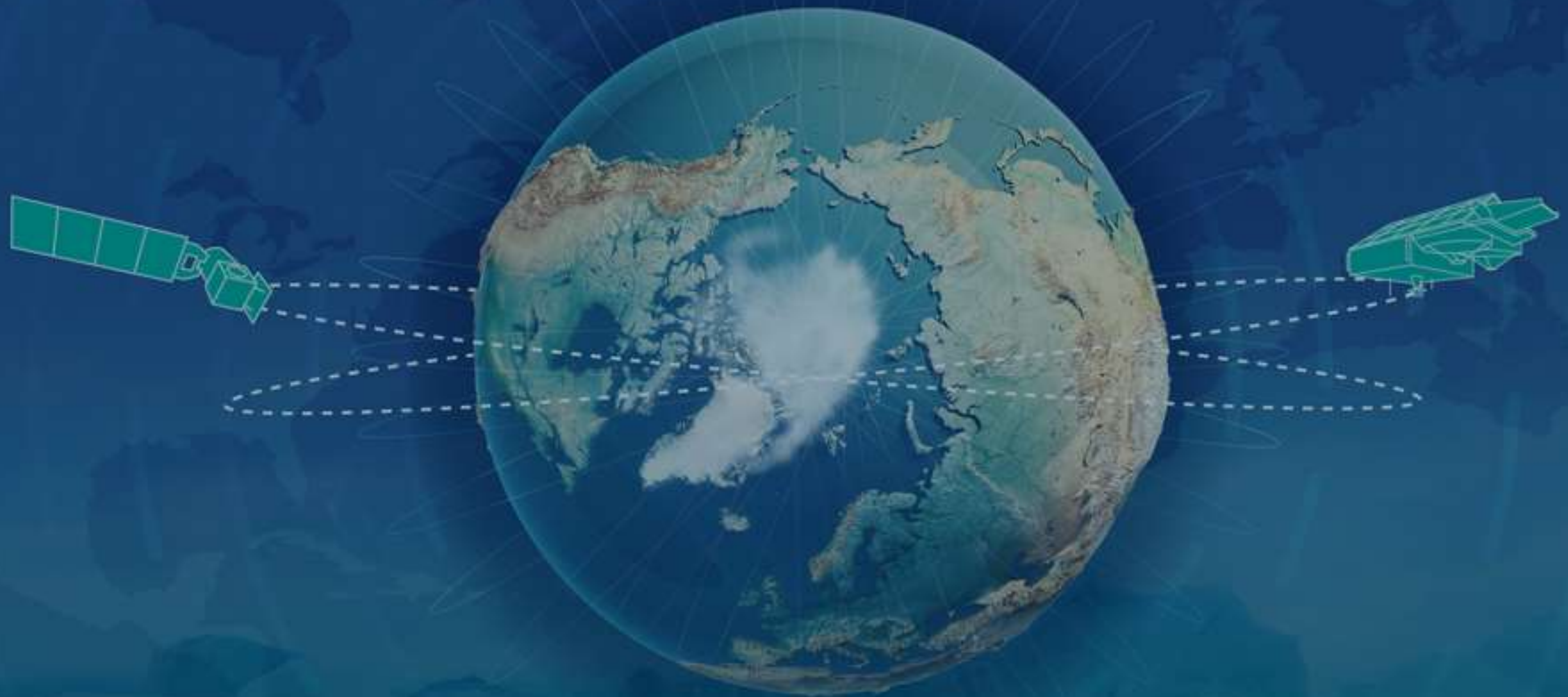
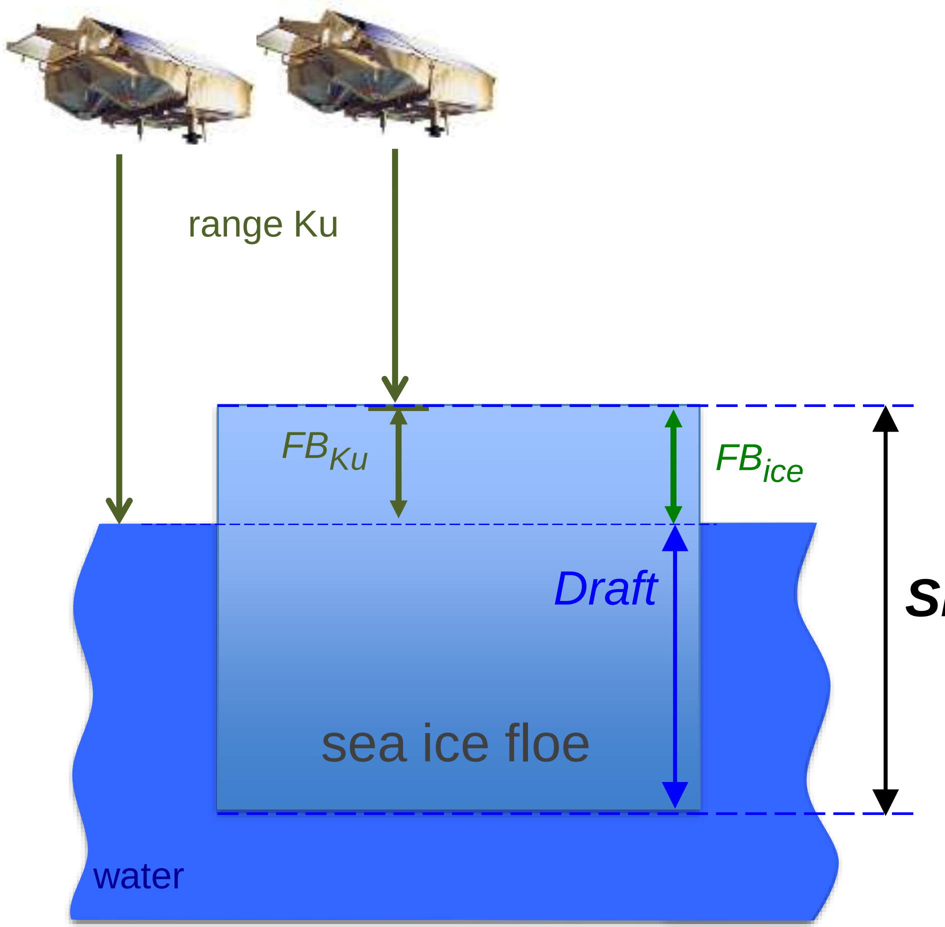


