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HELMHOLTZ-ZENTRUM FÜR POLAR- UND MEERESFORSCHUNG

User Guide

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AWI CryoSat-2 Sea Ice Thickness Data Product

HELMHOLTZ ASSOCIATION

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Important Note

This service does not intent to be an operational data service. Updates on monthly ice thickness fields will happen irregularly and revisions of the entire data time series might occur at any time. We stress the fact that the interpretation of CryoSat-2 radar signals over sea ice and the uncertainties of freeboard retrieval and conversion into sea ice thickness are still an active field of research. This product shall therefore be a tool for the scientific community to enable further development of sea ice thickness retrieval algorithms and not be used in the sense of a fully calibrated and validated data product. It is our aim however, to implement progress in algorithm development in new revisions and provide robust uncertainty estimations for CryoSat-2 freeboard and sea ice thickness.

We encourage users to give feedback (info@meereisportal.de) for further improvements of the AWI CryoSat-2 level-2 sea ice processor.

Introduction

Purpose of this Document

Purpose of this document is the documentation of the CryoSat-2 level-2 processor developed at the Alfred Wegener Institute for Polar and Marine Research and data release of Arctic sea ice freeboard & thickness. This document will give a short description of the algorithm and methods applied to infer CryoSat-2 sea-ice freeboard and conversion into sea-ice thickness including the corresponding uncertainties. The results of the AWI CryoSat-2 level-2 processor processing are publically available for download and a technical description of the data format is given here.

This document is aimed to the scientific community, therefore only a brief algorithm outline is given. Interested readers, who seek a comprehensive introduction in the principle of CryoSat-2 sea ice thickness retrieval, should refer to the ESA CryoSat-2 website.

Scope of the AWI CryoSat-2 Sea-Ice Thickness Data Product

The development of a sea-ice level-2 (freeboard & thickness) processor was started at the Alfred Wegener Institute (AWI) with the goal of estimating uncertainties of CryoSat-2 data over sea ice. AWI is engaged in several validation activities of CryoSat-2 for land and sea ice in the framework of the CryoSat Validation Experiment (CryoVEx).

Further Information

For all information of the CryoSat-2 mission and ESA data products please refer to the *CryoSat Product Handbook*, which is available for download at the ESA Earthnet Online. Additional information can be found on the following websites:

German CryoSat-2 Project Office

ESA – Living Planet Programme - CryoSat

UCL - CryoSat Performance and Quality Monitoring

AWI Sea-Ice Level-2 Processor

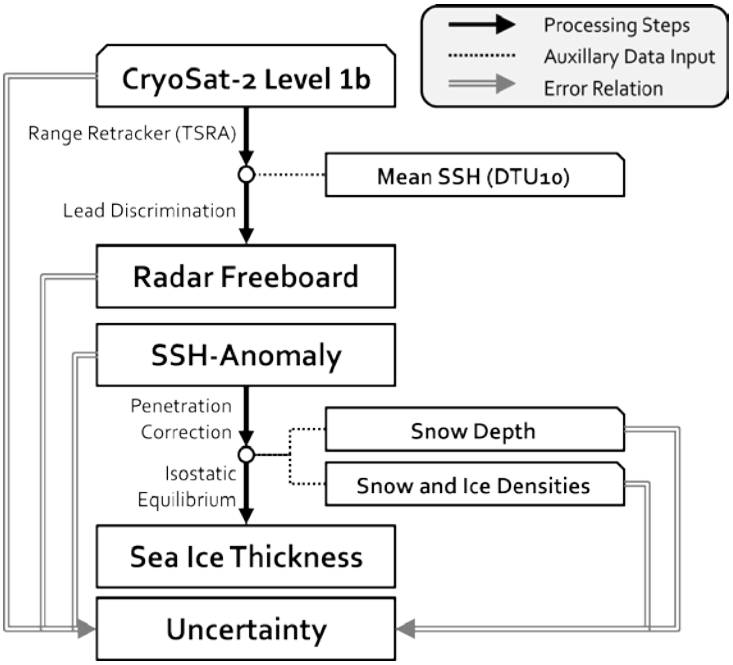


Figure 1: AWI CryoSat-2 sea ice level-2 processor scheme

The AWI sea-ice level-2 processor consists of two major steps:

1. Estimation of sea-ice freeboard from CryoSat-2 radar waveforms
2. The conversion of sea-ice freeboard into sea-ice thickness with auxiliary datasets

The first step requires the processing of all available CryoSat-2 level-1b data over Arctic sea ice, while the second step consists of the interpretation of the retrieved freeboard values. Both steps require assumptions and simplifications, which are based on results of validation activities by ESA and partner organizations. These are described in the following sections. It is a major goal of this processor to estimate not only sea-ice thickness, but also the quantification of uncertainties, which arise from of the quality of the level-1b and the necessary assumptions and simplifications.

