Incertitudes sur l’estimation de l’épaisseur de glace de mer à partir de l’altimétrie satellitaire

Atelier glaciologie et altimétrie - 25/06/2019

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Introduction

- For many years, the Sea Ice Thickness computed from altimeter measurement is derived from the freeboard measurement thanks to the Hydrostatic Equilibrium equation

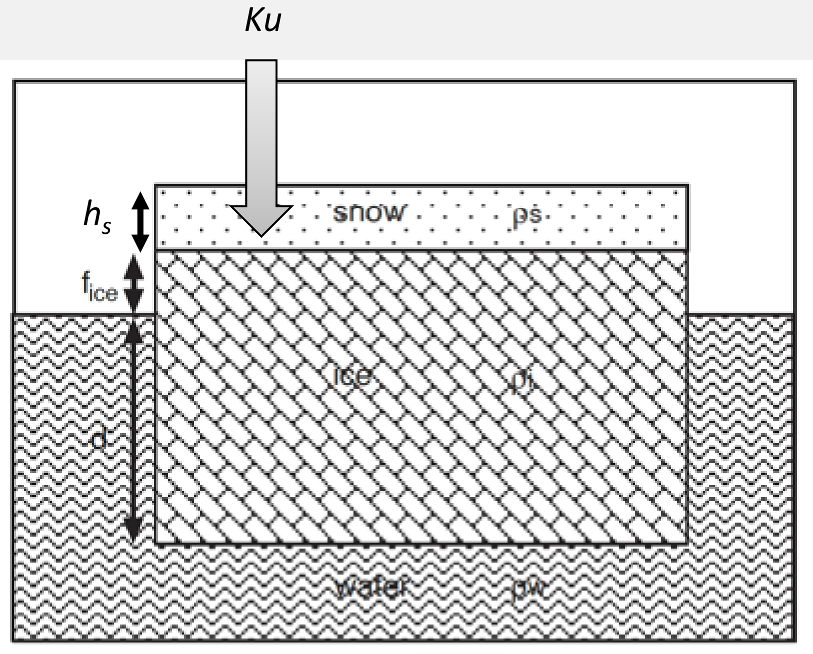
- SIT uncertainty is hard to estimate from measurements since large scale validation is not easy (there is no other Pan-Arctic/Antarctic ice thickness measurements, only local validation can be made thanks to in-situ measurements or airborne campaign)

- In the frame of the ESA POLARICE project, a review of the ice thickness uncertainty has been done based on literature in order to prepare the CRISTAL mission

- We propose here a summary of the uncertainty analysis on the SIT derived from satellite altimetry.

Hydrostatic Equilibrium (Ku-band)

HYPOTHESIS: The Ku waveform is reflected at the snow/ice interface



$$SIT = \frac{\rho_w}{\rho_w - \rho_{ice}} f_{ice} + \frac{\rho_s}{\rho_w - \rho_{ice}} h_s$$

- Water Density → ρ_w
- Ice Freeboard → f_{ice}
- Snow Density → ρ_s
- Sea Ice Thickness → SIT
- Ice Density → ρ_{ice}
- Snow Depth → h_s

Accounting for snow delay

- Range delay due to the snow : $f_{ice} = f_{radar} + (1 - \frac{c_s}{c})h_s$

- In literature :

