ESA Climate Change Initiative (CCI+)

Essential Climate Variable (ECV)

Antarctic Ice Sheet CCI+ (AIS cci+)

Algorithm Development Plan (ADP)

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Table of Contents

Change Log

Issue	Author	Affected Section	Change	Status
1.0	D. Floricioiu, Lead author, DLR	All	Document Creation	Released to ESA
1.1	D. Floricioiu, Lead author, DLR	Sections 2.1. and 2.2	Update end of year 1	Released to ESA
2.0	J. Wuite, new lead author, ENVEO	All	Updated for Phase 2	Released to ESA

Acronyms and Abbreviations

Acronym	Explanation
AIS	Antarctic Ice Sheet
ADP	Algorithm Development Plan
AIS_cci+	Antarctic Ice Sheets CCI project Extension
API	Antarctic Peninsula
ATBD	Algorithm Theoretical Basis Document
CAR	Climate Assessment Report
CCI(+)	Climate Change Initiative (Extension)
CFL	Calving Front Location
CONAE	Comisión Nacional de Actividades Espaciales
DEM	Digital Elevation Model
DLR	Deutsches Zentrum für Luft- und Raumfahrt
DTU	Danish Technical University
EAIS	East Antarctic Ice Sheet
ECV	Essential Climate Variable
ENVEO	ENVironmental Earth Observation GmbH
EO	Earth Observation
ESA	European Space Agency
GLL	Grounding Line Location
GLM	Grounding Line Migration
GMB	Gravimetric Mass Balance
ISCL	Ice Shelf Coast Line
IV	Ice Velocity
IV-TDM	Ice Velocity Tidal Correction Module
IVC	Ice Velocity Change
MFID	Mass Flux Ice Discharge
MPC	Mission Performance Cluster
SEC	Surface Elevation Change
SL	Science Lead
SOW	Statement of Work
ST	Science & Technology AS
TOPS	Terrain Observation by Progressive Scans
TUD	Technical University of Dresden
UB	University of Bristol
UCL	University College London
UL	University of Leeds
UN	University of Northumbria
WAIS	West Antarctic Ice Sheet
NASA	National Aeronautics and Space Administration
SAR	Synthetic Aperture Radar
InSAR	Interferometric SAR

ML	Machine Learning

1 Introduction

1.1 Purpose and Scope

This document contains the Algorithm Development Plan (ADP) for Phase 2 of the Antarctic Ice Sheet CCI+ (AIS CCI+) in accordance with the contract and SoW [AD1 and AD2]. The purpose of the ADP is to outline the conceptual principles for novel and further algorithm development planned in the project for retrieval of essential climate variable (ECV) products from Earth Observation (EO) satellite data for the Antarctic Ice Sheet (AIS) which include [RD1]:

- Surface Elevation Change (SEC)
- Ice Velocity (IV)
- Ice Velocity Change (IVC)
- Gravimetric Mass Balance (GMB)
- Grounding Line Location (GLL)
- Grounding Line Migration (GLM)
- Ice Shelf CoastLines (ISCL)

1.2 Document Structure

This document is structured as follows:

- Chapter 1 provides an introduction to the document.
- Chapter 2 provides descriptions of planned algorithm developments for each ECV parameter.

1.3 Applicable and Reference Documents

Table 1.1: List of Applicable Documents

No	Doc. Id	Doc. Title	Date	Version
AD1	ESA/Contract No. 4000143397/23/I-NB CCI+ PHASE 2 - AIS	CCI+ PHASE 2 - NEW R&D ON CCI ECVS for AIS CCI	13.02.2024	NA
AD2	ESA-EOP-SC-AMT-2023-12 and its appendix 2	STATEMENT OF WORK, ESA EXPRESS PROCUREMENT – EXPRO CCI+ Phase 2 – Theme II – Antarctic Ice Sheet (AIS)	14.07.2023	1.2

Table 1.2: List of Reference Documents

No	Doc. Id	Doc. Title	Date	Version
RD1	NU-ESA-AISCCI+-URD-001	User Requirements Document (URD)		2.0

Note: If not provided, the reference applies to the latest released version

2 Planned Algorithm Developments

The core algorithms for all ECV parameters of the Antarctic Ice Sheet CCI+ project have been developed in the framework of the previous project phases or within other projects. In the current phase of the project further developments of these algorithms are foreseen that involve novel implementations, sensors or corrections that meet new specifications and user requirements [RD-1]. The planned algorithm developments are described below.