Validation and uncertainties of a multi frequency altimetry snow depth product over the Arctic ocean at different scales

Carret A[1], Fleury S[2], Di Bella A[3], Landy J[4], Lawrence I[3], Kurtz N[5], Laforge A[2], Bouffard J[3], Parrinello T[3]

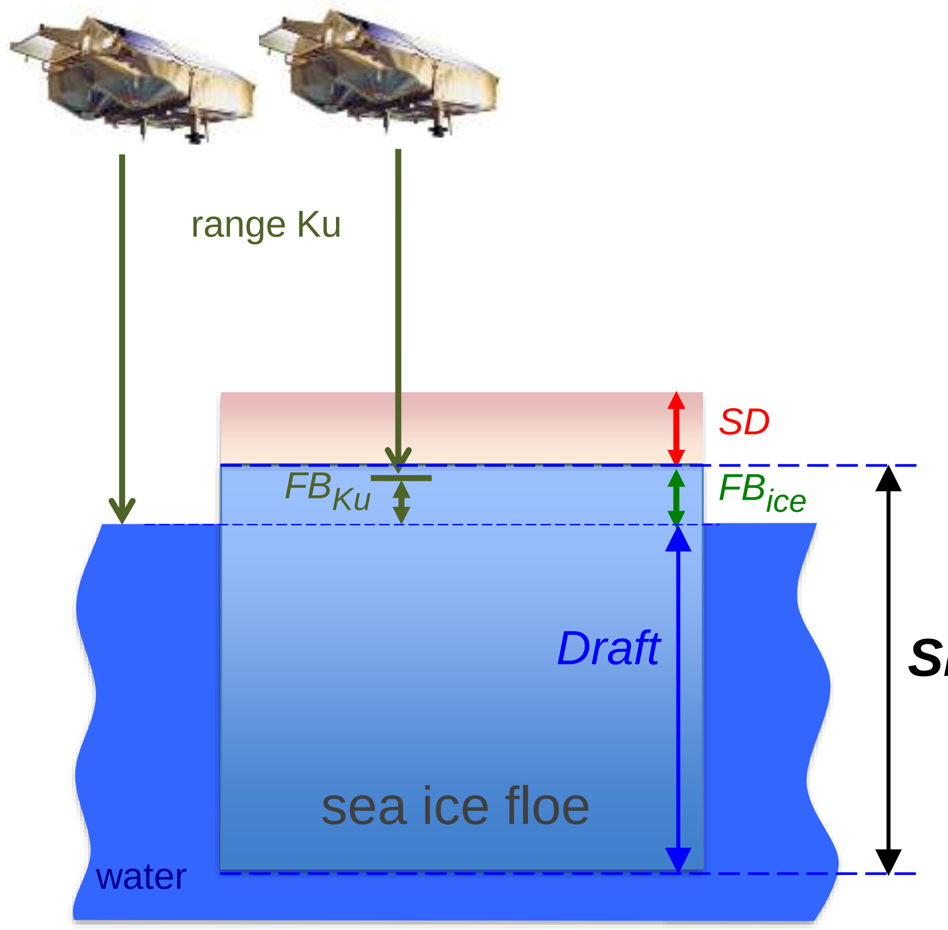
[1] Serco [2] LEGOS [3] ESA [4] UIT [5] NASA