Ulaby et al. 1986 → $\frac{c_s}{c} = (1 + 0.51\rho_s/1000)^{-1.5}$

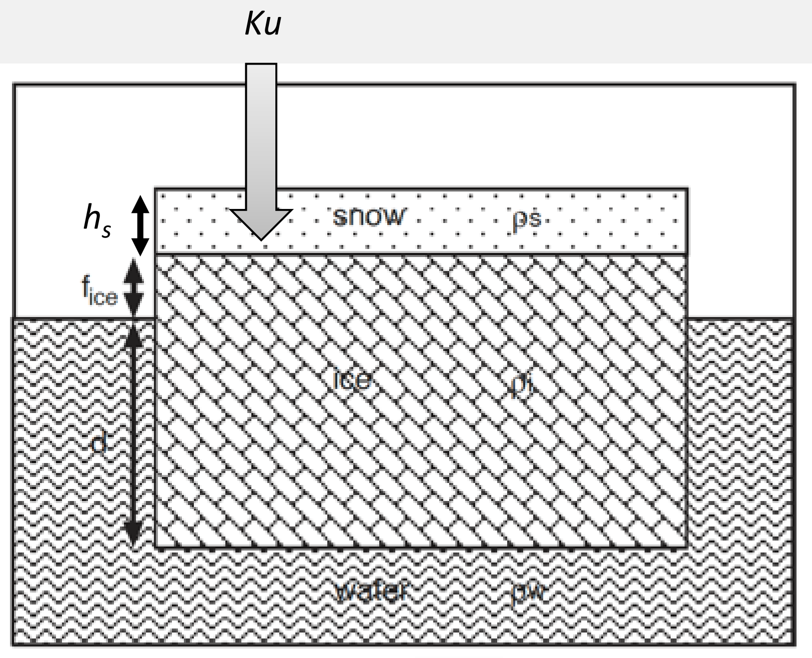
$with\ \rho_s = 290\ kg/m^3$

Tiuri et al. 1984 → $\frac{c_s}{c} = \frac{1}{\sqrt{1 + 1.7\rho_s/1000 + 0.7(\rho_s/1000)^2}}$

$$SIT = \frac{\rho_w}{\rho_w - \rho_{ice}} f_{radar} + \frac{(1 - {}^{c_s}/_{c})\rho_w + \rho_s}{\rho_w - \rho_{ice}} h_s$$

Hydrostatic Equilibrium (Ku-band)

HYPOTHESIS: The Ku waveform is reflected at the snow/ice interface



$$SIT = \frac{\rho_w}{\rho_w - \rho_{ice}} f_{radar} + \frac{\left(1 - {c_s}/{c}\right)\rho_w + \rho_s}{\rho_w - \rho_{ice}} h_s$$

Water Density

Freeboard

Snow Density

Ice Density

Velocity ratio

Snow Depth

Uncertainty sources on SIT

$$\varepsilon_{SIT}^2 =$$

$$\varepsilon_{f_{ice}}^2\left(\frac{\rho_w}{\rho_w-\rho_{ice}}\right)^2+\varepsilon_{h_s}^2\left(\frac{-\frac{\rho_w}{(1+0.00051\rho_s)^{1.5}}+\rho_s+\rho_w}{\rho_w-\rho_{ice}}\right)^2+\varepsilon_{\rho_s}^2\left(\frac{h_s\left(\frac{0.000765\rho_w}{(1+0.00051\rho_s)^{2.5}}+1\right)}{\rho_w-\rho_{ice}}\right)^2$$

$$+\varepsilon_{\rho_w}^2\left(-\frac{\rho_{ice}f_{ice}+h_s\left(\rho_s-\frac{\rho_{ice}}{(1+0.00051\rho_s)^{1.5}}+\rho_{ice}\right)}{(\rho_w-\rho_{ice})^2}\right)^2+\varepsilon_{\rho_{ice}}^2\left(\frac{f_{ice}\rho_w+h_s\left(-\frac{\rho_w}{(1+0.00051\rho_s)^{1.5}}+\rho_s+\rho_w\right)}{(\rho_w-\rho_{ice})^2}\right)^2$$

Based on CS-2 performances

MYI

$$\varepsilon_{SIT}^2 = \varepsilon_{f_{ice}}^2 52.002 + \varepsilon_{h_s}^2 11.492 + \varepsilon_{\rho_s}^2 1.554e^{-5} + \varepsilon_{\rho_w}^2 2.657e^{-4} + \varepsilon_{\rho_{ice}}^2 3.273e^{-4}$$

FYI

$$\varepsilon_{SIT}^2 = \varepsilon_{f_{ice}}^2 91.075 + \varepsilon_{h_s}^2 20.127 + \varepsilon_{\rho_s}^2 5.376e^{-6} + \varepsilon_{\rho_w}^2 1.758e^{-4} + \varepsilon_{\rho_{ice}}^2 2.056e^{-4}$$

In the CryoSat-2 SIT error budget, only one error source comes from the altimeter measurement, all the others come from external measurements / models.