2.1 Surface Elevation Change (SEC)

Surface Elevation Change (SEC) Products were developed during phase-1 using the latest Level-2 input data from suitable ESA radar altimetry missions operational since 1991. These missions were ERS-1 (1991-1996), ERS-2 (1995-2003), ENVISAT (2002-2012), CryoSat-2 (2010-), Sentinel-3A (1996-), and Sentinel-3B (2018-).

Since the end of phase-1, a new range of improved ESA Level-2/3 thematic land ice along-track products have been released for current operational missions (CryoSat-2 and Sentinel-3A, and Sentinel-3B) (Table 2.1). These offer significant improvements in the coverage, accuracy and precision of elevation measurements over ice sheets, and the ice sheet margins in particular. Members of the Antarctic and Greenland CCI+ Phase-2 consortium have had a leading role in the development and commissioning of these new thematic land ice products (developed in the Sentinel-3 MPC (2016-2021, 2022-), and the ESA Cryo-TEMPO (2020-) projects), and therefore have an in-depth knowledge and experience of processing these new data over ice sheets.

Table 2.1: New thematic Level-2 products available for AIS_cci+ phase 2

Mission	Phase-1 L2 Inputs	New Improved Thematic L2 Evolutions Available for Phase-2	Scheduled Availability of Full Mission Thematic Data
CryoSat-2	ESA Baseline-D/E L2	Cryo-TEMPO Land Ice Thematic products (Baseline-B)	Jan 2023 (full data set already processed, awaiting release).
Sentinel-3A/B	ESA SR_2_LAN BC4 (ocean optimised only)	ESA S3 Land Ice Thematic L2	Q2 2023 (limited TDS available now).

During phase-2 we plan to integrate these new thematic land ice product baselines into the SEC processing chain in order to benefit from the improved measurement coverage and accuracy. We will also address a backscatter correction upgrade by exploring the use of adding waveform parameters such as the leading edge width and trailing edge slope within the processing system. In addition, a requirement of phase-2 is to produce SEC products from new sensors such as the NASA Laser Altimetry mission ICESat-2 (launched in September 2018). ICESAT-2's laser altimeter (lidar) measures the air-snow interface whereas conventional radar altimeters are subject to penetration through the snow layer. To merge elevation measurements from the two different instruments (radar and lidar) requires development of new firn correction, cross-calibration and merging algorithms. This necessitates the comparison of firn models and merging algorithms in an algorithm round robin against validation data to pick the best algorithms. Following the development of the new CCI+ mission ingest and cross-calibration algorithms a test and validation phase will follow before inclusion in the operational SEC products. Further, operationalization of the R&D within the AIS CCI+ phase 2 will be conducted within the C3S, and we strive to ensure the quality and uptake of AIS CCI+ phase 2 developments into C3S.

ICESat-2 ATL-06 height products (Figure 2.1) were still in commissioning and not mature enough during AIS CCI+ phase-1's development and production phases and therefore were only used during final validation stages. Since then ICESat-2 has completed commissioning and released a range of Level-0 through Level-3B products, including version 5 of the ATL-06 land ice height data, required by the AIS CCI+ SEC chain. It should be noted that NSIDC have also released ATL-11 (height time series) and ATL-15 (gridded height change). Due to the different measurement epoch requirements of the AIS CCI products, ATL-15 products may not be directly used as an input. These will be used instead for validation of the AIS CCI+ products.

We have performed a comparison of elevation changes recorded by ICESat-2 and CryoSat-2 over the Greenland Ice Sheet between 2018 and 2022 to assess their similarities and differences. We used the ALT06 Version 5 and

Cryo-TEMPO Baseline-B products as our ICESat-2 and CryoSat-2 datasets, respectively. We applied the model fit method (McMillan et al., 2016; Slater et al., 2021) to estimate time series of elevation changes over the whole ice sheet, the interior and the ablation zone, and calculate rates of elevation change and seasonal elevation changes (only in the ablation zone) from both ICESat-2 and CryoSat-2. To understand the influence of processing parameters such as outlier exclusion limit, epoch window and interpolation distance, on the observed elevation changes from both missions, we carried out a sensitivity analysis in the interior and the ablation zone. Our analysis showed that the rates of elevation changes are strongly influenced by the spatial sampling whereas the seasonal elevation changes are primarily influenced by the temporal sampling for both missions. The sensitivity analysis most importantly highlighted that the elevation changes observed by ICESat-2 and CryoSat-2 are in very good agreement over most of Greenland Ice Sheet, with parameters leading to both rates of elevation change and seasonal changes agreeing within their respective uncertainties. A similar intercomparison will be performed over Antarctica adapting the methods developed for Greenland to assess the similarities between both missions.