Measurement of sea ice thickness by altimetry



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

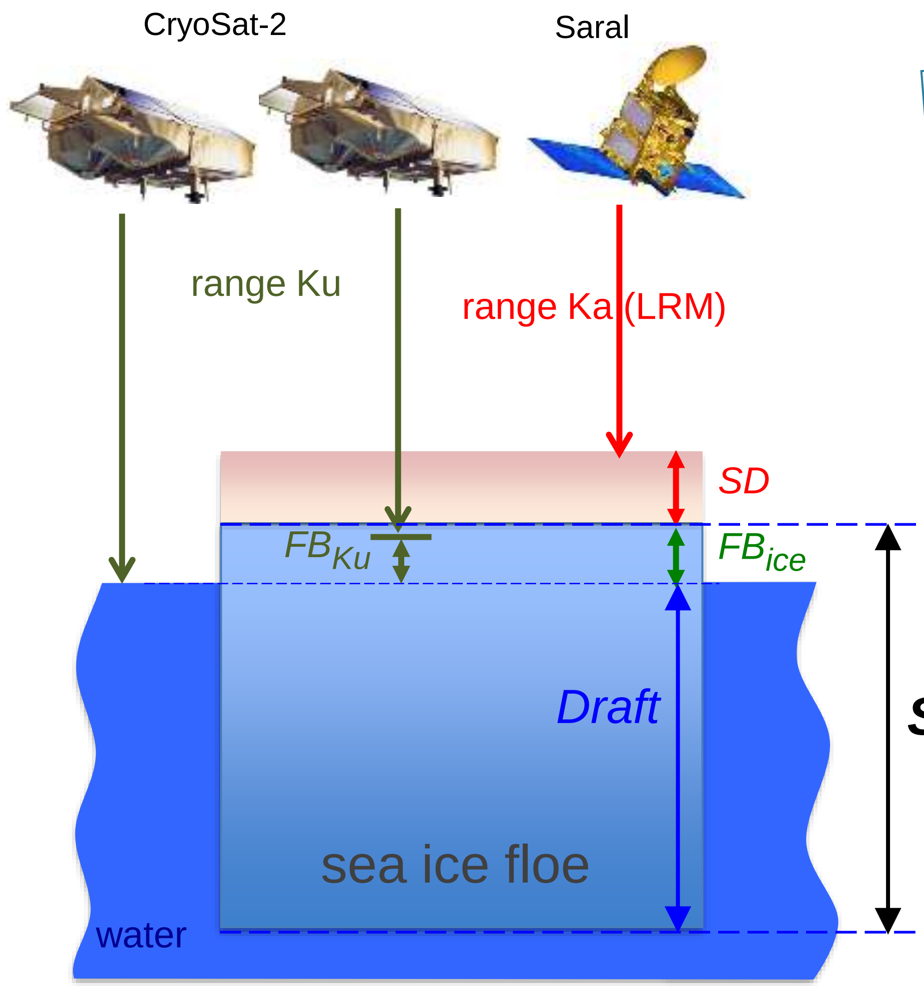
Measurement of sea ice thickness by altimetry