Uncertainty sources on SIT

$$\varepsilon_{SIT}^2 =$$

$$\varepsilon_{f_{ice}}^2\left(\frac{\rho_w}{\rho_w-\rho_{ice}}\right)^2 + \varepsilon_{h_s}^2\left(\frac{-\frac{\rho_w}{(1+0.00051\rho_s)^{1.5}}+\rho_s+\rho_w}{\rho_w-\rho_{ice}}\right)^2 + \varepsilon_{\rho_s}^2\left(\frac{h_s\left(\frac{0.000765\rho_w}{(1+0.00051\rho_s)^{2.5}}+1\right)}{\rho_w-\rho_{ice}}\right)^2$$

$$+\varepsilon_{\rho_w}^2\left(-\frac{\rho_{ice}f_{ice}+h_s(\rho_s-\frac{\rho_{ice}}{(1+0.00051\rho_s)^{1.5}}+\rho_{ice})}{(\rho_w-\rho_{ice})^2}\right)^2 + \varepsilon_{\rho_{ice}}^2\left(\frac{f_{ice}\rho_w+h_s\left(-\frac{\rho_w}{(1+0.00051\rho_s)^{1.5}}+\rho_s+\rho_w\right)}{(\rho_w-\rho_{ice})^2}\right)^2$$

Based on CS-2 performances

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$$\varepsilon_{SIT}^2 = \varepsilon_{f_{ice}}^2 52.002 + \varepsilon_{h_s}^2 11.492 + \varepsilon_{\rho_s}^2 1.554e^{-5} + \varepsilon_{\rho_w}^2 2.657e^{-4} + \varepsilon_{\rho_{ice}}^2 3.273e^{-4}$$

$\rho_{ice} = 882$ kg/m^3 Alexandrov et al. 2010

$\rho_w = 1024$ kg/m^3 Wadhams et al. 1992

$\rho_s = 290$ kg/m^3 Warren et al. 1999

FYI

$$\varepsilon_{SIT}^2 = \varepsilon_{f_{ice}}^2 91.075 + \varepsilon_{h_s}^2 20.127 + \varepsilon_{\rho_s}^2 5.376e^{-6} + \varepsilon_{\rho_w}^2 1.758e^{-4} + \varepsilon_{\rho_{ice}}^2 2.056e^{-4}$$

$\rho_{ice} = 916.7$ kg/m^3 Alexandrov et al. 2010

$\rho_w = 1024$ kg/m^3 Wadhams et al. 1992

$\rho_s = 290$ kg/m^3 Warren et al. 1999

(varies between 240 and 340 kg/m^3)

Average errors on Sea Ice Thickness

Currently (CryoSat-2)

MYI

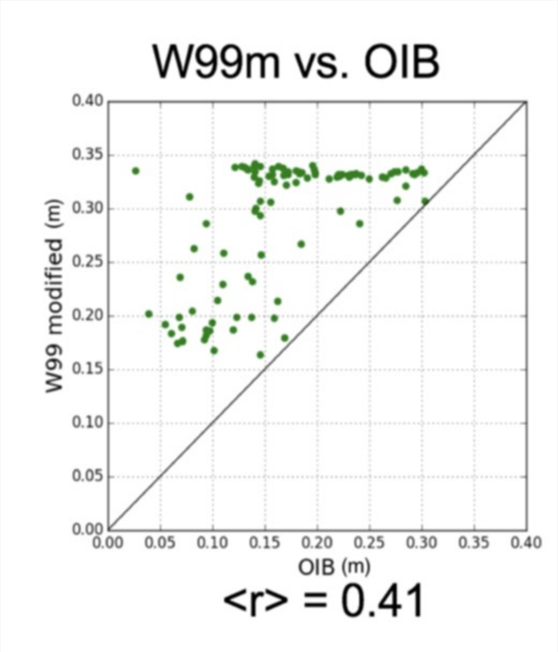
$\varepsilon_{f_{ice}} = 0.03$ m	Ricker et al. 2014
$\varepsilon_{\rho_{ice}} = 23$ kg/m^3	Alexandrov et al. 2010
$\varepsilon_{h_s} = 0.09$ m	Warren et al. 1999
$\varepsilon_{\rho_s} = 3.2$ kg/m^3	Warren et al. 1999
$\varepsilon_{\rho_w} = 0.5$ kg/m^3	Wadhams et al. 1992
$f_{ice} = 0.187$ m	Ricker et al. 2014 (March 2013 TFMRA50)
$h_s = 0.36$m	Warren et al. 1999 (March)

