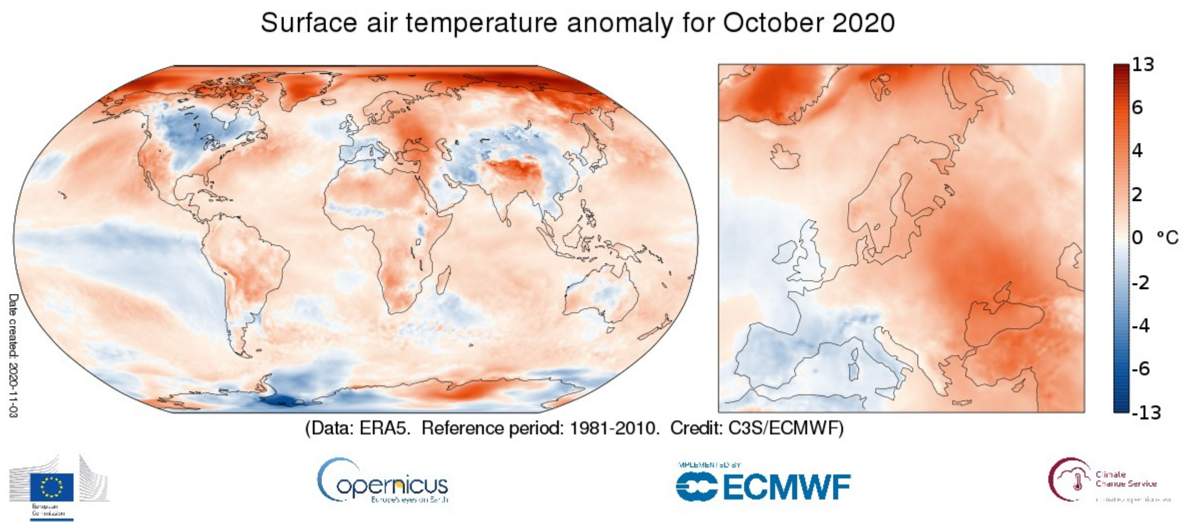
# Understanding the behavior of altimetric measurements of Laser and Ku-band over sea-ice

A. Carret, S. Fleury, J. Bouffard, A. Di Bella

# Introduction : Sea ice thickness

**Why do we observe the sea ice thickness ?**

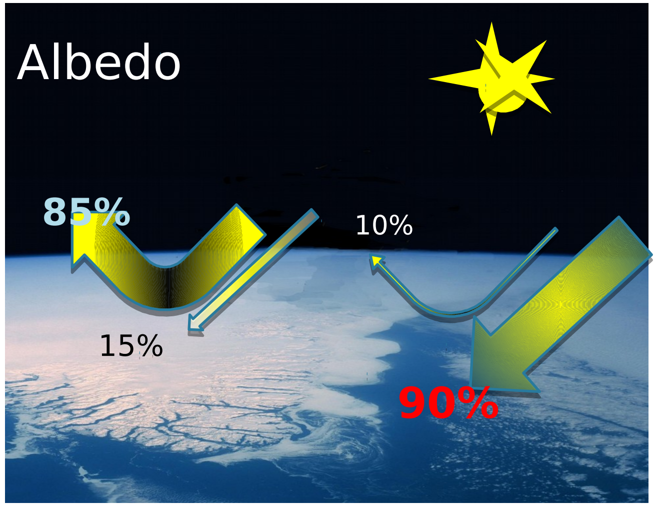
1. It is the first witness and actor of global warming




↘ albedo

⟷

Arctic amplification




Decreaseof sea ice thickness → embrittlement of the ice → Reduction of sea ice extent → A smaller albedo, more absorbtion of the radiation

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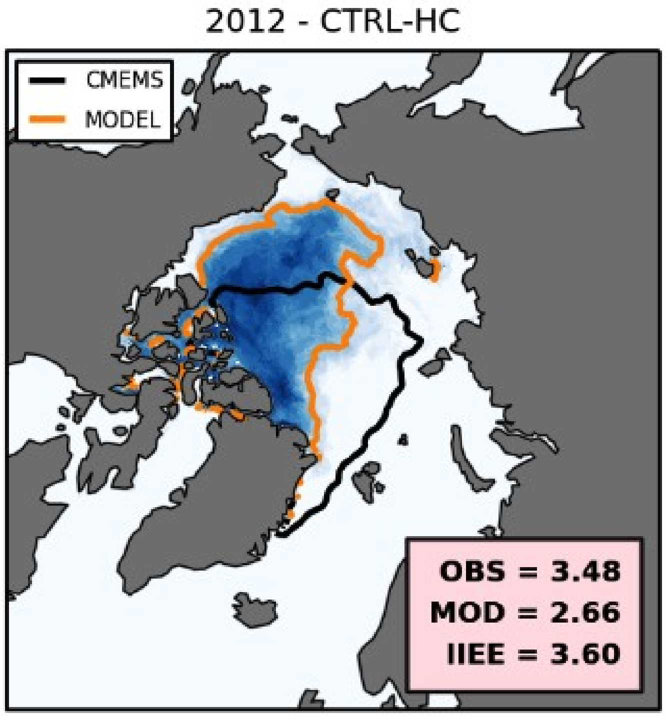
**Sea ice extent**

— 4-month forecast from **concentrations** observations

— What was actually observed




September mean

*Blockley and Peterson, 2018*

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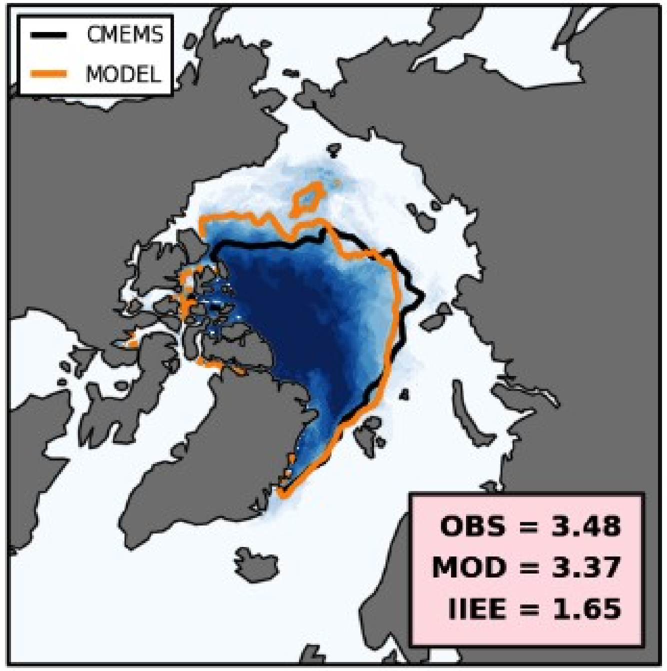
**Sea ice extent**

— 4-month forecast from **thickness** observations

— What was actually observed

2012 - ThkDA-HC




September mean

*Blockley and Peterson, 2018*

*Mignac et al., 2022*

# Introduction : Sea ice thickness

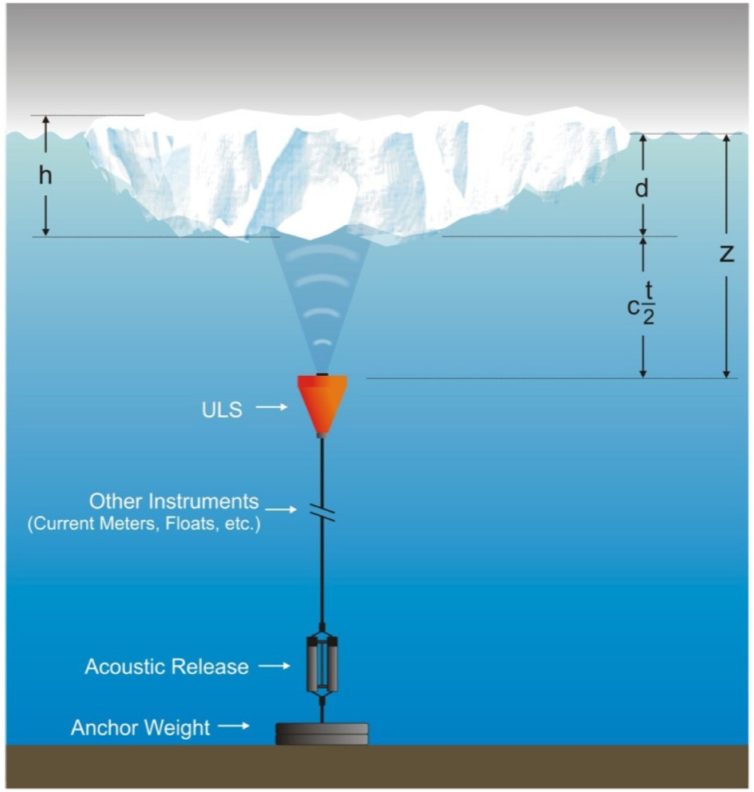
**How do we observe the thickness of sea ice ?**