In addition, annual DEMs from the full radar altimetry timeframe will be added as new products alongside the existing single mission and multi-mission 5-year mean SEC products.

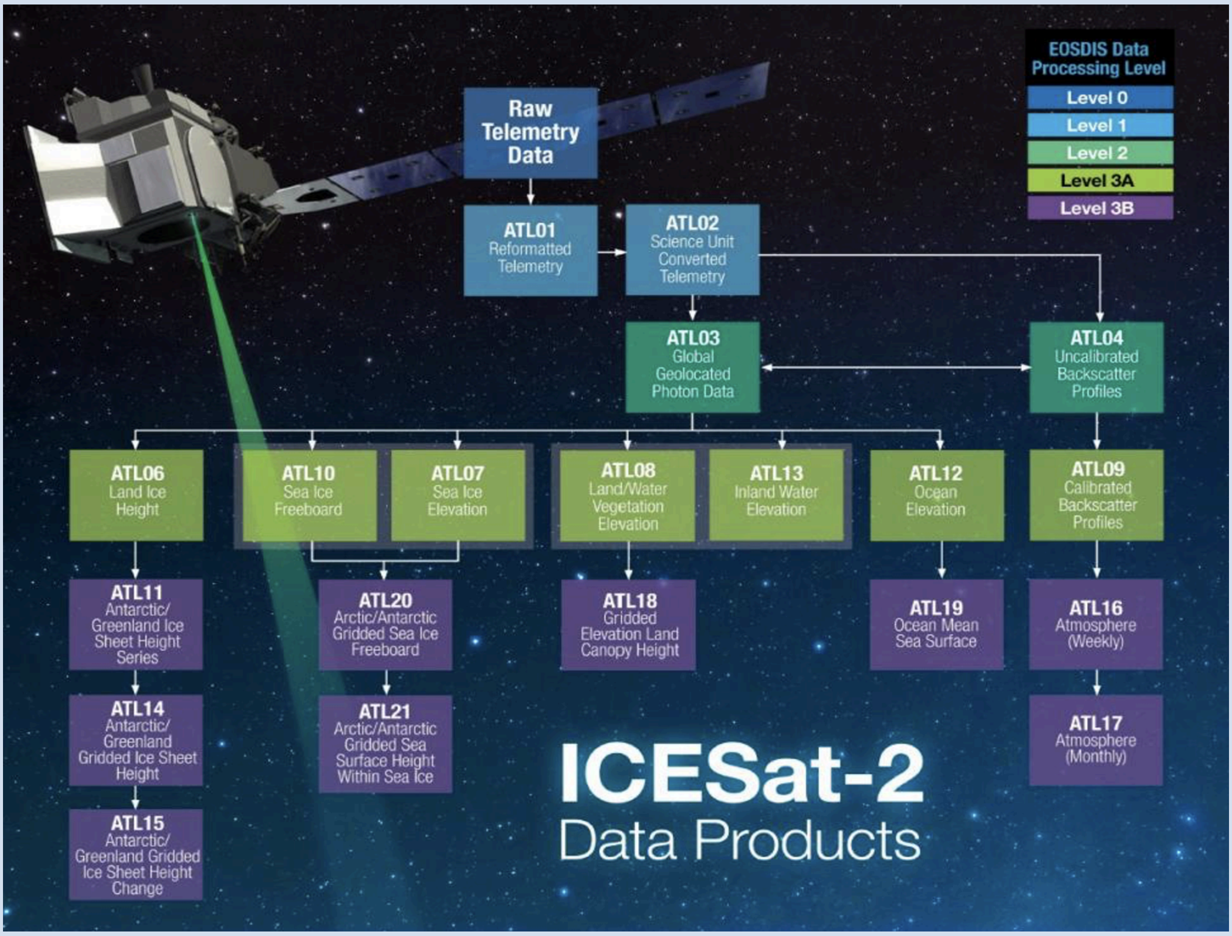

Figure 2.1: ICESat-2 Data Products from NSIDC. AIS CCI+ phase-2 will process ATL06, and use ATL11 and ATL15 for validation of SEC products (credit NSIDC)