FYI

$\varepsilon_{f_{ice}} = 0.03$ m	Ricker et al. 2014
$\varepsilon_{\rho_{ice}} = 35.7$ kg/m^3	Alexandrov et al. 2010
$\varepsilon_{h_s} = 0.09$ m	Warren et al. 1999
$\varepsilon_{\rho_s} = 3.2$ kg/m^3	Warren et al. 1999
$\varepsilon_{\rho_w} = 0.5$ kg/m^3	Wadhams et al. 1992
$f_{ice} = 0.086$ m	Ricker et al. 2014 (March 2013 TFMRA50)
$h_s = 0.16$m	Warren et al. 1999 (March÷2 → modified version)

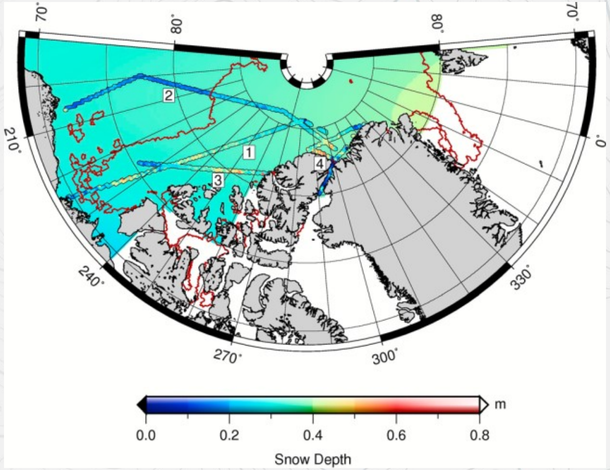
Snow depth impact

- Based on CS-2 performances
- **$\mathcal{E}_{hs}$ = 9 cm from Warren is largely too optimistic. A value of 15 cm seems more realistic**



The comparison of the Warren99 snow depth climatology with Operation Ice Bridge (OIB) snow depth shows important discrepancies

Courtesy of S. Fleury



From Kurtz & Farrell 2011

Uncertainty on SIT (Ku-band)

Currently (CryoSat-2)

MYI

freeboard | Snow depth | Snow density | Water density | Ice density

$$\varepsilon_{SIT}^2 = 0.0468 + 0.25857 + 1.59e^{-4} + 6.642e^{-5} + 0.173$$

$$\boldsymbol{\varepsilon_{SIT}} = \mathbf{0.69\ m}$$

FYI

freeboard | Snow depth | Snow density | Water density | Ice density

$$\varepsilon_{SIT}^2 = 0.0820 + 0.453 + 5.504e^{-5} + 4.395e^{-5} + 0.262$$

$$\boldsymbol{\varepsilon_{SIT}} = \mathbf{0.89\ m}$$

➔ **The snow depth is the main contributor to the SIT error budget**

- Uncertainty on FYI > MYI due to the ice density uncertainty which is largely higher for FYI than for MYI
- Ice density uncertainty is the second most important contributor to the SIT error budget

Improvements brought by CRISTAL

- **Dual frequency (Ku/Ka) → Potential estimation of the snow depth by difference of Ku and Ka ranges**