**Local scale**

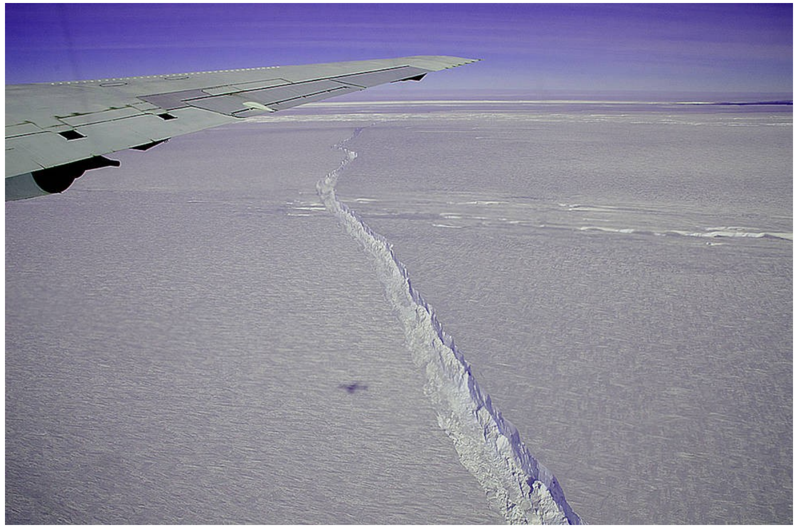
Buoys

Field measurements

Moorings




Airborne observations
(OIB, CryoVEx)



# Introduction : Sea ice thickness

**How do we observe the thickness of sea ice ?**

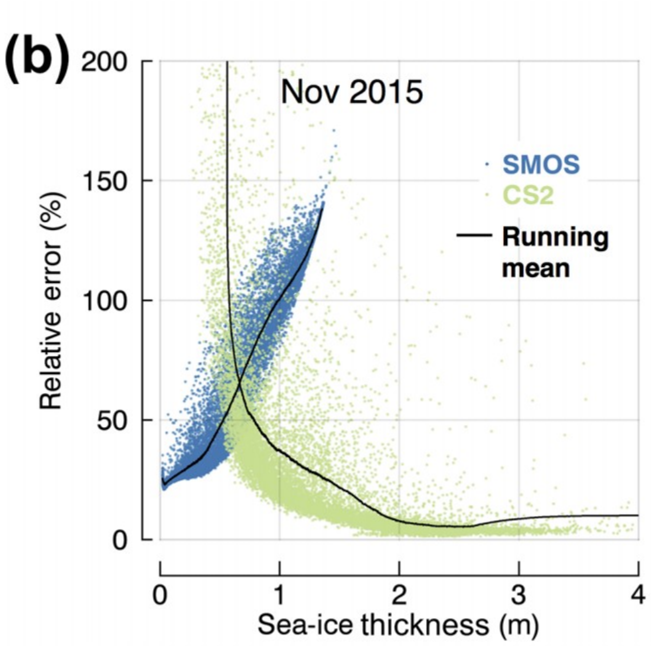
**Global scale**

Passive microwave radiometer

SMOS

No sensitivity over thick ice

Complementarity between the methods



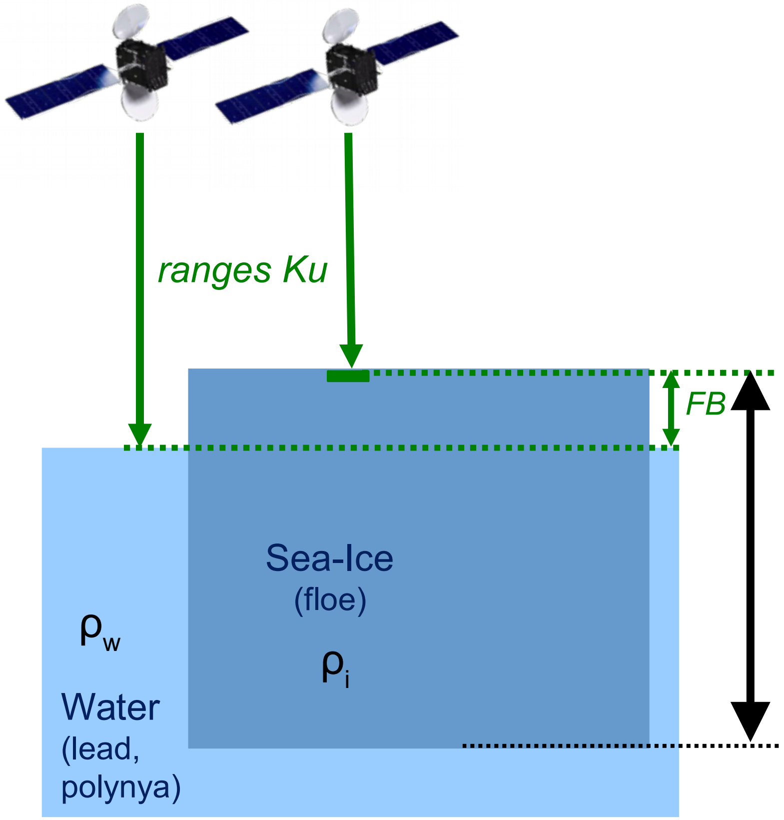

*Ricker et al., 2017*

Altimetry

CryoSat-2

Large uncertainties over thin ice

## Measurement of sea ice thickness by altimetry

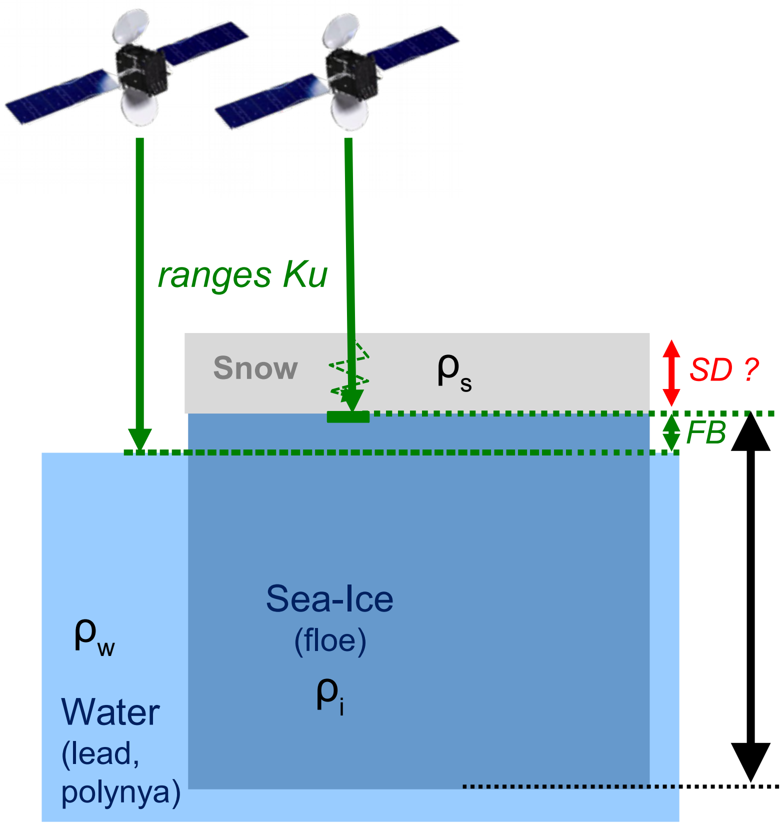



$$SIT = \frac{\rho_w}{\rho_w - \rho_i} FB$$

FB: FreeBoard

SIT: Sea Ice Thickness

## Measurement of sea ice thickness by altimetry




FB$_{Ku}$ : FreeBoard

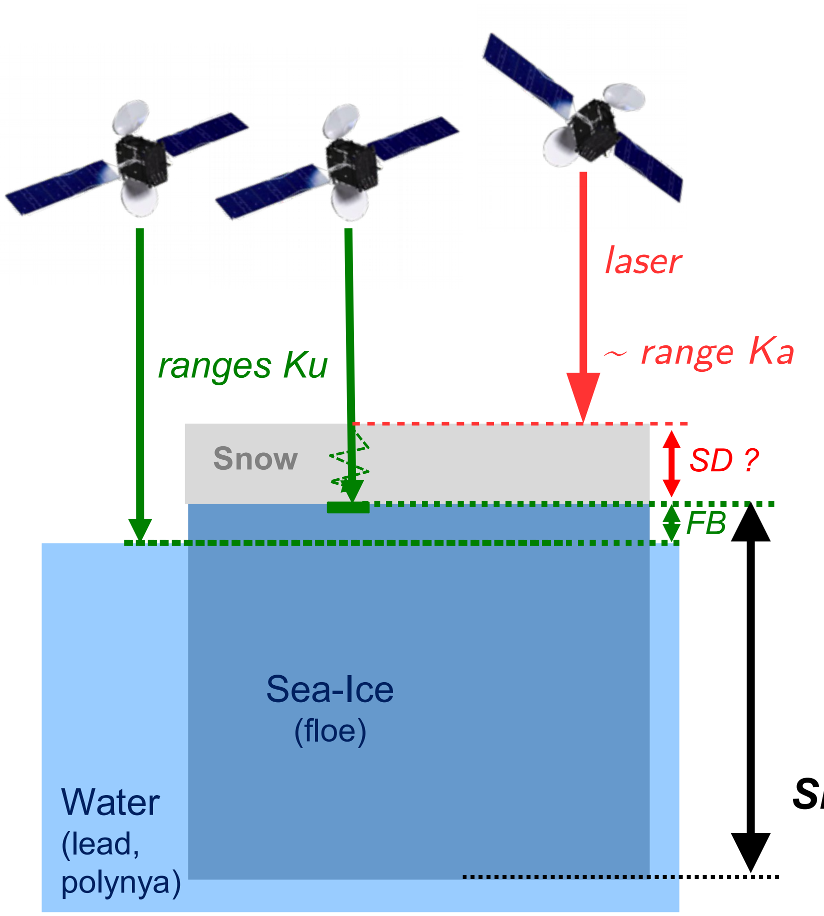
SIT: Sea Ice Thickness

SD: Snow Depth

Key geophysical variable

$$SIT = \frac{\rho_w}{\rho_w - \rho_i} FB_{Ku} + \frac{(1-c_s/c)\rho_w + \rho_s}{\rho_w - \rho_i} SD$$

## Measurement of sea ice thickness by altimetry




FB$_{Ku}$: FreeBoard

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$$SIT = \frac{\rho_w}{\rho_w - \rho_i} FB_{Ku} + \frac{(1-c_s/c)\rho_w + \rho_s}{\rho_w - \rho_i} SD$$

$$\boxed{SD = range\_Ku - laser}$$

Need to know the snow depth !