2.2 Ice velocity (IV)

The key novel development for the ice velocity (IV) retrieval algorithm in Phase 1 of the project was the implementation of an Ice Velocity Tidal Correction Module (IV-TCM) in the IV processing chain. The IV-TCM corrects the ice velocity on ice shelves and floating extensions of outlet glaciers (e.g. ice tongues) for tidally induced vertical motion. In Phase 2 of the project the focus of development is on 1) the inclusion of SAOCOM SAR data in the processing chain, 2) testing of InSAR-augmented IV retrieval, 3) preparation for the new IV derived Ice Velocity Change (IVC) product (see section 2.3).

The development of Sentinel-1 Terrain Observation by Progressive Scans (TOPS) mode InSAR started in phase 1 of the Greenland CCI+ project and culminated in the generation of a comprehensive high-resolution ice sheet wide velocity map at 50 m posting by combining InSAR and offset-tracking (Nagler et al., 2015). In this project we plan to extend the InSAR IV retrieval by testing it for selected key regions in Antarctica using Sentinel-1 SAR data. Additionally, we investigate methods for combining C-Band and L-Band data using InSAR by combining Sentinel-1 and SAOCOM SAR data. The SAOCOM- A/B dual satellite constellation, operated by CONAE, provides repeat-pass L-Band StripMap SAR data over the Antarctic Peninsula with a revisit time of 8 (two satellites) to 16 days (one satellite only) (Figure 2.2). Further improvement for ice velocity monitoring can be expected from the combination of L-band and C-band data as simulations have shown that L-band SAR data have a reduced fringe frequency, and that the coherence is less affected by changing surface conditions compared to C-band. Within the project we plan to develop, implement and test tools for processing SAOCOM data to enhance the ice velocity retrieval in Antarctica in synergy with Sentinel-1 and to evaluate the quality of the products against velocity reference data sets from other sources. Issues in processing SAOCOM data are low quality of current orbit information and very large baselines requiring accurate topographic correction. The planned work will be carried out in close coordination with the activities proposed for Greenland Ice Sheet CCI+ and 4DGreenland and prepares for the upcoming NISAR (scheduled for launch in 2024) and Copernicus ROSE-L Mission.