- Higher Ku bandwidth (500 MHz) → Better range accuracy

- SAR mode for the first time in Ka band → Better resolution and range accuracy

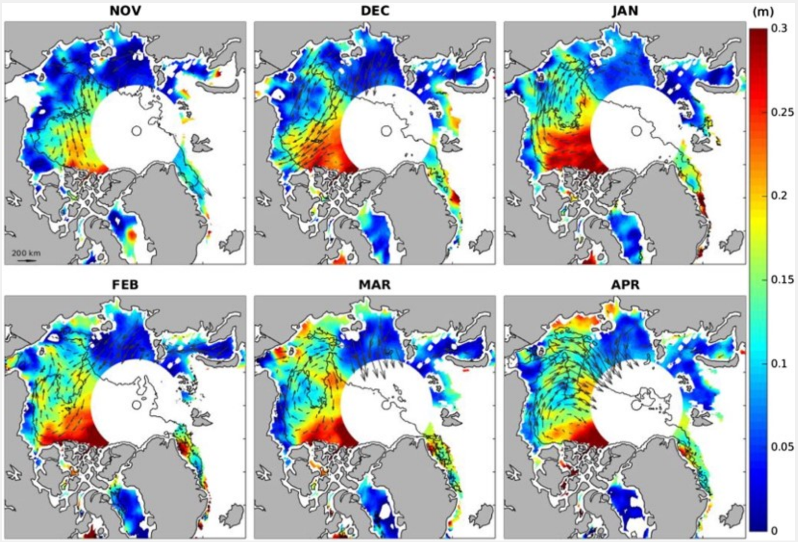
- Interleaved mode → Potential exploitation of Fully Focused SAR processing

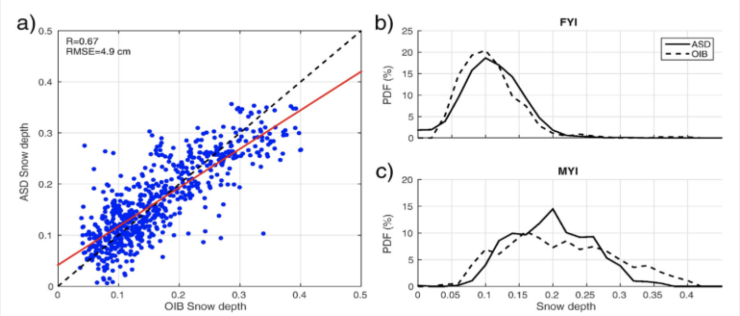
- SARin Ku → Better exploitation of off-nadir returns

- Potential improvements of ground processing (Physical retrackers and freeboard computation/interpolation)

Ku/Ka Snow Depth: Firsts results/products

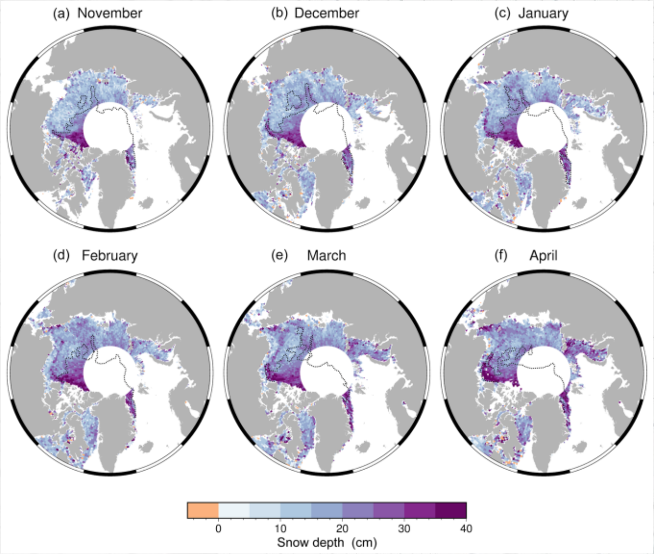
Guerreiro et al. 2016

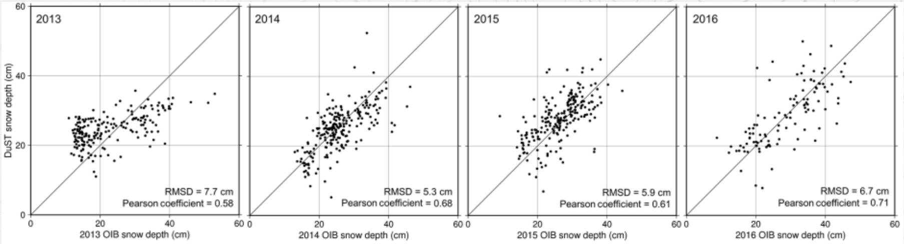




Snow Depth computed using AltiKa and CryoSat-2 measurements at crossovers

Lawrence et al. 2018





Reducing the SIT uncertainty with CRISTAL

- Accounting for CRISTAL larger bandwidth

- $\mathcal{E}_{hs}$ can be improved using the Ku/Ka differences for snow depth estimation
  ➔ 6.5 cm (Lawrence et al 2018)
  ➔ 5.0 cm (Guerreiro et al. 2016)