## Uncertainties in sea ice thickness estimation

$$SIT = \frac{\rho_w}{\rho_w - \rho_i} FB_{Ku} + \frac{(1-c_s/c)\rho_w + \rho_s}{\rho_w - \rho_i} SD$$

Error propagation equation

$$\begin{aligned}
\varepsilon^2_{SIT} = \; & \varepsilon^2_{FBku} \left[ \frac{\rho_w}{\rho_w - \rho_i} \right]^2 + \\
& \varepsilon^2_{SD} \left[ \frac{\rho_w (1 + 0.00051\, \rho_s)^{1.5} - \rho_w + \rho_s}{\rho_w - \rho_i} \right]^2 + \\
& \varepsilon^2_{\rho s} \left[ \frac{1 + 0.000765\, \rho_w (1 + 0.00051\, \rho_s)^{0.5}}{\rho_w - \rho_i} \; SD \right]^2 + \\
& \varepsilon^2_{\rho w} \left[ - \frac{\rho_i FB_{Ku} + SD\, (\rho_s - \rho_i + \rho_i (1 + 0.00051\, \rho_s)^{1.5})}{(\rho_w - \rho_i)^2} \right]^2 + \\
& \varepsilon^2_{\rho i} \left[ \frac{\rho_w FB_{Ku} + SD\, (\rho_s - \rho_w + \rho_w (1 + 0.00051\, \rho_s)^{1.5})}{(\rho_w - \rho_i)^2} \right]^2
\end{aligned}$$

## Uncertainties in sea ice thickness estimation

$$\varepsilon^2_{SIT} = c^2_{FBku}\varepsilon^2_{FBku} + c^2_{SD}\varepsilon^2_{SD} + c^2_{\rho s}\varepsilon^2_{\rho s} + c^2_{\rho i}\varepsilon^2_{\rho i} + c^2_{\rho w}\varepsilon^2_{\rho w}$$

| | FYI | | | | MYI | | | |
|---|---|---|---|---|---|---|---|---|
| | mean | $\varepsilon$ | $c^2$ | $c^2\varepsilon^2$ | mean | $\varepsilon$ | $c^2$ | $c^2\varepsilon^2$ |
| ***FB*** **(m)** | 0.10 | 0.05 | 91.59 | **0.23** | 0.20 | 0.05 | 52.00 | **0.13** |
| ***SD*** **(m)** | 0.15 | 0.15 | 24.11 | **0.54** | 0.35 | 0.15 | 13.69 | **0.31** |
| $\rho_i$ **(kg/m³)** | 917 | 36.0 | $25.05\ 10^{-5}$ | **0.32** | 882 | 23.0 | $37.15\ 10^{-5}$ | **0.20** |
| $\rho_s$ **(kg/m³)** | 290 | 3.2 | $66.50\ 10^{-7}$ | **0.00** | 290 | 3.2 | $20.55\ 10^{-6}$ | **0.00** |
| $\rho_w$ **(kg/m³)** | 1024 | 0.5 | $21.23\ 10^{-5}$ | **0.00** | 1024 | 0.5 | $29.93\ 10^{-5}$ | **0.00** |
| $\varepsilon_{SIT}$ | | | | 1.05 | | | | 0.80 |

$\rho_s$ and $\rho_w$ uncertainties have negligible effects
$FB_{ku}$, SD and ρi uncertainties are of some order of magnitude

# Introduction : Sea ice thickness

**ERS1**

LRM

Ku

**ERS2**

LRM

Ku

**Envisat**

LRM

Ku

**CryoSat-2**

SAR

Ku

- 12 years of service
- Capabilities to observe sea ice thickness

**SARAL**

LRM

Ka

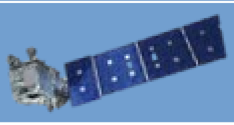
What are the effects of ice roughness in the footprint ?
What is the Ku and Ka frequency penetration level in the snow cover ?
What is the impact of the processing ?

# Methodology: CRYO2ICE project

On July the 16th 2020, CryoSat-2's orbit was raised in order to periodically align ICESat-2 orbits over the Arctic ocean every 20/19 orbits (IS2/CS2).

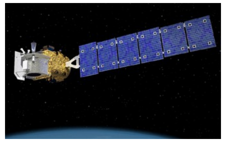
- 20 tracks of coincidental measurements per month
- With a 2-3 hours delay
- Thousands of kilometers transects

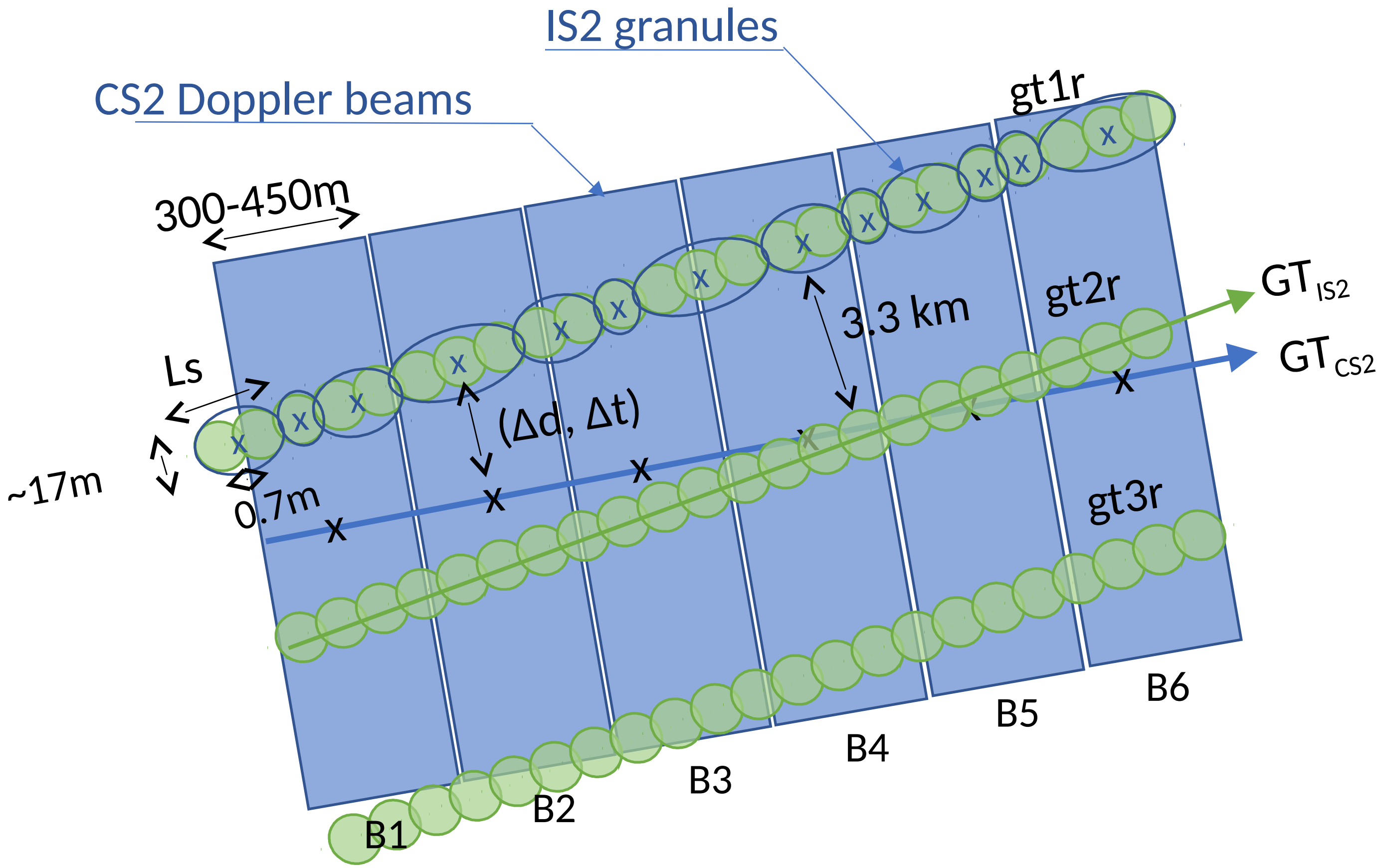
✔ Monitoring same surface (same sea-ice conditions)
✔ Enabling direct comparison of Laser vs Ku-band
✔ Evaluate the characteristics of each sensor

| Missions | | Launched | Expected end | Main Payload |
|---|---|---|---|---|
| CryoSat-2 |  | April 2010 | 2023-2025 (15y) | Ku-band SAR (SIRAL) |
| IceSat-2 |  | Sept 2018 | 2023 (3-5y) | 6 beams LIDAR (ATLAS) |