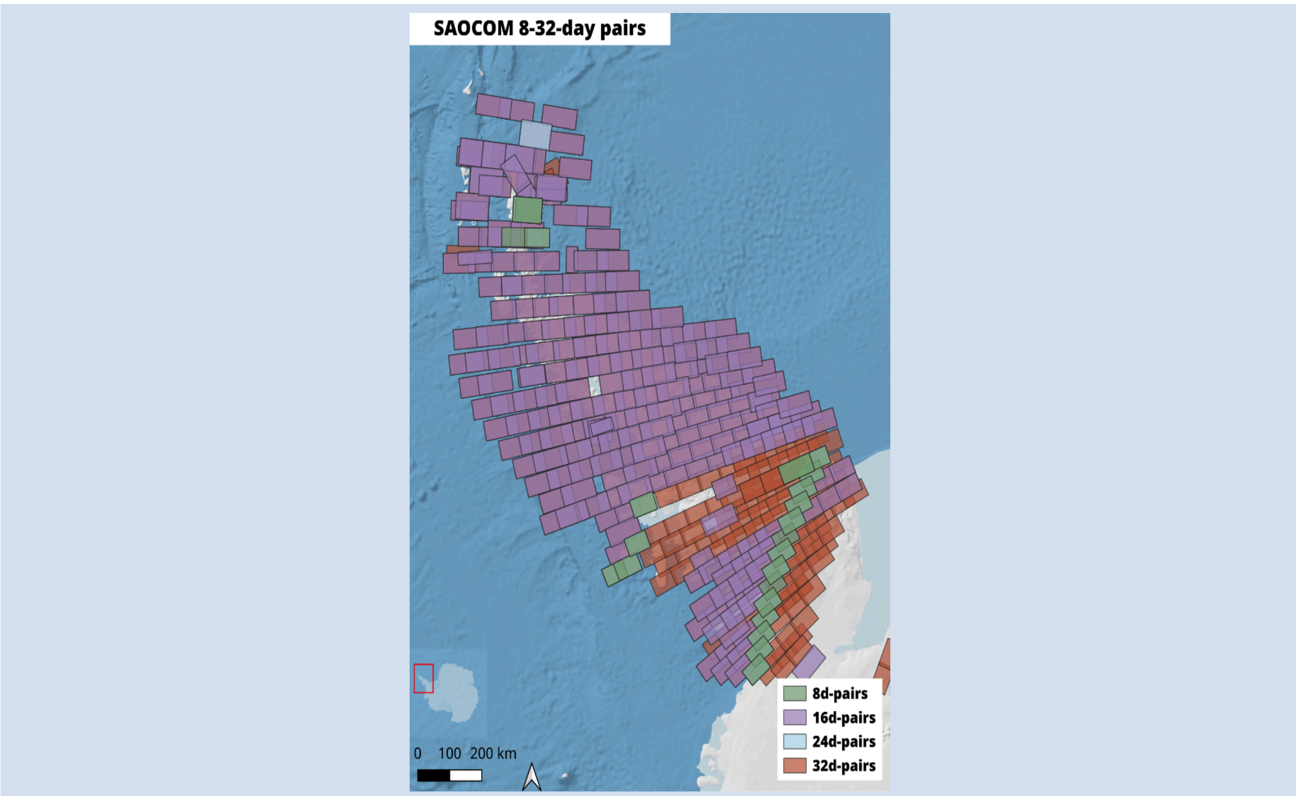

Figure 2.2: Antarctic Peninsula coverage of SAOCOM 1A and 1B Stripmap S4 and S5 acquisitions with 8, 16, 24 & 32 days repeat coverage (Nov 2021- Mar 2022).

Many small-scale dynamic phenomena have a rapid time variation and/or a vertical displacement (subsidence/uplift) component that is not preserved in the IV product (Neckel et al, 2021). The high resolution and low noise level of InSAR measurements provides an opportunity to study these phenomena from time-series based on individual image pairs, i.e., with a 6-12 day time resolution, but this is only possible by using the line-of-sight velocities, along with supporting information required for users to interpret the data correctly. In close coordination with Greenland Ice Sheet CCI+, a prototype time-series line-of-sight velocity product will be defined, and an example time-series will be generated for an area of interest in Antarctica, to be defined during the project.

2.3 Ice Velocity Change (IV)

One of the main outcomes of the Antarctic Ice Sheet CCI project was the development of an operational system for regular retrieval of ice velocity based on Copernicus Sentinel-1 SAR, that has since been further adapted and improved to accommodate new user requirements and increasing data coverage and temporal resolution. Based on this system, ENVEO has generated an extensive archive of IV maps covering the Antarctic Ice Sheet margins during the Sentinel-1 era (2015-onwards), with additional IV maps from other historic and ongoing SAR missions (TerraSAR-X, TanDEM-X, ERS-1, ERS-2, ENVISAT) covering key regions since the early 1990's. In this project we plan to exploit this archive and study the feasibility of a new ECV product on ice velocity change (IVC), detailing the spatial distribution of changes in ice flow rate over specified time intervals (Figure 2.3). IVC is a fundamental ice sheet parameter which is key to detecting and investigating dynamic instabilities and to identify and distinguish short term fluctuations from longer term trends that may be induced by climatic and/or oceanographic changes. IVC is currently not provided by any of the main EO programs or operational services. In this project, we aim to develop, test and integrate an IV system module for generating IVC on a routine basis and to provide demonstration products covering key areas in the API and WAIS.

