Merged sea-ice thickness product from complementary L-band and altimetry information
<table>
<thead>
<tr>
<th>Contributors</th>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td><strong>AWI Team</strong></td>
<td>Stefan Hendricks</td>
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<td></td>
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<tr>
<td></td>
<td>Kirill Khvorostovskiy</td>
<td>University St. Petersburg</td>
</tr>
</tbody>
</table>
Managing Expectations

Digital Elevation Model with 25cm Resolution (Airborne Laserscanner)

No satellite or model can resolve true variability of sea ice
SIT Remote Sensing

ERS-1
ERS-2
Envisat
IceSat
CryoSat-2
SMOS
AltiKa
SMAP
Sentinel-3A

Altimeter
- Pulse-limited (Ku-Band)
- Pulse-limited (Ka-Band)
- SAR / SAR interferometric (Ku-Band)
- Laser

Radiometer
- L-Band
Radar Altimetry

Pioneering work by with ERS (Laxon et al. 2003)

Breakthrough for sea ice altimetry with CryoSat-2
Sea Ice Radar Altimetry

Step 1

Freeboard Retrieval

A Priori Information
- Snow Depth

Main Uncertainty Sources
- Complex radar echos over rough sea ice surfaces
- Potential bias from radar backscatter in snow layer
- Snow wave propagation

Step 2

Freeboard to Thickness Conversion

A Priori Information
- Snow Depth
- Snow Density
- Sea Ice Density
- Water Density

Main Uncertainty Sources
- Freeboard uncertainties
- Unknown regional and temporal variability of snow depth, snow density and sea ice density
Radar Echo Waveforms

Evolving radar altimeter concepts
(Improved footprints ▶ less surface type mixing)

Per echo waveform surface type and range
Radar Altimeter Processing Chain

Primary Data
Geolocated Radar Echoes

External Auxiliary Data
Mean Sea Surface
Sea ice type / MYI area fraction
Sea Ice Concentration
Snow Depth / Density
Orbit Freeboard Example

Sea Surface Height

Freeboard (Scale ×10)
Radar Altimetry - Coverage

Daily Trajectory  Weekly Grid  Monthly Grid

Sea ice thickness (m)

0.0  1.0  2.0  3.0  4.0  5.0
CryoSat-2 – Central Arctic Volume

SIV: Central Arctic Ocean (< 88N°) Sea Ice Volume in 1000 km³
Radar Altimetry – Validation

Airborne Validation March/April 2017

(CryoSat Mean: 2.57 m, Airborne-EM Mean: 2.65 m)
Radar Altimetry – Precision

Monthly collection of daily cross-overs (25km window SIT differences)

- Potential error sources: Range Noise | Sea-Surface Height | Selection Bias

▷ Average CryoSat SIT precision: ~ 40 cm
Product Intercomparison

Multi Year Ice (Lincoln Sea) - March

Multi Year Ice (Lincoln Sea) - November

Sea Ice Mass Reconciliation Exercise (SIMRE)

ESA Arctic+ Theme 2 (Ice Mass)
Long-Term Data Records

Envisat thickness retrieval

- calibrated at Envisat / CryoSat-2 overlap
- consistent auxiliary datasets and snow assumptions
<table>
<thead>
<tr>
<th><strong>Strength / Opportunities</strong></th>
<th><strong>Weaknesses / Threats</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Data Record</strong></td>
<td></td>
</tr>
<tr>
<td>▪ Longest continuous (2002 - …)</td>
<td>▪ No summer data (May – Sept.)</td>
</tr>
<tr>
<td>▪ ERS back to 1993</td>
<td>▪ Sentinel-3 not high inclination (S3/Envisat pole hole)</td>
</tr>
<tr>
<td>▪ Sentinel-3 program</td>
<td></td>
</tr>
<tr>
<td>▪ Dual-Band Altimetry</td>
<td></td>
</tr>
<tr>
<td><strong>Uncertainty</strong></td>
<td></td>
</tr>
<tr>
<td>▪ No indication of large scale bias in spring (CryoSat)</td>
<td>▪ Local uncertainty significant</td>
</tr>
<tr>
<td>▪ Auxiliary data may improve</td>
<td>▪ Thin ice under-represented</td>
</tr>
<tr>
<td><strong>Operational Status</strong></td>
<td></td>
</tr>
<tr>
<td>▪ Several centers</td>
<td></td>
</tr>
<tr>
<td>▪ Copernicus Climate Change Service (C3S) in prep</td>
<td></td>
</tr>
<tr>
<td><strong>Timeliness</strong></td>
<td></td>
</tr>
<tr>
<td>▪ CryoSat-2 (2 days)</td>
<td></td>
</tr>
<tr>
<td>▪ Sentinel-3 (3 hrs)</td>
<td></td>
</tr>
</tbody>
</table>
L-Band Radiometry