Snow load +
lower speed propagation in Ku within snow

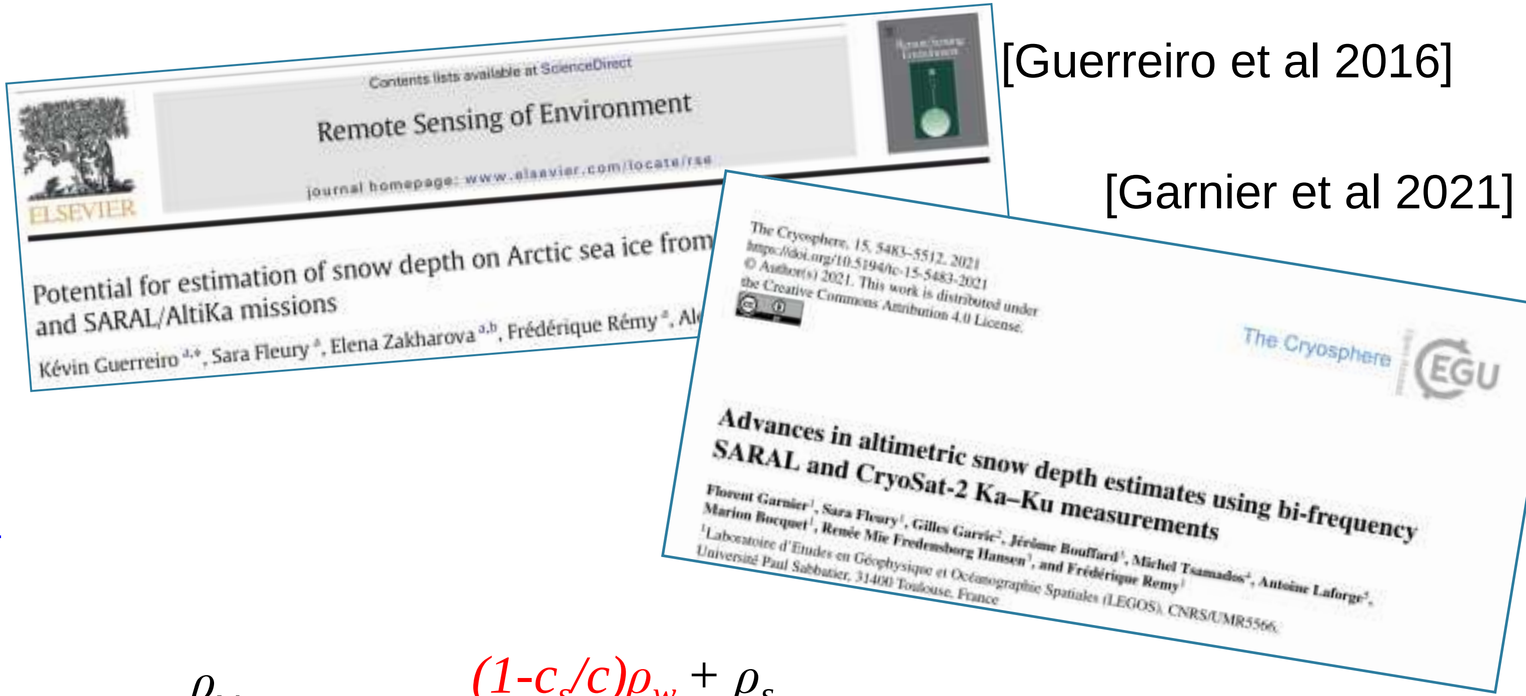
$$SIT = \frac{\rho_w}{\rho_w - \rho_i} FB + \frac{(1-c_s/c)\rho_w + \rho_s}{\rho_w - \rho_i} SD$$

Measurement of sea ice thickness by altimetry



[Guerreiro et al 2016]

[Garnier et al 2021]


Contents lists available at ScienceDirect
Remote Sensing of Environment
journal homepage: www.elsevier.com/locate/rse
ELSEVIER
Potential for estimation of snow depth on Arctic sea ice from CryoSat-2 and SARAL/AltiKa missions
Kévin Guerreiro [a,*], Sara Fleury [a], Elena Zakharova [a,b], Frédérique Rémy [a], Al...