Freeboard Retrieval

Getting Elevation from CryoSat-2 data

Quality issues with the original ESA level-2 data (Baseline-A) led to the investigations of the performance of several retracker algorithms, which retrieve the distance below the altimeter from the return echo power of the level-1b data files. For the AWI CryoSat-2 sea-ice product we apply a modified TSRA (Threshold-Spline-Retracker-Algorithm) retracker (Ferraro and Swift, 1995). It uses a cubic spline interpolation and a running mean to interpolate and slightly smooth the waveform. In a second step the leading edge of the first maxima of the waveform is tracked at a certain threshold level considering the noise floor. The mean distance to the surface is assumed to be at this retracked position. The TSRA is applied for all surface types (water, sea ice, mixed) to estimate the ellipsoidal elevation L.

From Elevation to Freeboard

In order to obtain sea-ice freeboard, the elevation L must be referenced to the local sea-surface height. This is done in two steps:

1. Subtraction of the mean sea-surface height product DTU10 (MSS) from the elevation L to remove the major contribution to the sea-surface height changes
2. Automatic detection of open water spots in the ice cover (leads). The elevations of leads define the sea-surface anomaly (SSA), which is the deviation of the actual sea-surface height from the mean sea-surface height.

The first step reduces errors in the detection of the leads and uncertainties in areas, where leads are scarce. The second step accounts for deviations (SSA) of the actual local sea-surface height and is calculated for each CryoSat-2 ground track individually.

The subtraction of mean sea-surface height (MSS) and sea-surface anomaly (SSA) from the elevations L subsequently yield the height of the sea-ice surface as seen by the radar altimeter. No assumptions or corrections of the radar wave penetration into the snow are made at this point; therefore the result is termed radar freeboard F_R.

$$F_R = L - (MSS + SSA)$$

Lead Detection

The accurate retrieval of freeboard crucially depends on the classification of leads in the ice cover. Radar waves over these leads can be automatically classified by the specular shape of the radar waveforms, compared to more diffuse reflections over sea ice. These specular returns are more “peaky” than their ice counterparts and the AWI CryoSat-2 sea-ice processor uses statistical parameters of the waveform stack (namely pulse peakiness PP, Kurtosis K and standard deviation STD) in the level-1b data to automatically detect them.

Leads are identified in the AWI sea-ice level-2 processor with the following settings:

$$PP > 40,\ K \geq 40 \text{ and } STD < 4$$

However, off-nadir reflections from leads can still dominate the echo and hence bias the range retrieval (snagging). Those echoes are detected and subsequently removed by calculating a modified PP on both sides of the power maximum of adjacent waveforms, the ’left’ (PP_{l}) and ’right’ (PP_{r}). The left peakiness should be high if the lead is in nadir position, though some minor contribution at the sides might be present ($PP_{\mathrm{l}} > 40$ and $PP_{\mathrm{r}} > 30$). Echoes from ice floes exhibit a lower peakiness at the tail of the waveform and therefore are identified by $PP_{\mathrm{r}} < 15$ and $K < 8$.

After classification for each CryoSat-2 profile, the elevations of the leads are interpolated and smoothed over a 100 km window.

Radar Penetration into Snow

Complex and regional as well as temporal varying physical properties (temperature, density, roughness) of the snow layer above Arctic sea ice are a source of uncertainty for the interpretation of the radar freeboard in terms of its location at or above the snow-ice interface. At dry and cold conditions, the main reflector of Ku-Band signal of SIRAL should theoretically be the snow-ice interface. However results from validation experiments (Hendricks et al., 2010, Willatt et al., 2010, Willatt et al., 2011) have shown that the retracked elevation is often within the snow layer or sometimes the air-snow interface, e.g. by ground radar observations or comparisons between airborne laser and radar altimeter. Since validation data regarding penetration are sparse at basin scale, we apply a simplified parameterization which is taking into account seasonal changes.Therefore we introduce an additional penetration factor P, which describes the penetration of the radar reflection horizon. For the entire Arctic we assume a maximum penetration P_{max} of 23 cm from November till April, 11 cm for October and May, and 0 cm from June till September. The penetration factor is set to not exceed local snow depth.

$$P(Z) = \begin{cases} Z & : Z < P_{max} \\ P_{max} & : Z \geq P_{max} \end{cases}$$

$$F = F_R + P$$

Note: The choice of setting an Artic-wide penetration factor very likely does not reflect the regional different snow conditions and is one important factor of uncertainty for CryoSat-2 Arctic freeboard. However, the knowledge of regional and temporal variation of CryoSat-2 radar penetration into the snow layer is limited by the lack of airborne validation data in early winter and the central and eastern part of the Arctic Ocean. Future revisions of the AWI CryoSat-2 sea-ice level-2 processor shall contain an improved handling of this parameter in freeboard retrieval.

