Snow depth on sea ice from altimetry for 2013-2019 Arctic and Austral winters

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Why do we need snow depth?

Crucial impact...

- Sea ice growth (*insulating role*), albedo, freshwater balance...
- Snow => Sea ice sinking + reduction of the radar echo speed propagation
- **Snow depth uncertainty** => *between* 30 and 100% of error on sea ice thickness (*Hippert-2016*)

...but snow depth is poorly known!

- Warren-99 climatology (*In situ data from 1957-90!*)
- From space: AMSR and IceSat x Envisat, bi-frequency KA/KU
- Models

**Equation:**

\[
SIT = \frac{\rho_w FB + \rho_s SD(1 + \alpha)}{\rho_w - \rho_i}
\]
Summary

1) Bi-frequency altimetric Snow depth measurement

2) Comparisons with OIB and AMSR in Arctic

3) First comparisons in Antarctica

4) Towards the CRISTAL mission  *(Sinead Farrell presentation this morning)*
1) Bi-frequency altimetric Snow depth measurement

The freeboard methodology (Laxon, 2003)

3 steps

1. Identification of Leads and Floes (Pulse Peakiness)
   \[ PP = \frac{\text{Max} (WF)}{\sum_i WF_i} \]

2. Retracking on Leads/Floes (TFMRA)

3. Radar Freeboard = \( H_{\text{floes}} - H_{\text{leads}} \)

- Lead echo
- Thick ice echo

© Sentinel-2 (Dec 2016)
1) Bi-frequency altimetric Snow depth measurement

Based on the difference of penetration between Ka (35.7 GHz) and Ku (13.5 GHz) frequencies (Guerreiro et al 2016, Armitage et al, 2015)

\[ SD = FB_{Saral/AltiKa} - FB_{Cryosat-2} \]

But be careful of the methodology !!

Time period: 2013-now
1) Bi-frequency altimetric Snow depth measurement

Footprint differences between SAR (CS-2) and LRM (Saral)

- **High impact** of surface roughness on the range retrieval on both CS-2 and Saral can compensate each other

\[ \text{Ka} - \text{Ku} = \text{penetration depth} + \text{roughness} \]

\[ \text{Ka} - \text{Ku} \approx \text{penetration depth} \]
1) Bi-frequency altimetric Snow depth measurement

To calculate snow depth from SARAL/Altika and Cryosat-2
We need CS-2 SAR/PLRM data
1) Bi-frequency altimetric Snow depth measurement

Saral/Altika :
SGDR AVISO L2
Cryosat-2 :
ESA (B-C)GOP PLRM L1b

The Snow Depth data will be on the CTOH by the end of 2019 in NetCDF

Arctic : 2013-2019
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Antarctica

2015 (ongoing Antarctica+ ESA)
2) Comparisons with OIB and AMSR-2

Validation with **OIB**: Operation Ice Bridge airborne data

Campaigns every year
*In Arctic between March and April*

2013-2017 OIB tracks

**Saral** < 81.5°N
### 2) Comparisons with OIB and AMSR-2

**AMSR:**

Advance Microwave Scanning Radiometer data

<table>
<thead>
<tr>
<th>NSIDC</th>
<th>Cavalieri et al./Meier et al.</th>
<th>only FYI</th>
<th>yes</th>
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<tbody>
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<td>Bremen Univ.</td>
<td>Rostosky et al.</td>
<td></td>
<td></td>
<td>Nov-May</td>
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<tr>
<td>Danish Met. Inst.</td>
<td>Winstrup et al. @LPS2019</td>
<td></td>
<td></td>
<td>March/April (OIB calib.)</td>
<td></td>
</tr>
</tbody>
</table>