The Cryosphere, 15, 5483–5512, 2021
https://doi.org/10.5194/tc-15-5483-2021
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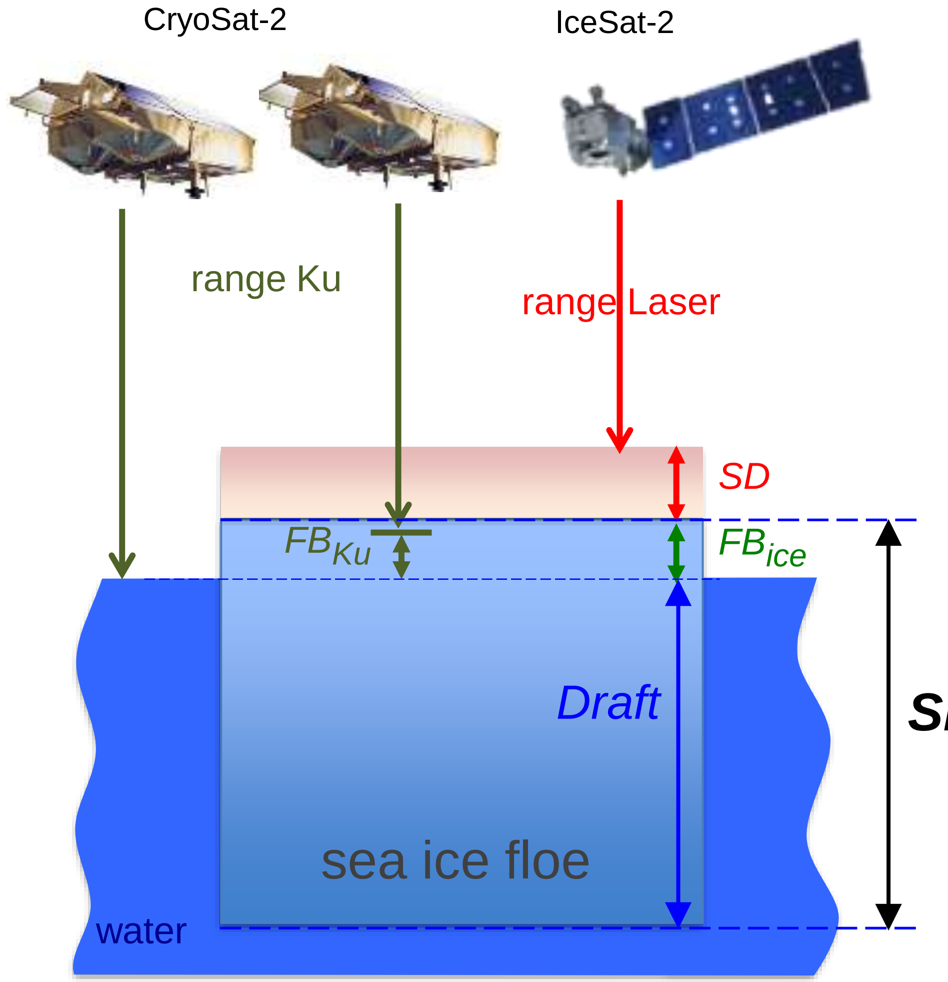
The Cryosphere
EGU
Advances in altimetric snow depth estimates using bi-frequency SARAL and CryoSat-2 Ka–Ku measurements
Florent Garnier[1], Sara Fleury[1], Gilles Garric[2], Jérôme Bouffard[3], Michel Tsamados[4], Antoine Laforge[1], Marion Bocquet[1], Renée Mie Fredensborg Hansen[5], and Frédérique Remy[1]
[1]Laboratoire d'Etudes en Géophysique et Océanographie Spatiales (LEGOS), CNRS/UMR5566, Université Paul Sabatier, 31400 Toulouse, France