SMOS ice thickness: Support to Science Element
Utilize low-frequency radiometry for sea ice
Principle of L-Band Radiometry

Sky radiation

Permittivity depends on brine volume

$V_b = f(S_{ice}, T_{ice})$

Sea ice thickness

Ice

Water
# L-Band Radiometry Summary

<table>
<thead>
<tr>
<th></th>
<th>Strength / Opportunities</th>
<th>Weaknesses / Threats</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data Record</td>
<td>Daily global coverage</td>
<td>No summer data</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SMOS follow-on?</td>
</tr>
<tr>
<td>Uncertainty</td>
<td>Impact of snow might lead to snow depth information</td>
<td>Upper thickness limit</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Large footprint</td>
</tr>
<tr>
<td>Operational Status</td>
<td>Operational (U. Hamburg)</td>
<td></td>
</tr>
<tr>
<td>Timeliness</td>
<td>SMOS (2 days)</td>
<td></td>
</tr>
</tbody>
</table>
CryoSat-2 / SMOS Data Fusion

ESA Project: SMOS+ Sea Ice
Develop merged thickness prototype
Data Fusion Concept

- **CryoSat-2 L3 SIT**
- **SMOS L3 SIT**

Optimal Interpolation (weighted by uncertainties)

Merged L4 SIT
Bridging Temporal Coverage

14 - 20 Mar

First-Year Ice  Multiyear Ice

CS2 Sea-Ice Thickness (m)

0  1  2  3  4

SMOS Sea-Ice Thickness (m)

0.0  0.2  0.4  0.6  0.8  1.0  1.2
Merged Product – Background Field

(a)

CS2

Week

[i-2] [i-1] [i] [i+1] [i+2]

SMOS

Ice conc.

Ice type

Observation

Background

Optimal Interpolation: Innovation of background (weighted mean) by observations

(b) 14–20 Mar 2016

Background thickness (m)

0 1 2 3 4
Weekly Thickness Fields

09 - 15 Nov

14 - 20 Mar
Merged Product – Validation

CS2SMOS

AEM Total Thickness (m)

WM

SMOS

CS2

AEM mean survey ice thickness = 2.2 m
AEM modal survey ice thickness = 1.2 m

Multiyear Ice Area

AEM Modal

AEM Mean

Multiyear Ice

Total Thickness (m)

AEM Total Thickness (m)

CS2SMOS Total Thickness (m)

WM Total Thickness (m)

SMOS Total Thickness (m)

CS2 Total Thickness (m)
<table>
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<th>Strength / Opportunities</th>
<th>Weaknesses / Threats</th>
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<tbody>
<tr>
<td><strong>Data Record</strong></td>
<td></td>
</tr>
<tr>
<td>Weekly gapless</td>
<td>No summer data</td>
</tr>
<tr>
<td><strong>Uncertainty</strong></td>
<td></td>
</tr>
<tr>
<td>The best of two worlds</td>
<td>Smoothing removes localized features</td>
</tr>
<tr>
<td>(full thickness resolution)</td>
<td>Uncertainties depend on input where one method dominates</td>
</tr>
<tr>
<td><strong>Operational Status</strong></td>
<td></td>
</tr>
<tr>
<td>SMOS &amp; CryoSat-2 Sea Ice</td>
<td>Only reprocessed product</td>
</tr>
<tr>
<td>PDS in Q4 2018</td>
<td></td>
</tr>
<tr>
<td><strong>Timeliness</strong></td>
<td></td>
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<tr>
<td>Improved background field for NRT (2 day) service</td>
<td></td>
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</tbody>
</table>
## Conclusions – Product Guide

<table>
<thead>
<tr>
<th>Use</th>
<th>Don‘t use</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Altimetry</strong></td>
<td></td>
</tr>
<tr>
<td>▪ First-year / multi-year sea ice</td>
<td>▪ Young thin ice (freeze-up)</td>
</tr>
<tr>
<td>▪ Climate applications</td>
<td>▪ Areas close to ice edge</td>
</tr>
<tr>
<td>(longest data record)</td>
<td>▪ High coverage &amp; temporal resolution</td>
</tr>
<tr>
<td><strong>Radiometry</strong></td>
<td></td>
</tr>
<tr>
<td>▪ Daily observations of thin ice</td>
<td>▪ Older first-year, multi year ice</td>
</tr>
<tr>
<td><strong>Merged</strong></td>
<td></td>
</tr>
<tr>
<td>▪ Weekly observations for entire</td>
<td>▪ You want to use observation operators</td>
</tr>
<tr>
<td>northern hemisphere and thickness range</td>
<td>▪ You want to assimilate observations individually</td>
</tr>
</tbody>
</table>

1  2  3  4  5                      6                      7  8  9  10
Thank you!


ftp://data.meereisportal.de
user: altim
password: altim
/altim/sea_ice/product/north/cryosat2-smos/cs2smos_v1.4/