Freeboard Uncertainty

Summarizing, the uncertainty budget of the freeboard retrieval depends on

1. The quality of the level-1b radar echoes
2. The skill of the SSA detection algorithm, that references the elevations to the actual sea-surface height
3. The knowledge of radar penetration into the snow

Assuming uncorrelated and errors and thus standard error propagation, the uncertainty of each individual freeboard measurement from CryoSat-2 can be described as:

$$\sigma_F^2 = \sigma_L^2 + \sigma_{SSA}^2 + \sigma_P^2$$

with σ_L the uncertainty for the range measurements (radar speckle), σ_{SSA} the uncertainty of sea-surface anomaly and σ_P the uncertainty of the approximation of radar penetration.

This uncertainty is likewise calculated for each data point individually. Except the SSA uncertainty, which is a function of the standard deviation of lead elevation and the distance to the next lead, all other uncertainty contribution are set to a fixed value (see table below).

	Parameter	Value	Reference
σ_L	radar speckle	0.12 – 0.14 m	Wingham et al., 2006
σ_{SSA}	local sea level	variable	Function of distance to next detected lead
σ_P	radar-snow interaction	0.1 m	Results from CryoVEx campaigns

Sea-Ice Thickness Conversion

Likewise to the freeboard retrieval, the calculation of sea-ice thickness is done for each CryoSat-2 data point individually to allow point-wise uncertainty estimation. Following the assumptions made for the penetration into the snow, we add the penetration to the radar freeboard to obtain the elevation of the snow layer above the local sea level. This elevation than can be used to calculate sea-ice thickness T, if the depth of the snow layer Z and the densities of sea water, sea ice and snow are known (ρ_W, ρ_I, ρ_Z):

$$T = (F_R + P) \cdot \frac{\rho_W}{\rho_W + \rho_I} + Z \cdot \frac{\rho_S - \rho_W}{\rho_W - \rho_I}$$

Snow Depth

The main challenge for sea-ice thickness retrieval with satellite altimeters is the parameterization of snow depth on sea ice, which is not measured routinely. There are promising efforts to use passive microwave to estimate snow depth with different approaches, but the current processors uses snow climatology instead of remote-sensing data. Warren et al., 1999 established this climatology with results from drifting station mainly on multi-year sea ice collected over the past decades. But since the Arctic Ocean shows a significant higher fraction of first-year sea ice, we follow the approach proposed by Kurtz et al., 2010 and multiply the climatological snow depth values over first year ice with a factor of 0.5.

Note: This approach is identical to Laxon et al., 2013. The climatology is given as a fit function for each month and only valid for the central Arctic Ocean. Significant error may occur if this fit is used also for region farther south (e.g. Baffin Bay), however this is included in the data product for the reason of completeness.

Snow and Sea-Ice Densities

The processor uses a fix value for the density of sea water (1024 kg/m^3), while the densities of sea ice are different for first-year and multi-year sea-ice regions (916.7 kg/m^3, 882.0 kg/m^3). The snow densities are retrieved from the Warren climatology (Warren et al., 1999).

Sea-Ice Thickness Uncertainty

The estimation of sea-ice thickness follows the same principles as the estimation of freeboard uncertainty for each data point. A more detailed description and weighting of the different sources of uncertainty is given in Giles et al., 2007.The thickness uncertainty depends on the uncertainty of freeboard, snow and ice density as well as snow depth. The density water varies not significantly and is neglected in the uncertainty budget.

$$\sigma_T^2 = \left(\frac{\rho_W}{\rho_W - \rho_I}\right)^2 \cdot \sigma_F^2 \; + \left(\frac{Z}{\rho_W - \rho_I}\right)^2 \cdot \sigma_{\rho_S}^2 + \left(\frac{F \cdot \rho_W + (\rho_S - \rho_W) \cdot Z}{\rho_W - \rho_I}\right)^2 \cdot \sigma_{\rho_I}^2 + \left(\frac{\rho_S - \rho_W}{\rho_W - \rho_I}\right)^2 \cdot \sigma_Z^2$$

An estimation of the individual errors is given in the table below.