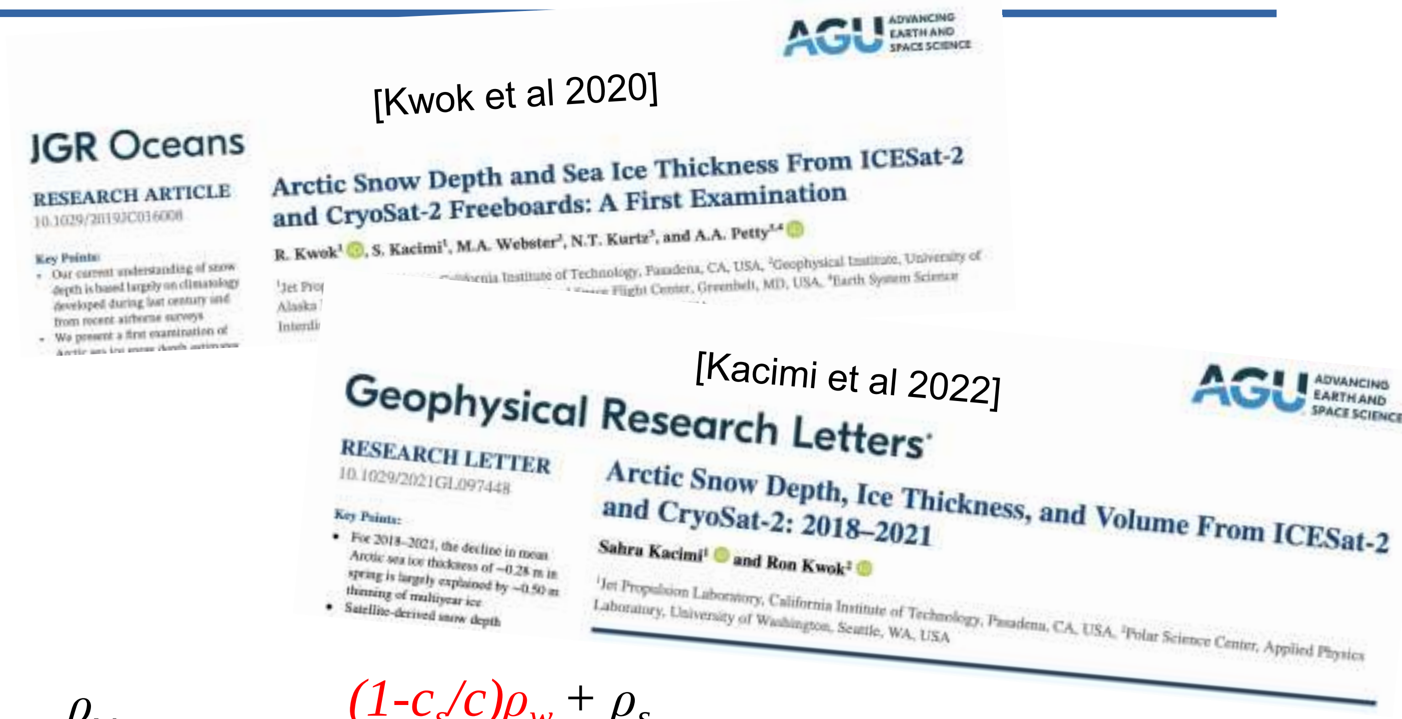
$$SIT = \frac{\rho_w}{\rho_w - \rho_i} FB + \frac{(1-c_s/c)\rho_w + \rho_s}{\rho_w - \rho_i} SD$$

"ASD or KaKu solution"

- still in production at LEGOS (2013-2024, NH+SH)
- but LRM altimetry and bellow 81.5° of latitude

Measurement of sea ice thickness by altimetry





JGR Oceans

RESEARCH ARTICLE

10.1029/2019JC016008

Arctic Snow Depth and Sea Ice Thickness From ICESat-2 and CryoSat-2 Freeboards: A First Examination

R. Kwok[1], S. Kacimi[1], M.A. Webster[2], N.T. Kurtz[3], and A.A. Petty[3,4]

Geophysical Research Letters

RESEARCH LETTER

10.1029/2021GL097448

Arctic Snow Depth, Ice Thickness, and Volume From ICESat-2 and CryoSat-2: 2018–2021

Sahra Kacimi[1] and Ron Kwok[2]

[1]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA, [2]Polar Science Center, Applied Physics Laboratory, University of Washington, Seattle, WA, USA

Key Points:

- For 2018–2021, the decline in mean Arctic sea ice thickness of ~0.28 m in spring is largely explained by ~0.50 m thinning of multiyear ice
- Satellite-derived snow depth

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

Snow product Arctic 2018-2021

https://icesat-2.gsfc.nasa.gov/sea-ice-data/kacimi-kwok-2022

“LaKu solution”

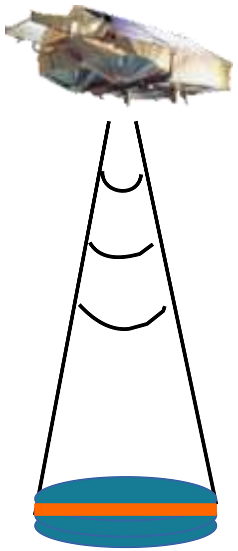
LaKu snow depth product

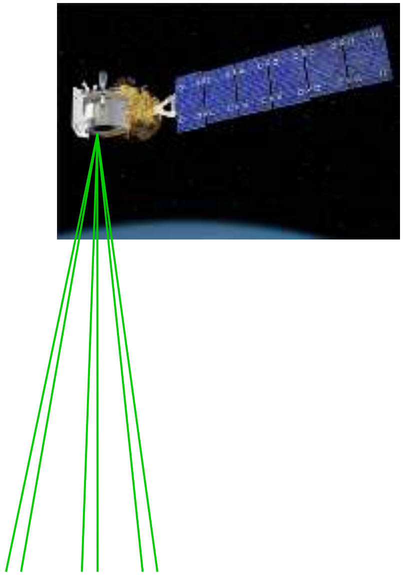
CryoSat-2:

Doppler beam: (300-450)m x 1.5 km

IceSat-2:

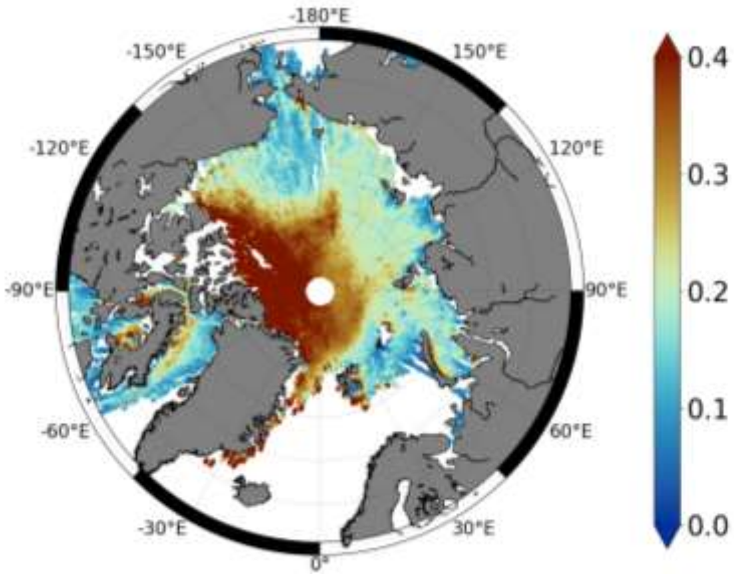
Granules: Ls x 17m , Ls ϵ [10m,150m]
Swath: 6.6 km x 10 km





Missions		Launched	Main payload
CryoSat-2		April 2010	Ku-band SAR (SIRAL)
ICESat-2		Sept 2018	6 beams LIDAR (ATLAS)