**AMSR-E (Aqua):**

June 2002– Sept 2011

**AMSR-2 (GCOM-W1):**

July 2012 - now

NH | SH | NH | SH
---|----|----|---
only FYI | yes | on FYI only | yes

**AMSR:**

Advance Microwave Scanning Radiometer data
Comparisons with OIB and AMSR-2

2013
2014
2015
2017
IGS Sea Ice Winnipeg
Comparisons with OIB and AMSR-2

OIB trajectory 2015/03/29

Windstrup data ~ KaKu

But

Windstrup recalibrated on OIB

NSIDC AMSR tend to overestimate SD compare to OIB
Comparisons with OIB and AMSR-2

Good consistency between KA/KU snow depth data and OIB
Snow depth altimetric measurement: Arctic

Validation with Operation Ice Bridge (OIB) airborne data

- **Warren-99**
  - Validation with Operation Ice Bridge (OIB) airborne data
  - Snow depth altimetric measurement: Arctic

- **Ka/Ku data**
  - Validation with Operation Ice Bridge (OIB) airborne data
  - Snow depth altimetric measurement: Arctic

### Graphs

- **OIB snow radar**
  - Warren 99 modified
  - Ka/Ku snow depth

- **Bias**
  - 0.06 m
  - 0.0 m

- **R**
  - 0.59
  - 0.79

- **RMSE**
  - 0.1 m (42.1%)
  - 0.04 m (25.4%)
Snow depth altimetric measurement: Antarctic

~ Comparable spatial distributions
- Stronger patterns of depth snow in AMSR data.
- AMSR tend to overestimate (as in Arctic)

ongoing in the ESA Antarctica+ project
Snow depth altimetric measurement: Antarctic

NSIDC AMSR

STONG LACK OF IN-SITU MEASUREMENTS

Aspect

ongoing in the ESA Antarctica+ project
CRISTAL: Towards and Ice and Snow Satellite

**CRISTAL: Copernicus Radar for Ice and Snow Topographic Altimeter**
Preselected high priority Copernicus Mission (HPCM)

- Bi-frequency Ka/Ku SAR/SARin Polar Altimeter

- Primary objectives: Sea ice, Polar Caps and Glaciers survey
- Secondary objectives: Polar ocean topography; coasts, rivers and Lakes; permafrost

- Measure simultaneously Snow depth and freeboard → **SIT**

- Only project to ensure the continuity of altimetric measures over polar regions (**CS-2 orbit**)

- If selected, should be launched in mid 2020-2030 (**hopefully before the end of CS-2**)
Conclusion

- Snow depth is a strong limitation for SIT
- Already **KaKu** snow depth time series since 2013 with consistent results in Arctic.
  - Soon in Antarctica (end 2019-early 2020)
- Still open questions:
  - Doesn't Ka penetrate the snow at all?
  - Does Ku always penetrate the entire the snow cover?
    - CryoVex airborne Ka/Ku with Karen/ASIRAS (*ESA CryoSea-NICE*)
    - IceSat2 (~ 1 year of data)
    - MOSAIC (*started september 2019*)
- Preparation for **Ka/Ku** CRISTAL satellite
Thanks you for your attention !!!!!
CONCLUSION

Snow depth is a strong limitation for SIT thickness estimation

- The altimetric measurement of snow depth from Ka/Ku bi-frequency is a promising approach

  - already quite demonstrated in Arctic (Guerreiro et al, 2016)
  - with applications in Antarctica
Altimetric Sea Ice thickness measurement

The Freeboard methodology (ESA SI-CCI project, Ridout and Tonboe, 2012)

Freeboard (FB) : sea ice emerged height

\[ FB = H_{\text{floes}} - H_{\text{leads}} \]

Floes : sea ice surface
Leads : sea ice cracks

Hydrostatic equilibrium :

\[ SIT = \frac{\rho_w FB}{\rho_w - \rho_i} \]
Context: why observing sea ice thickness?

Sea Ice thickness is still poorly known

Thermodynamic weakening (*melting*)

Mechanical weakening (*fracture and export*)

Sea ice thickness time series in Arctic coming from ICESat, the PIOMAS model and from the satellite Envisat and Cryosat-2 (source: guerreiro et al, 2017)