# Methodology: CRYO2ICE project

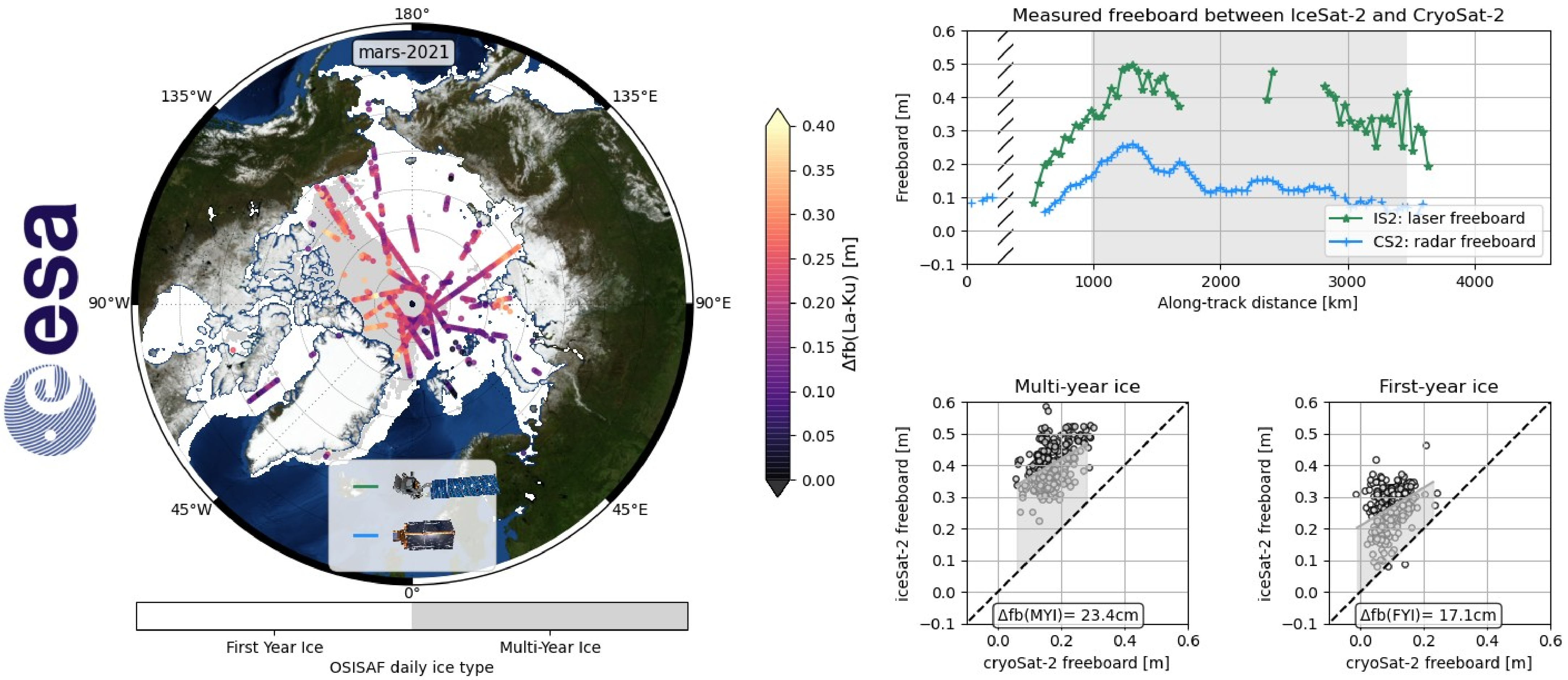
## Satellite footprints:

- **CryoSat-2:** 
  - ➢ Doppler beam: (300-450)m x 1.5 km
- **IceSat-2:** 
  - ➢ Granules: Ls x 17m , Ls ϵ [10m,150m]
  - ➢ Swath: 6.6 km x 10 km



# Results: CRYO2ICE project

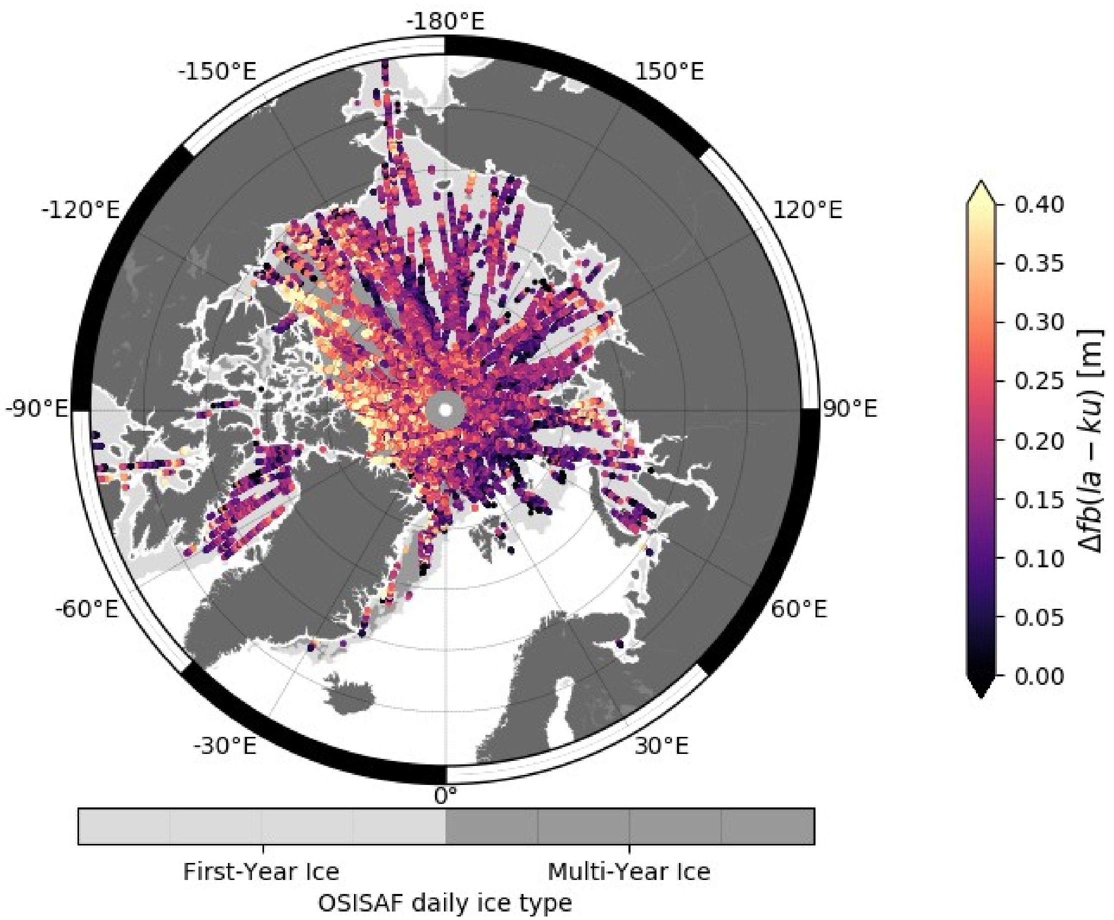
## Example of CRYO2ICE collocated tracks for March 2021