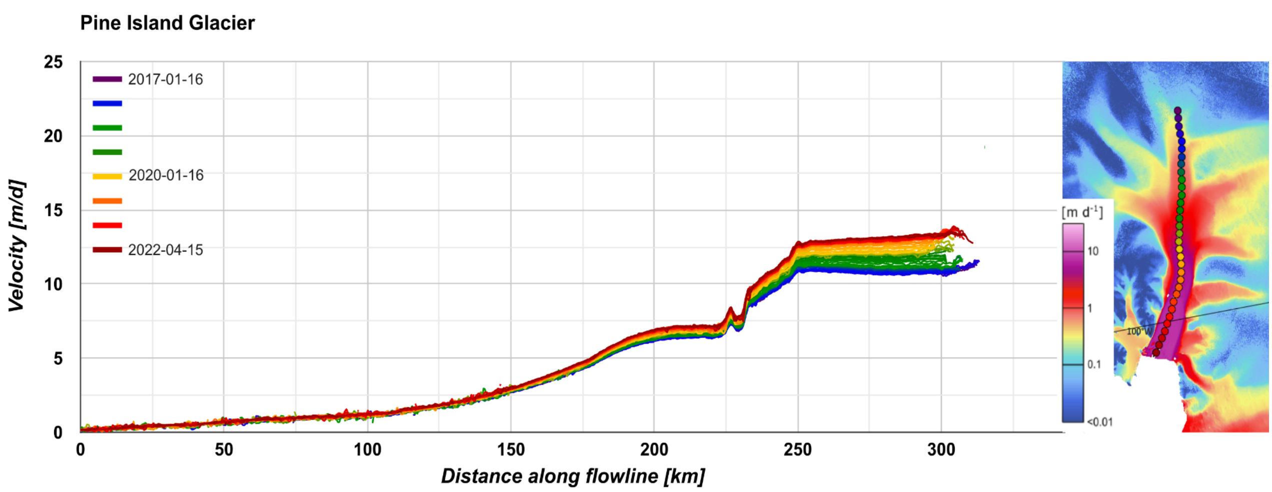

Figure 2.3: Monthly ice velocity along a profile on Pine Island Glacier (WAIS) between January 2017 and April 2022 derived from Copernicus Sentinel-1 (S1) data in AIS CCI+ Phase 1. The relative velocity increase towards the floating terminus is in the order of 25%. The figure demonstrates the feasibility of detecting ice velocity change (IVC) from time series of S1 data in order to establish longer term trends.

2.4 Gravimetric Mass Balance (GMB)

We will perform new research and development to establish a solution to bridge the gap in observations between GRACE and GRACE-FO. We will evaluate a range of approaches to bridge the observation gap between GRACE and GRACE-FO. These approaches include solutions driven by external data, specifically based on gravity field determination by high-low satellite-to-satellite tracking with ESA's SWARM mission (Lück et al., 2018; Forootan et al., 2020; Richter et al., 2021). Possible approaches also include data-adaptive methods purely driven by the GRACE and GRACE-FO models (Wang et al., 2021; Yi and Sneeuw, 2021). After assessment of these approaches, the most effective approach will be implemented.

As an additional work, an ellipsoidal correction will be developed and implemented to make the inference of ice mass changes from gravity field changes more accurate. Recent research has highlighted some limitations of the spherical approximation applied so far (Chao 2016, Li et al. 2017; Ditmar et al. 2018; Ghobadi-Far et al. 2019). We will review the literature, assess different novel approaches for an ellipsoidal correction and choose the most effective one.

In addition, we will follow developments in the recommendations of the GRACE-FO Science and Data System on how to handle low-degree components (degree-one, C20, C30) and implement them in our algorithms.

2.5 Grounding Line Location (GLL)

In Phase 1 of the project the focus was on processing 6-days repeat pass Sentinel-1 A/B data to double difference interferograms to obtain time series of grounding lines on selected key glaciers. No algorithm development was foreseen for the GLL. So far, a large-scale, continent-wide mapping of the GLL has been hampered by the labour-intensive manual mapping of the GLL on double difference interferograms and the time-consuming search for coherent combinations of interferograms over the fast-decorrelating, fast-moving glaciers of interest. In both aspects a Machine Learning (ML) and filtering algorithm can lead to an increased number of delineations and a more streamlined production of the GLL in the Phase 2.

- During algorithm development, we will explore the influence of different features like phase, DEM, IV and coherence on ML- based algorithms by using the current AIS CCI GLL product as input training data.
- Different network architectures (Figure 2.4) will be explored with the potential to develop an automatic deep learning pipeline which is supposed to substitute the manual delineation step in the current production process.

Details on the proposed algorithm are currently under review in (Ramanath et al, 2024). The scope of the ML-based mapping of the GLL is currently limited to a prototype within the present baseline proposal. However, if additional funding should become available through a dedicated option, two potential outcomes could be envisaged:

- A complete stand-alone pipeline for automatic delineations in case of a superior performance to manual Mapping
- A combination of both delineation methods to use ML-delineated GLLs as an indicator of areas with substantial grounding line migration or to fill temporal gaps in the manual GLL product. Such a combination has already been foreseen in the current product format by allowing for a “delineation type” parameter.

A higher number of delineations also lays the groundwork in preparation for the new GLL-derived Grounding Line Migration (GLM) product (Section 2.6) by producing the required long time-series and filling temporal gaps in existing delineations.