MYI

freeboard — Snow depth — Snow density — Water density — Ice density

$$\varepsilon_{SIT}^2 = 0.019 + 0.048 + 1.59e^{-4} + 6.642e^{-5} + 0.173$$

FYI

freeboard — Snow depth — Snow density — Water density — Ice density

$$\varepsilon_{SIT}^2 = 0.034 + 0.085 + 5.504e^{-5} + 4.395e^{-5} + 0.262$$

ε_{SIT} = 0.49 m (Lawrence's snow)

ε_{SIT} = 0.47 m (Guerreiro's snow)

ε_{SIT} = 0.62 m (Lawrence's snow)

ε_{SIT} = 0.59 m (Guerreiro's snow)

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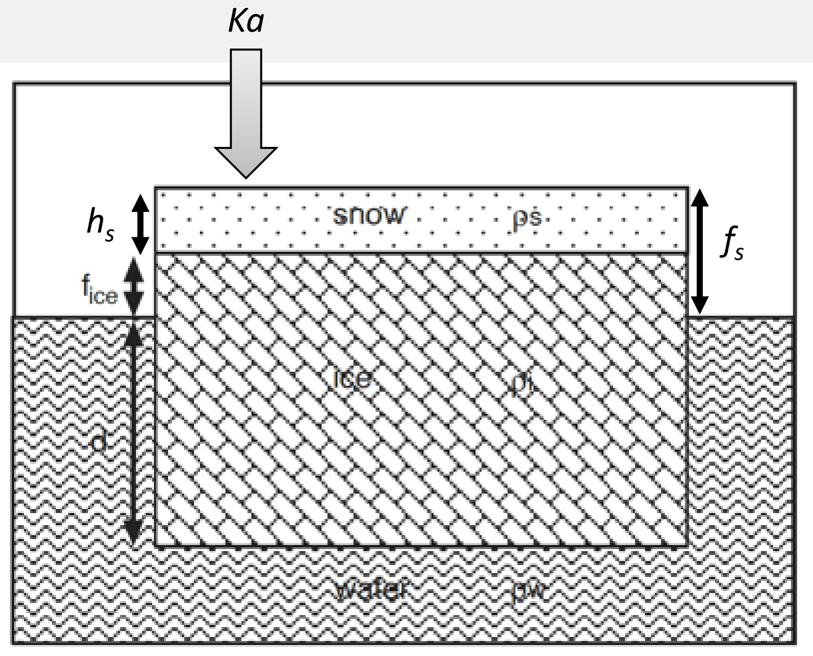
Hydrostatic Equilibrium (Ka-Band/LRM)



Water Density

Snow Freeboard

Snow Density

$$SIT = \frac{\rho_w}{\rho_w - \rho_{ice}} f_s - \frac{\rho_w - \rho_s}{\rho_w - \rho_{ice}} h_s$$

Sea Ice Thickness

Ice Density

Snow Depth

Hypothesis:

Ka-band is reflected by the air/snow interface

Error on Sea Ice Thickness (Ka-Band/LRM)

$$\varepsilon_{SIT}^2 = \varepsilon_{f_s}^2 \left(\frac{\rho_w}{\rho_w - \rho_{ice}}\right)^2 + \varepsilon_{h_s}^2 \left(\frac{\rho_s}{\rho_w - \rho_{ice}} - \frac{\rho_w}{\rho_w - \rho_{ice}}\right)^2 + \varepsilon_{\rho_s}^2 \left(\frac{h_s}{\rho_w - \rho_{ice}}\right)^2$$

$$+\varepsilon_{\rho_w}^2 \left(\frac{f_s}{\rho_w - \rho_{ice}} - \frac{h_s}{\rho_w - \rho_{ice}} - \frac{f_s \rho_w}{(\rho_w - \rho_{ice})^2} - \frac{h_s \rho_s}{(\rho_w - \rho_{ice})^2} + \frac{h_s \rho_w}{(\rho_w - \rho_{ice})^2}\right)^2$$

$$+\varepsilon_{\rho_{ice}}^2 \left(\frac{f_s \rho_w}{(\rho_w - \rho_{ice})^2} + \frac{h_s \rho_s}{(\rho_w - \rho_{ice})^2} - \frac{h_s \rho_w}{(\rho_w - \rho_{ice})^2}\right)^2$$