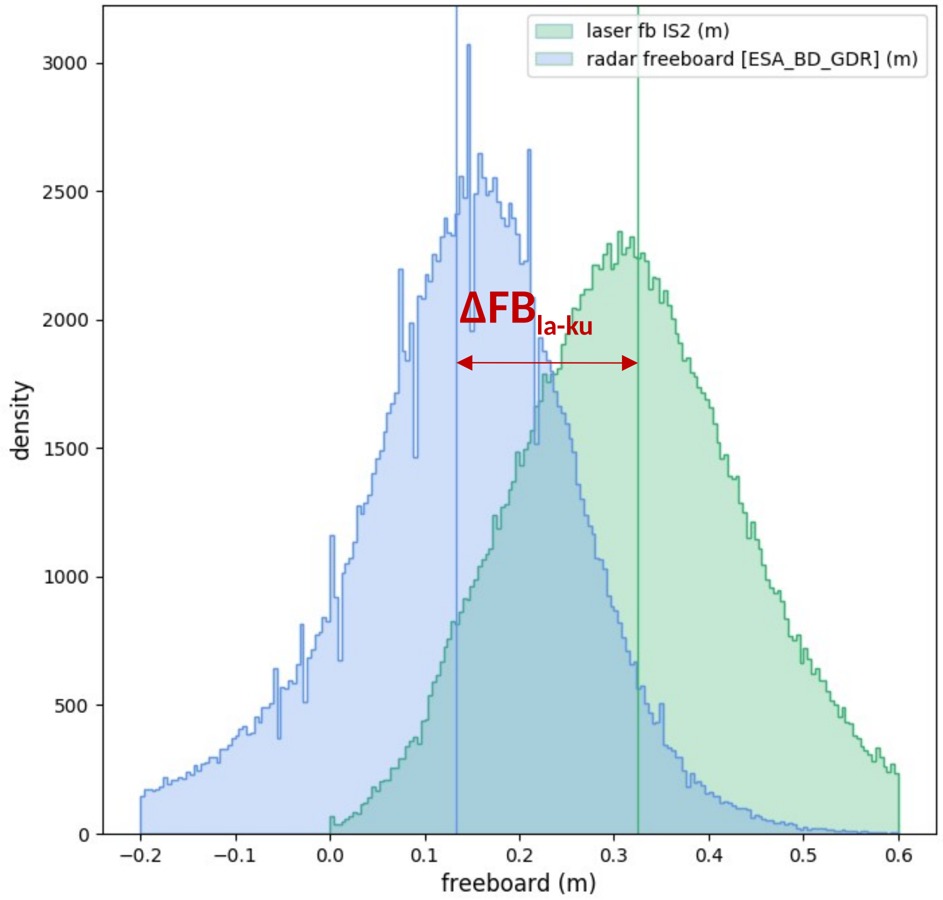



**For the whole animation for all the months → https://we.tl/t-bMVW1rODEh**

# Results: CRYO2ICE project

**7 months (Oct 20 – April 21) of CRYO2ICE winter collocated tracks**



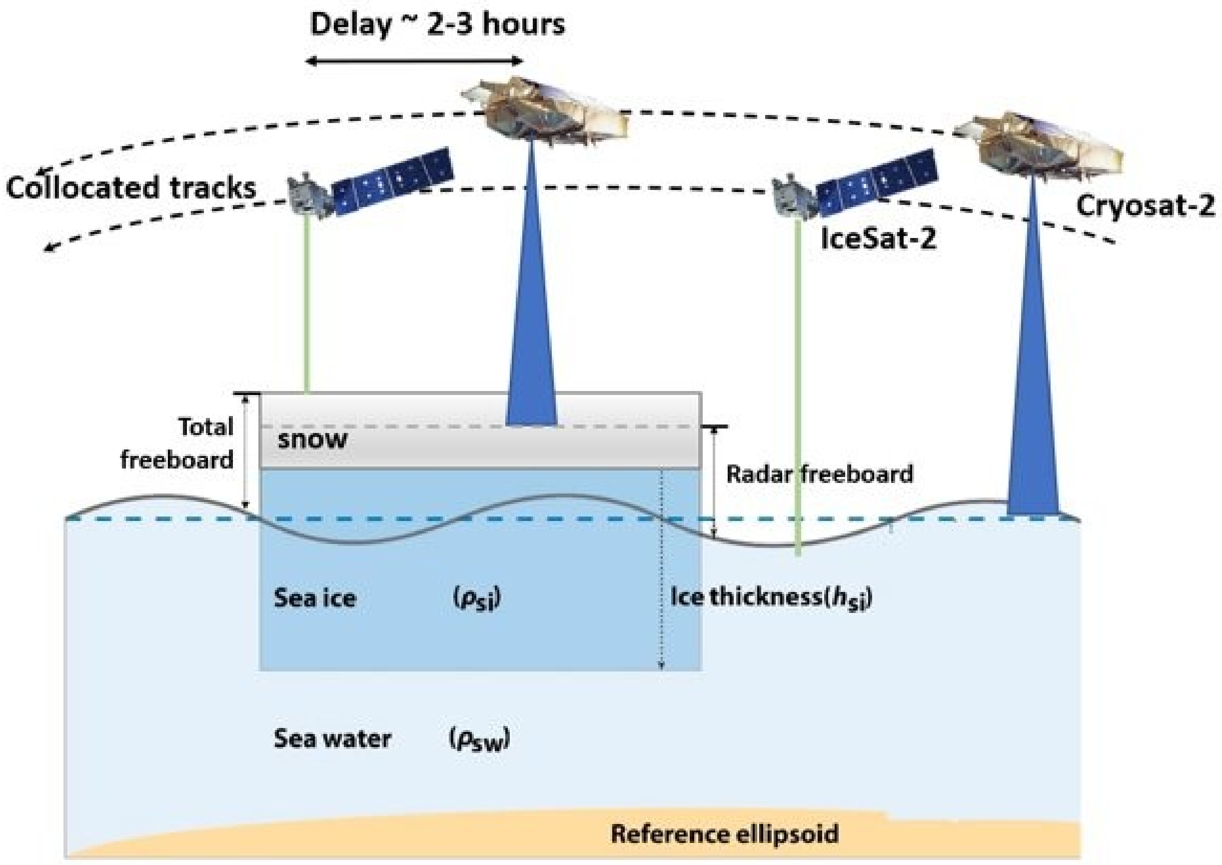



# Interpretation of the signal

## $\Delta FB_{la\text{-}ku}$ measure = snow depth ?

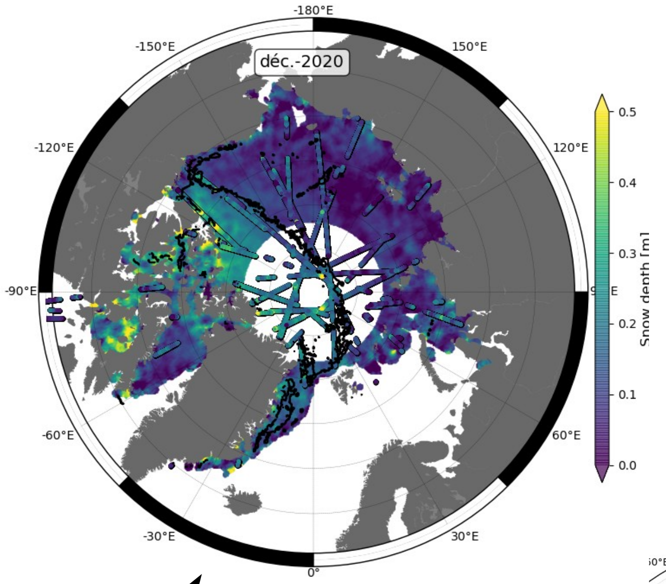
Assuming full penetration of Ku-band radar

- ❑ Penetration depends on snow properties (brines.. etc) (*Nandan et al, 2020*)




→ Need comparisons to other products !

# Interpretation: comparison to other snow products

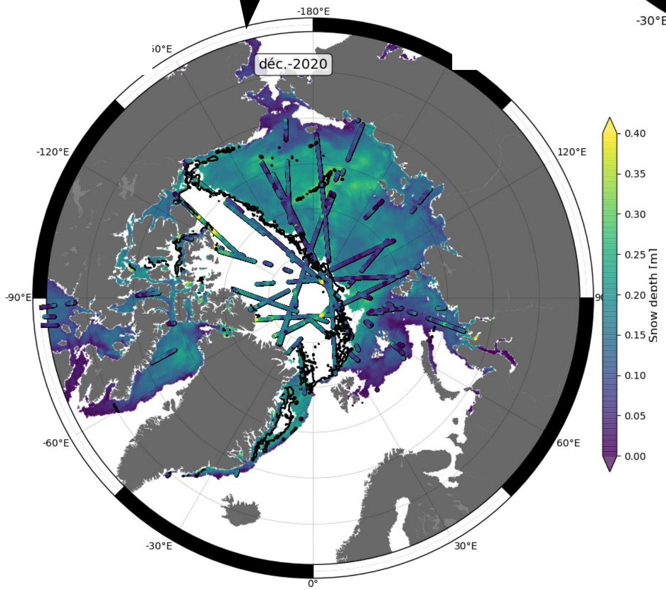


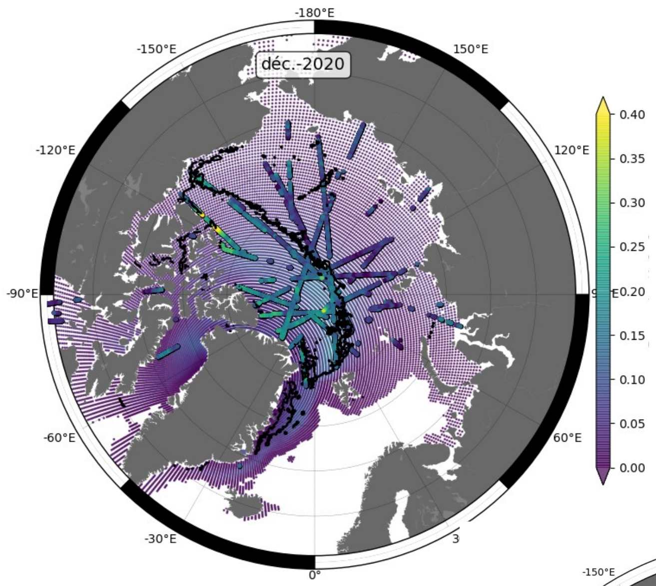

ASD (monthly)

*Ka (Saral) -*
*Ku (CryoSat-2 –pLRM)*
*(Garnier et al, 2021)*

AMSR (daily)

*NSIDC microwave product* (Markus et al. 2018)