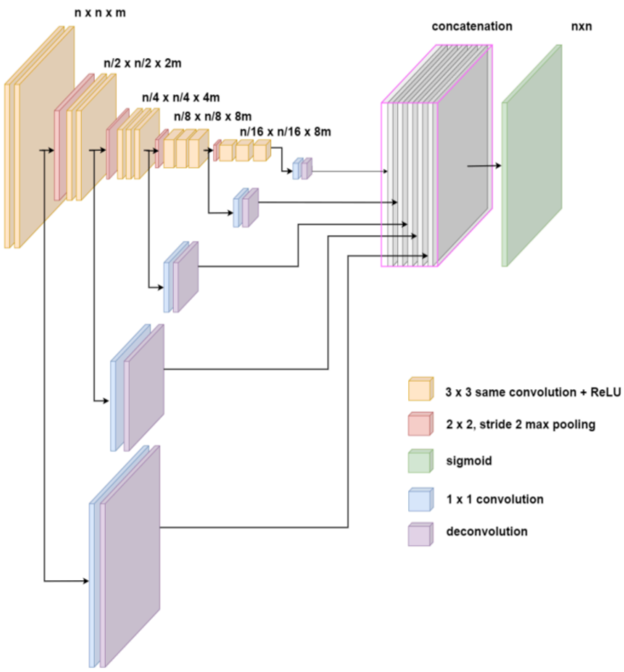

Figure 2.4: A possible network architecture for the ML-based GLL delineation is the Holistically-Nested Edge Detection architecture (Xie and Tu 2015). The superscripts show the dimensions of the resulting tensor after convolution. n is the height/width of the input and m is the number of convolution filters.

2.6 Grounding Line Migration (GLM)

A consistent gapless time series of GLL mappings produced as a baseline product requirement will serve for the development of the grounding line migration algorithm. Here different approaches are possible. For a preliminary GLM product will explore the following metrics:

- An area averaged grounding line change measurement using the box-method (also sometimes called Area over Front) (Moon and Joughin, 2008)
- Pointwise distance distributions between closest points on two different grounding lines. In this case, an equal line sampling distance and the directionality (e.g. reference grounding line to target grounding line) is important.

Apart from the two aforementioned approaches which measure retreat for an entire glacier or ice shelf, the GLM product can also include point measurements along the glacier centre line or selected flowlines on the terminus. The metric for polygons and line segments (PoLiS) described in (Avbelj et al., 2014) to estimate the distance between polygons will also be investigated.

A tide-corrected grounding line migration product is currently out of scope for this phase, but the time series of grounding lines will allow for a separation of shorter tide-induced variations and a long-term migration signal due to ice shelf thinning.

2.7 Ice Shelf CoastLine (ISGL)

The objective of the proposed activity is to investigate the added benefits of combining radar measurements (Sentinel-1) with altimetry (CS2) in the delineation of ice shelf coastlines. This investigation will be conducted over three selected ice shelves (Larsen-C, Ronne, Filchner). Those three ice shelves cover a large area and have been subject to large calving events in the recent past. Furthermore, they represent challenging areas with the simultaneous presence of glaciers and islands.

Delineation of the Ice Shelf CoastLine (ISCL) will be performed using both SAR images from Sentinel-1 and elevation data from CryoSat-2 tracks. The elevation data compiled from CS2 tracks will provide an initial guess for the model based on elevation differences that can indicate the start of the ice shelf coastline. That initial guess along with corresponding SAR imagery from the designated time and location from Sentinel-1 will be fed to a Convolutional Neural Network (CNN) That will combine the 2 inputs to predict a first iteration of the location of the ISCL. Then, the model will be run iteratively as a refinement network to refine the prediction until the location converges to the predicted ISCL.

The proposal has the following merits:

- Combination of S1 and CS2 sources exploiting their strengths
- Iteratively refining front lines explores the utility of updating a certain but outdated source by using high-resolution but ambiguous images. In the future, this approach could be used for updating previous manual delineation too.
- Iterative deep learning segmentations are less studied than traditional computer vision methods or convolutional neural network (CNN) architectures. Deep Snakes [5] and similar papers [6] demonstrated that segmentation of connected objects (border, etc.) can be more efficiently performed by deforming an existing line segment than pixel-wise segmenting the image into regions (sea, ice, etc.)

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