	Parameter	Value	Reference
σ_F	Freeboard	Variable	See estimation of freeboard uncertainty (this document)
σ_{ρ_S}	Snow density	100 kg/m^3	Climatological variability (e.g. Kurtz et al., 2011)
σ_{ρ_I}	Sea-Ice density	FYI : 35.7 kg/m^3 MYI: 23 kg/m^3	Alexandrow et al., 2010
σ_Z	Snow depth	Variable	From Warren Climatology (Warren et al., 1999)

Data Gridding

The delivery of freeboard and thickness data for individual orbits is impractical due to the large amount of data, which the user would be required to download. Therefore all parameter fields are gridded to an EASE 2.0 grid (see following section). While freeboard and thickness values of these gridded points are the mean of all values in one grid box, the estimation of gridded uncertainty is handled differently. Since all data points have their individual uncertainty, we calculate the uncertainty of the mean values by error propagation:

$$\sigma^2_{\bar{F},\bar{T}} = \frac{\sum_{i=1}^{N} \sigma^2_{F_i,T_i}}{N^2}$$

Note: Since the uncertainty of mean freeboard or mean thickness depends on the numbers of data points in one grid cell, the mean uncertainty cannot be projected or interpolated onto a different grid.

Auxiliary Data Sources

Besides the actual CryoSat-2 level-1b data, which is available for registered users from ESA, the AWI sea-ice level-2 processor depends on the additional sea ice and ocean data sets. A list of the parameters and their sources is given below. The parameters are available in the AWI CryoSat-2 sea-ice product files projected on the output grid and averaged over one month.

Parameter	Provider
CryoSat-2 (SIRAL) level-1b data	ESA (Access)
Sea-Ice Type	OSI-SAF (Link)
Sea-Ice concentration	OSI-SAF (Link)
Mean sea surface (MSS)	DTU10 Mean Sea Surface (Link)

Data Description

Grid

For simplicity and use with other data products, all parameter fields are projected on the EASE2.0 Grid (Brodzik et al., 2012) The EASE2.0 Grid is based on a polar aspect spherical Lambert azimuthal equal-area projection and thus suitable for gridding the CryoSat-2 data on equal sized grid cells.

File Format

The data files are given a standardized binary data format (Network common data form: NetCDF v4). Specifications and software can be found at: http://www.unidata.ucar.edu/software/netcdf/. The parameters are given as grid arrays.

Parameter	Description	Unit	Type
longitude	Longitude	degrees east	Float
latitude	Latitude	degrees north	Float
radar_freeboard	Sea-ice freeboard	meter	Float
n_valid_radar_freeboard	Total number of valid radar freeboard data points inside one grid cell		Float
sea_ice_thickness	Sea-ice thickness	meter	Float
n_valid_ice_thickness	Total number of valid sea-ice thickness data points inside one grid cell		Float
sea_surface_anomaly	Sea-surface anomaly	meter	Float
radar_freeboard_uncertainty	Radar-freeboard uncertainty	meter	Float
ice_thickness_uncertainty	Sea-ice thickness uncertainty	meter	Float
snow_depth	Snow depth (modified climatology)	meter	Float
radar_penetration	Radar penetration into snow (parameterized)	meter	Float
ice_density	Ice density (modified climatology)	kg/m^3	Float
snow_density	Snow density (Warren climatology)	kg/m^3	Float
ice_type	Sea-ice type		Float
ice_concentration	Sea-ice-concentration	percent	Float

Parameter & Abbreviation Index

Parameter	Description
L	Surface elevation of retracked level-1b data
MSS	Mean dynamic sea surface
SSA	Sea surface anomaly
F_R	Radar freeboard
FYI	first-year sea ice
MYI	multi-year sea ice
Z	Snow depth
P	Penetration of radar waves into snow layer
PP	Pulse peakiness
T	Sea ice thickness
$TSRA$	Treshold spline retracker algorithm
ρ_W	Density of sea water
ρ_I	Density of sea ice
ρ_S	Density of snow
σ_L	Uncertainty surface elevation
σ_{F_R}	Uncertainty radar freeboard
σ_{SSA}	Uncertainty sea surface anomaly
σ_Z	Uncertainty snow depth
σ_T	Uncertainty sea ice thickness
σ_{ρ_W}	Uncertainty sea water density
σ_{ρ_I}	Uncertainty sea ice density
σ_{ρ_S}	Uncertainty snow density

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