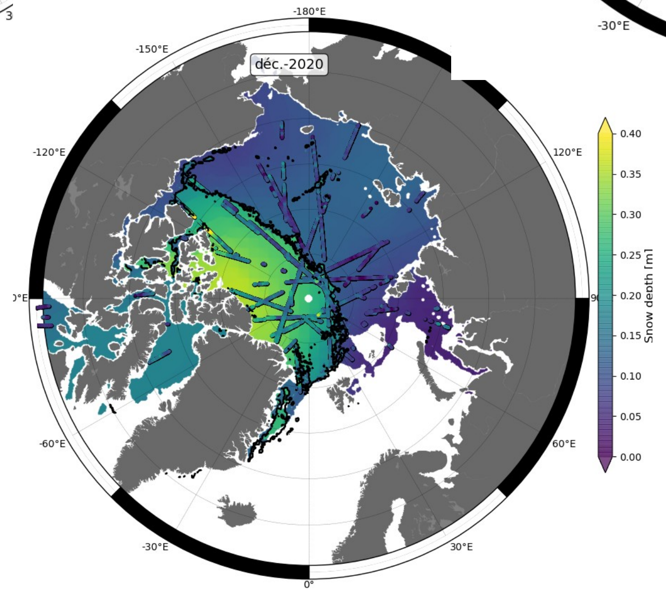



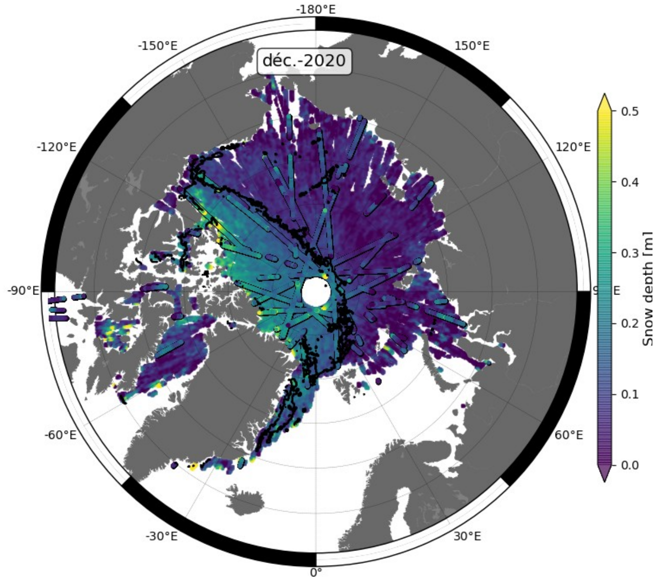

PIOMAS (monthly)

*UW assimilated model*
(*Zhang et* al. 2003)

W99m (monthly)

*Modified Warren climatology*
(*Warren et* al. 1999)



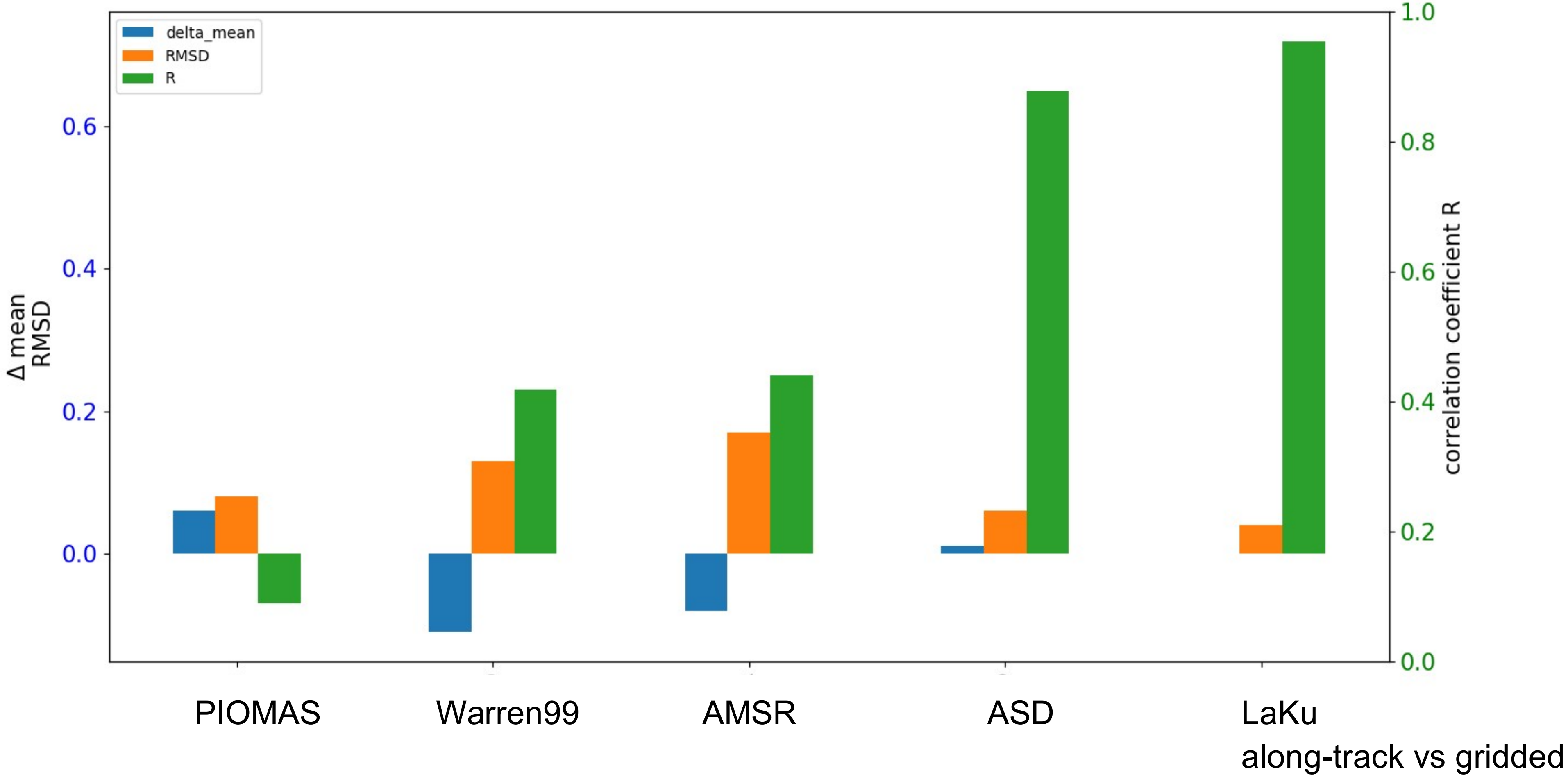




LaKu (monthly)

*La (IceSat-2) -*
*Ku (CryoSat-2)*

# Interpretation: comparison to other snow products

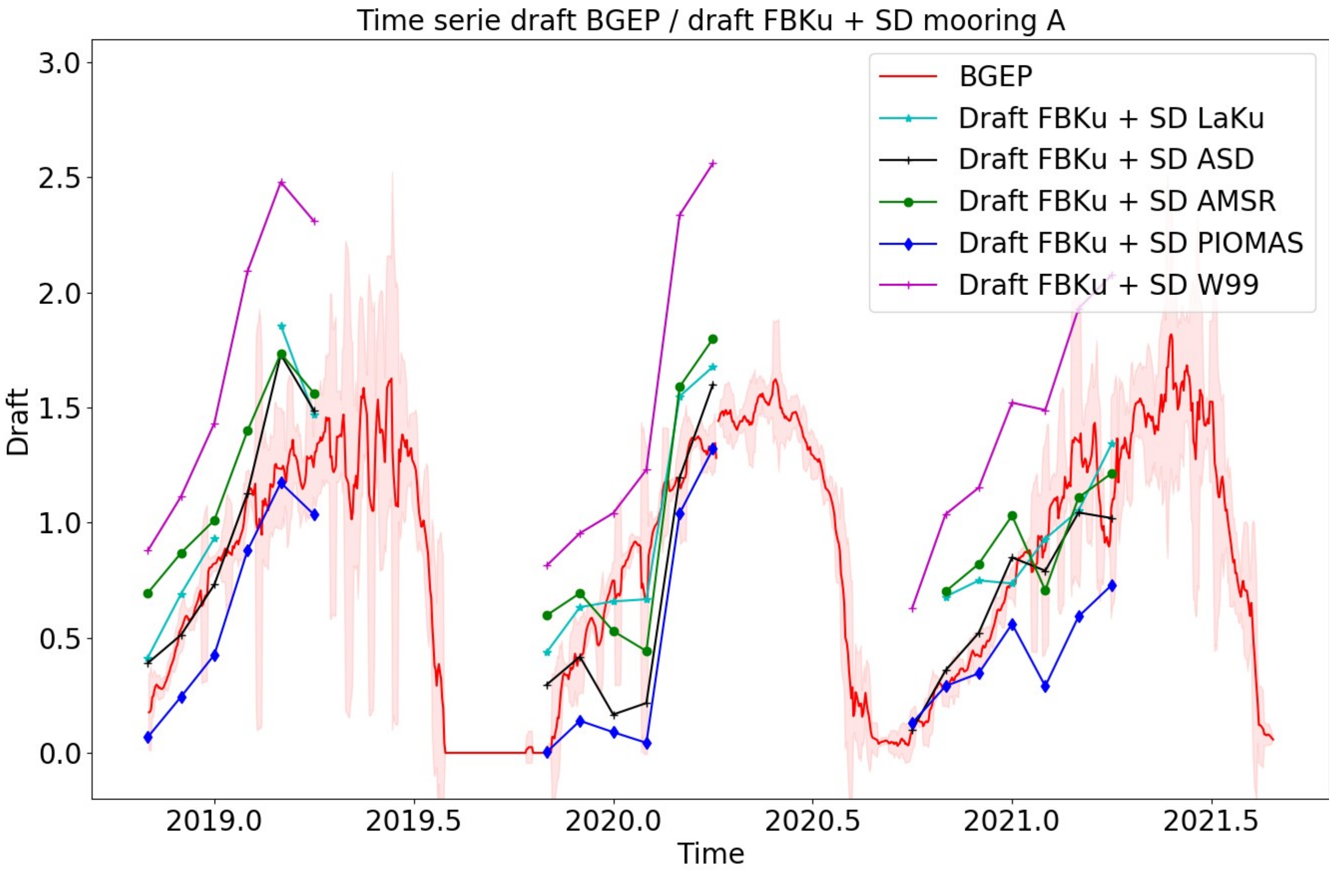
**Statistics (mean bias, RMSD and correlation coefficient R) with reference to the LaKu gridded product**