Giles et al. 2007

MYI

$\rho_{ice} = 882$ kg/m^3 Alexandrov et al. 2010

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$\rho_s = 290$ kg/m^3 Warren et al. 1999

FYI

$\rho_{ice} = 916.7$ kg/m^3 Alexandrov et al. 2010

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(ρ_s varies between 240 and 340 kg/m^3)

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Average Error on Sea Ice Thickness (Ka-Band)

Currently (AltiKa LRM)

MYI		FYI	
$\varepsilon_{f_s} = 0.015$ m	Bandwith ratio with CS-2 and 40Hz/20Hz ratio	$\varepsilon_{f_s} = 0.015$ m	Bandwidth ratio with CS-2 and 40Hz/20Hz ratio
$\varepsilon_{\rho_{ice}} = 23$ kg/m^3	Alexandrov et al. 2010	$\varepsilon_{\rho_{ice}} = 35.7$ kg/m^3	Alexandrov et al. 2010
$\varepsilon_{h_s} = 0.09$ m	Warren et al. 1999	$\varepsilon_{h_s} = 0.09$ m	Warren et al. 1999
$\varepsilon_{\rho_s} = 3.2$ kg/m^3	Warren et al. 1999	$\varepsilon_{\rho_s} = 3.2$ kg/m^3	Warren et al. 1999
$\varepsilon_{\rho_w} = 0.5$ kg/m^3	Wadhams et al. 1992	$\varepsilon_{\rho_w} = 0.5$ kg/m^3	Wadhams et al. 1992
$f_s = 0.547$ m	$f_s = f_{ice} + h_s$	$f_s = 0.246$ m	$f_s = f_{ice} + h_s$
$h_s = 0.36$m	Warren et al. 1999 (March)	$h_s = 0.16$m	Warren et al. 1999 (March÷2 → modified version)

Error on Sea Ice Thickness (Ka-Band)

Currently (AltiKa LRM)

MYI

$$\varepsilon_{SIT}^2 = \varepsilon_{f_s}^2 52.002 + \varepsilon_{h_s}^2 26.718 + \varepsilon_{\rho_s}^2 6.427e^{-6} + \varepsilon_{\rho_w}^2 1.784e^{-4} + \varepsilon_{\rho_{ice}}^2 2.153e^{-4}$$

$$\varepsilon_{SIT}^2 = 0.0117 + 0.2164 + 6.581e^{-5} + 4.460e^{-5} + 0.114$$

FYI

$$\varepsilon_{SIT}^2 = \varepsilon_{f_s}^2 91.075 + \varepsilon_{h_s}^2 46.794 + \varepsilon_{\rho_s}^2 2.224e^{-6} + \varepsilon_{\rho_w}^2 1.183e^{-4} + \varepsilon_{\rho_{ice}}^2 1.364e^{-4}$$

$$\varepsilon_{SIT}^2 = 0.0205 + 0.379 + 2.277e^{-5} + 2.958e^{-5} + 0.174$$

The impact of snow depth uncertainty is higher for Ka band than for Ku band

Conclusions

- SIT is computed from freeboard estimates and the Hydrostatic Equilibrium

- The Error budget derived from the Hydrostatic Equilibrium depends on many external error sources: the altimeter is only measuring the freeboard

- The main contributor to the SIT error budget is the snow depth uncertainty

- Ku/Ka combination allows to dramatically decrease the snow depth uncertainty
  ➔ Decrease of the SIT uncertainty

- A Ku/Ka mission is mandatory if we want to reduce the SIT uncertainty even if a target of 0.1 m is potentially too optimistic

- Ice density uncertainty is a strong contributor to the SIT error budget and needs to be investigated

Thank you for your attention!