "m";
        float h_sch(s, c);
        h_sch:units = "m";
        float h_ell(s, c);
        h_ell:units = "m";
        float lat(s, c);
        lat:units = "degrees_north";
        float lon(s, c);
        lon:units = "degrees_east";
    // global attributes:
        lat_peg = 67.032121769608;
        lon_peg = -48.4813644329581;
        hdg_peg = 94.9768062883605;
        ra_peg = 6396263.09397302;
        o_vector = 12.777253806125, -14.4331292284187, -39379.3061953578;
        M_matrix_row_1 = 0.258659327131351, 0.798863606625015, -0.543058275416211;
        M_matrix_row_2 = -0.292169645489064, 0.600558883297691, 0.744288872647593;
        M_matrix_row_3 = 0.920723764623652, -0.0338521151821215, 0.388743853398283;
}
```

4.4 Level 1 SAR data format

The SAR focusing algorithm takes as input a level 0c (range compressed) radar data file (and associated annotation and navigation data files), an output grid file (see previous section), and number specifying the desired azimuth resolution. The following procedure is then used to focus the data:

For each output grid point \((s_o, c_o)\):

1. Look up grid elevation, \(h_o\).
2. Interpolate sensor \((s_r, c_r, h_r)\)-position at \(s_r=s_o\). This point is used to define the phase reference.
3. Calculate broadside range, \(r_b\), and aperture length, \(L_a = r_b \lambda/(2 \rho_a)\).
4. For each input line in aperture, i.e. for all \((-\frac{L_a}{2} < s_r - s_o < \frac{L_a}{2})\).
   a. Calculate range, \(r\), from sensor to \((s_o, c_o, h_o)\).
   b. Calculate look angle and look up cross-track antenna pattern.
   c. Calculate azimuth weight (Hamming, inverse antenna gain and range attenuation).
   d. Calculate phase correction to the phase reference point, \(\phi = \left(\frac{4\pi}{\lambda}\right) (r - r_b)\).
   e. Interpolate radar data at \(r\), phase correct, multiply by azimuth weight and calibration constant, and add to output pixel.

Although focused data are registered to the output grid, the phase is referenced to the sensor position, when the sensor is broadside of the target. Thus when forming interferograms from two images, the interferometric phase is not flattened. Although for smaller scenes, one could define a common reference track to reference all acquisitions to, this is not straightforward for long scenes, where the
surface elevation (and correspondingly the sensor altitude) changes significantly along the track. The sensor positions, in $(s,c,h)$-coordinates interpolated to each output line, are provided along with the data. The netCDF SAR data format is shown in Table 4.3. For details regarding POLARIS modes and file naming conventions, which are similar for sounding and SAR, see [4].

Table 4.3 netCDF layout for SAR data

```
netcdf p120420_m121851_KTRot111a_1c_fhh0 {

dimensions:
  c = 1000 ;
  s = 135000 ;
  ri = 2 ;

variables:
  double c(c) ;
    c:units = “m” ;
    c:description = “horizontal cross-track pixel position” ;
  double s(s) ;
    s:units = “m” ;
    s:description = “along-track pixel position” ;
  double t_radar(s) ;
    t_radar:units = “s” ;
    t_radar:description = “along-track radar time of day at broadside” ;
  double c_radar(s) ;
    c_radar:units = “m” ;
    c_radar:description = “horizontal cross-track radar position at broadside” ;
  double h_radar(s) ;
    h_radar:units = “m” ;
    h_radar:description = “vertical cross-track radar position at broadside” ;
  double lat_radar(s) ;
    lat_radar:units = “degrees” ;
    lat_radar:description = “radar WGS84 latitude at broadside” ;
  double lon_radar(s) ;
    lon_radar:units = “degrees” ;
    lon_radar:description = “radar WGS84 longitude at broadside” ;
  double h_ell_radar(s) ;
    h_ell_radar:units = “m” ;
    h_ell_radar:description = “radar WGS84 ellipsoid height at broadside” ;
  int ri(ri) ;
    ri:description = “real (0) and imaginary (1) part dimension” ;
  float data(s, c, ri) ;
    data:description = “complex reflectivity estimate [sigma_nought]” ;
    data:date = 120420 ;
    data:mapNr = 121851 ;
    data:scene = “KTRot111a” ;
    data:level = “1c” ;
    data:rxPol = “h” ;
    data:txPol = “h” ;
    data:subApt = “0” ;
    data:fc = 435000000. ;
    data:mode = “Quad” ;
    data:setup = “SAR_4000m” ;
    data:antenna = “Small” ;
    data:beam = “Left” ;
    data:rxConf = “hbhavvbhb0v0” ;
    data:refHeight = 4000. ;
    data:azRes = 1. ;
    data:grdFn = “KTRot_grd” ;
    data:firstValidLine = 0 ;
    data:lastValidLine = 134999 ;
}
```
4.5 Level 2 – Experimental ice velocity maps from offset tracking

These ice velocity maps have been generated by averaging offset fields from all acquisitions for a pair of dates, weighted by the offset estimate signal-to-noise ratio. This increases coverage and reduces noise. The averaged offset fields are divided by the temporal baseline, and the resulting velocities are then transformed from the (s,c) SAR geometry to local East/North velocities. The format is shown in Table 4.4

Table 4.4 netCDF layout for level 2 ice velocity maps

```netcdf
dimensions:
c = 46 ;
s = 2699 ;
acquisition_date = 2 ;
pair_number = 8 ;
variables:
double c(c) ;
c:units = "m" ;
c:description = "horizontal cross-track pixel position" ;
double s(s) ;
s:units = "m" ;
s:description = "along-track pixel position" ;
double lat(s, c) ;
lat:units = "degrees" ;
lat:description = "pixel latitude" ;
double lon(s, c) ;
lon:units = "degrees" ;
lon:description = "pixel longitude" ;
double h_ell(s, c) ;
h_ell:units = "m" ;
h_ell:description = "pixel WGS84 ellipsoid altitude from GIMP DEM" ;
double v_ice_east(s, c) ;
v_ice_east:units = "m/y" ;
v_ice_east:description = "estimated eastwards ice velocity" ;
double v_ice_north(s, c) ;
v_ice_north:units = "m/y" ;
v_ice_north:description = "estimated northwards ice velocity" ;
double estimate_quality(s, c) ;
estimate_quality:units = "dimensionless" ;
estimate_quality:description = "relative quality measure for velocity estimate" ;
double acquisition_pairs_dates(pair_number, acquisition_date) ;
acquisition_pairs_dates:units = "YYYYMMDD integer" ;
double temporal_baselines(pair_number) ;
temporal_baselines:units = "days" ;
```

4.6 In-situ GPS positions

Positions of the IMAU GPS receivers placed on the ice along the K-transect are provided as text files (S*_pos.txt) with the following columns:

Year [y]
Day of Year [d]
UTC Seconds of day [s]
Latitude [deg]
Longitude [deg]
Altitude [deg]

These data can be used to verify the velocity measurements generated from radar data.
5 References