Best correlation with Altimetric Snow Depth (ASD) product (KaKu, Garnier et al., 2021)

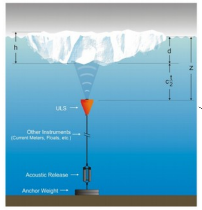
# Interpretation: comparison to in situ products

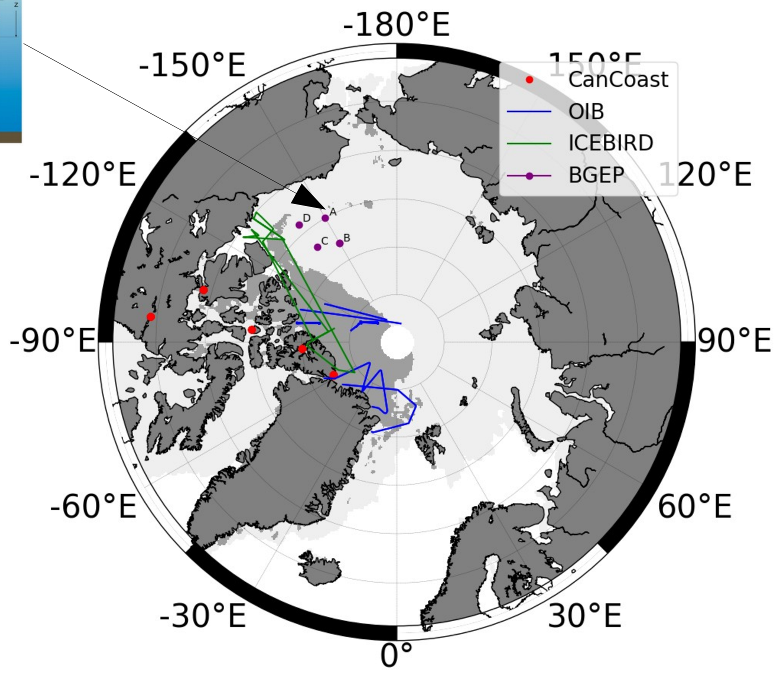
**Comparison of the draft obtained from BGEP and derived from the Ku freeboard added to different snow depth products**




## BGEP moorings

- Monitoring of the Canadian Basin
- Measurement of Draft with an upward-looking sonar
- Period of measurement: 2003-2021



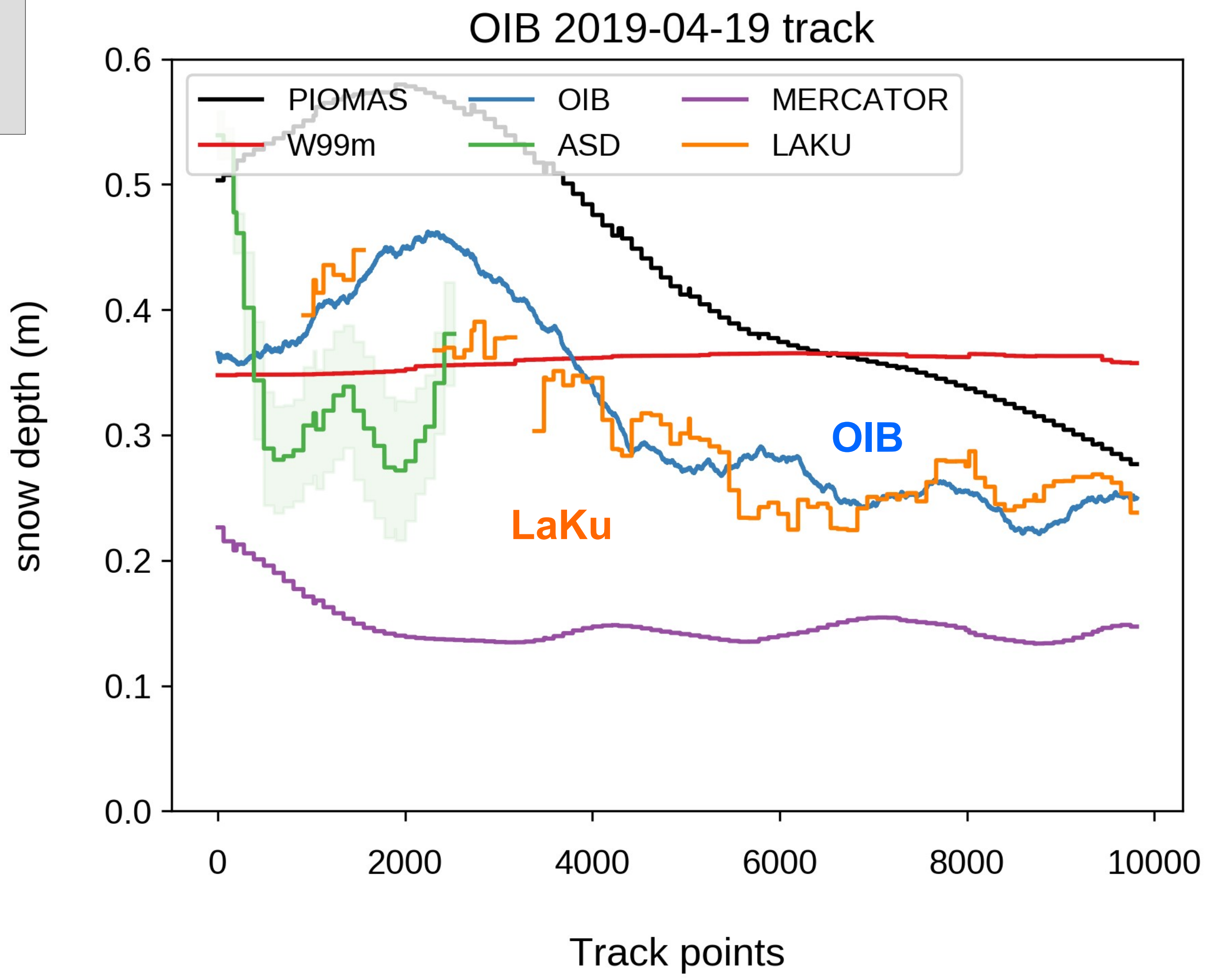


# Interpretation: comparison to in situ products

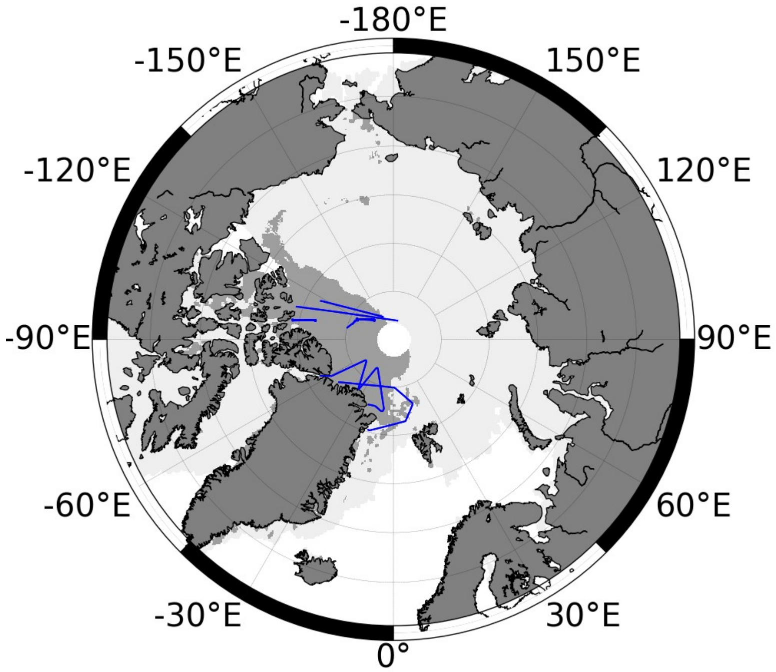
**Comparison of the snow depth obtained from OIB to different snow depth products**

OIB vs Gridded
LaKu projected

PIOMAS
MERCATOR
W99m
ASD
LAKU




**Operation IceBridge**
- 10-year mission to collect polar data between ICESat and ICESat-2
- Airborne measurements
- Period of campaign: April 2019

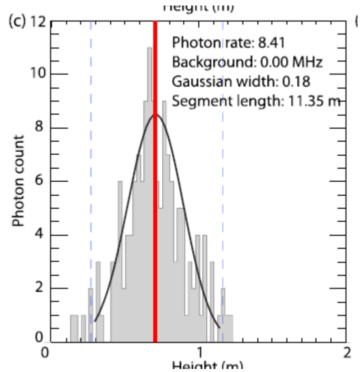


# Discussion: comparison to surface roughness

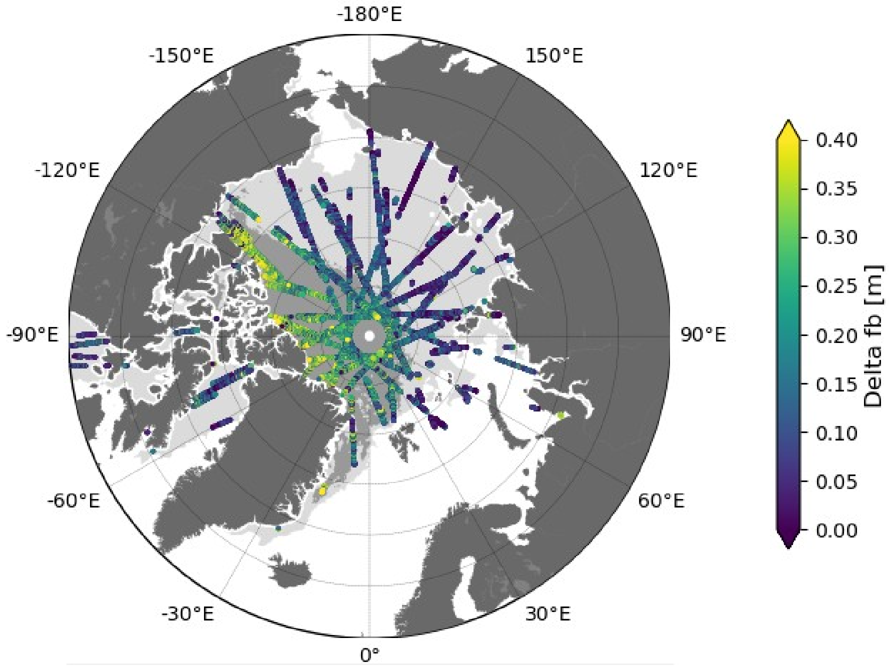
Hypothsesis: Surface roughness has an impact on the measures

The Gaussian width is the best Gaussian fit of 150 photon aggregates distribution

*"The Gaussian width parameter provides a measure of the surface roughness [...]"* Kwok et al. 2020

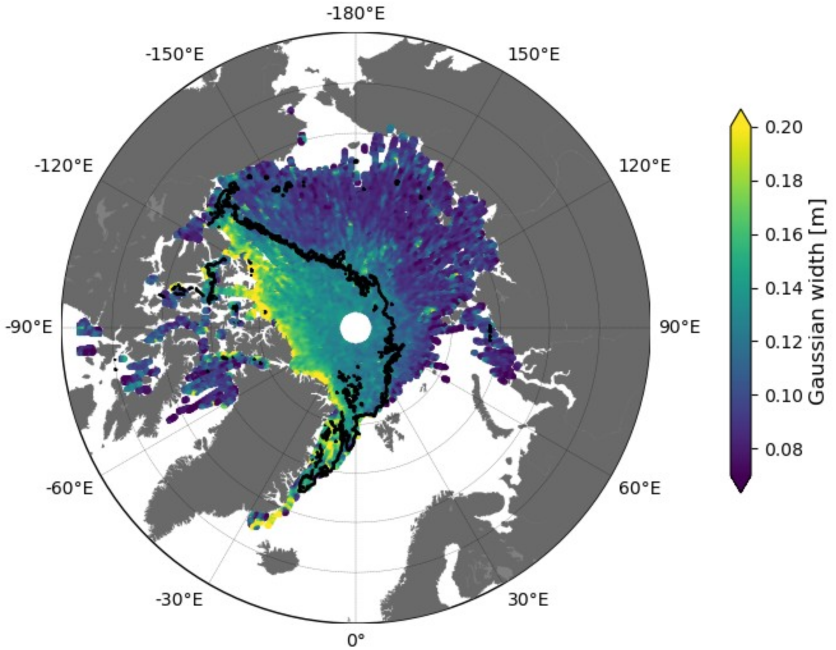


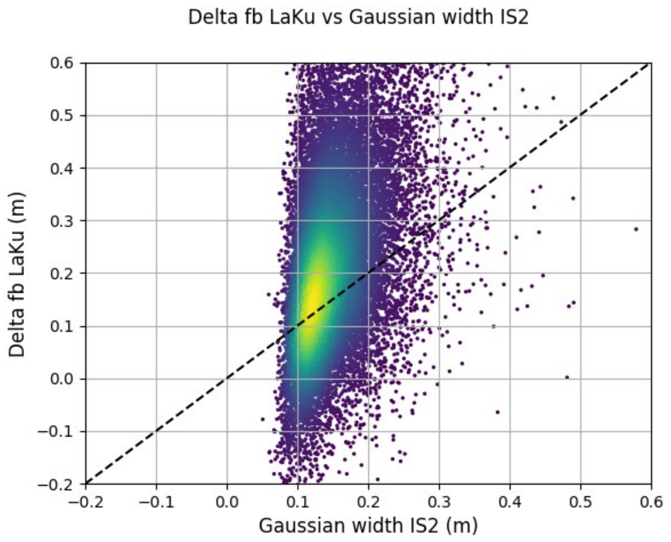

$FB_{laser} - FB_{Ku}$




vs

Gaussian width
(proxy of surface roughness)



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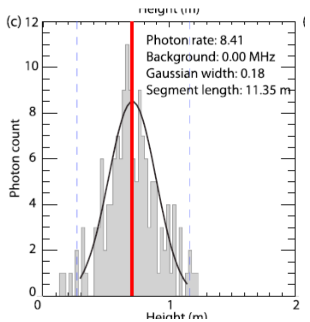
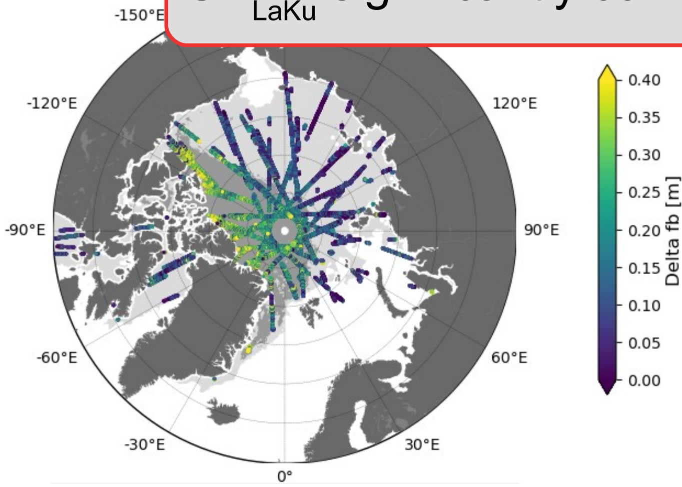
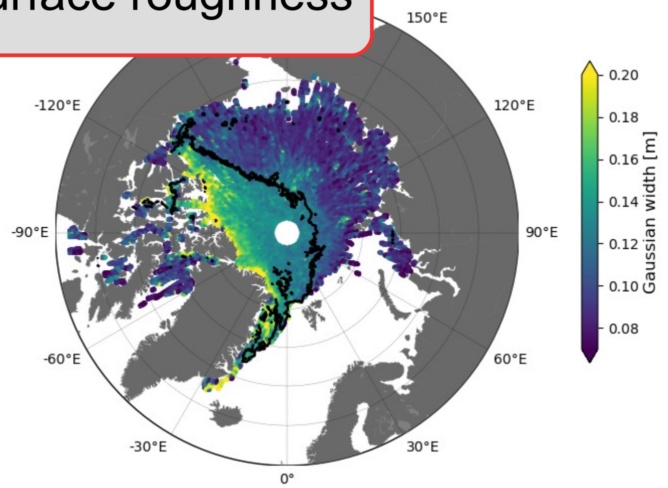
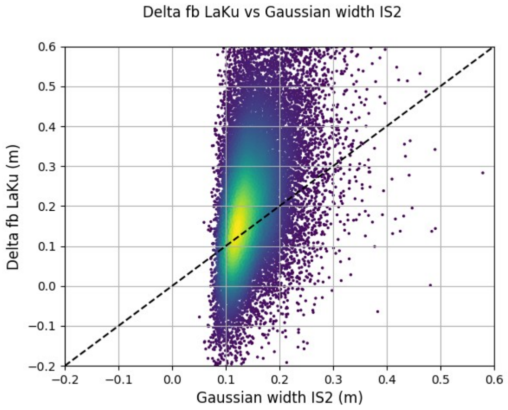



$SD_{LaKu}$ significantly correlated to surface roughness




vs




| | Oct | Nov | Dec | Jan | Feb | Mar | Apr |
|---|---|---|---|---|---|---|---|
| **R** | 0.54 | 0.62 | 0.57 | 0.42 | 0.41 | 0.46 | 0.43 |
| **R FYI** | 0.1 | 0.19 | 0.32 | 0.25 | 0.32 | 0.39 | 0.24 |
| **R MIY** | 0.51 | 0.47 | 0.45 | 0.17 | 0.29 | 0.33 | 0.47 |

# Conclusion and perspectives

## Conclusions:

- The Cryo2Ice project enables to compare coincidental measurements and to provide a snow depth product LaKu. However it is strongly required to have in situ data to analyse its added value
- We obtained quite good results comparing the $\Delta FB_{LaKu}$ product against in situ data
- The $\Delta FB_{LaKu}$ depends on snow layer properties (*Nandan et al., 2020*), footprint size, surface roughness

## Perspectives :

- Continue to investigate the added value of colocated measurement thanks to CRYO2ICE
- Better understand effect of roughness on radar altimetry over sea ice
- Demangle the roughness effect and the impact of the snow on the measurement
- In situ observations needed for validation
- Prepare the CRISTAL mission (bi-frequency altimeter)