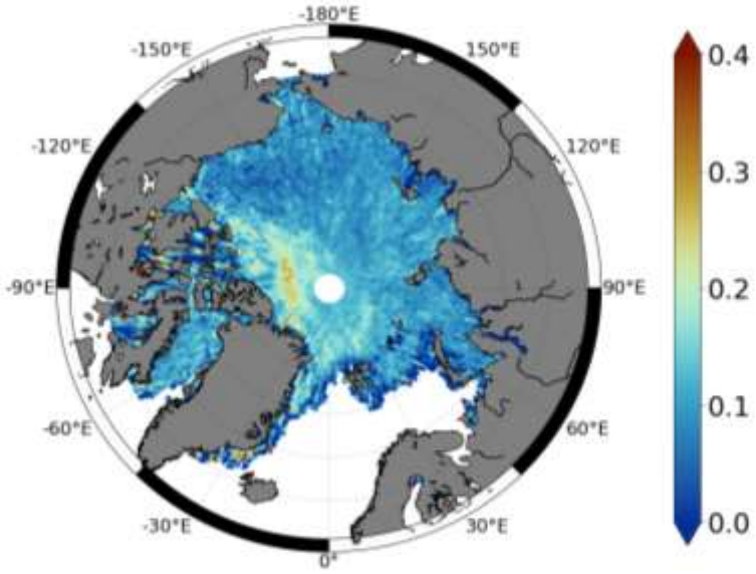
LaKu snow depth product



FB IS2

−

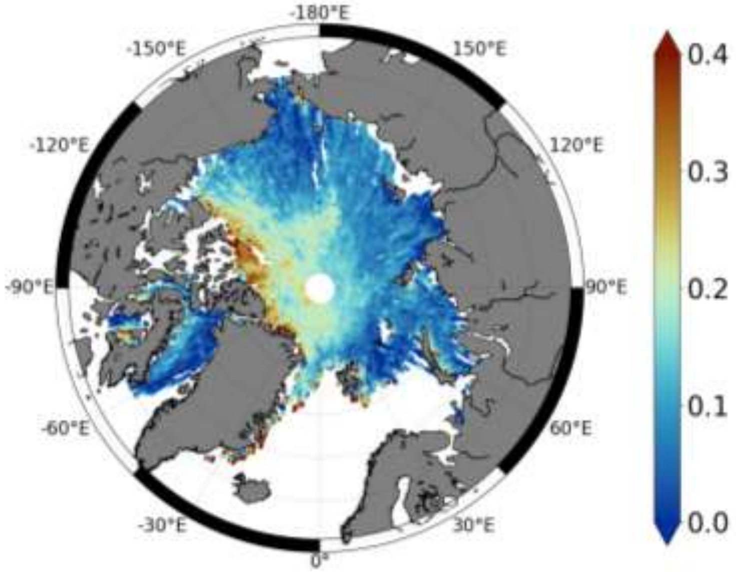
FB CS2



$$X\ (1+0.00051\rho_{snow})^{-1.5}$$

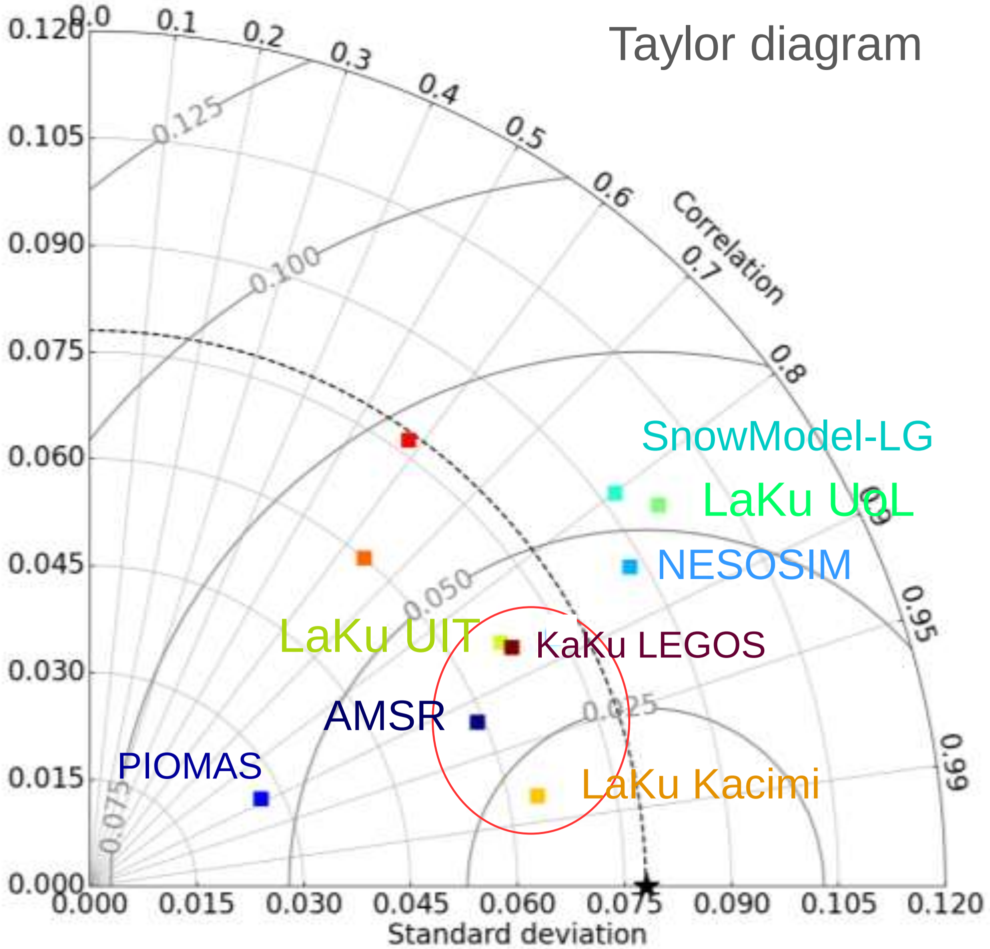
=

SD



- Monthly data
- 25 km pixel size resolution

Comparisons with other snow products



LaKu LEGOS

LaKu: LaKu UoL, LaKu UIT, LaKu Kacimi

KaKu: KaKu LEGOS, KaKu UoL, KaKu UIT

Radiometry: AMSR-Bremen

Models: PIOMAS, NESOSIM, SnowModel-LG

Climatology: W99m

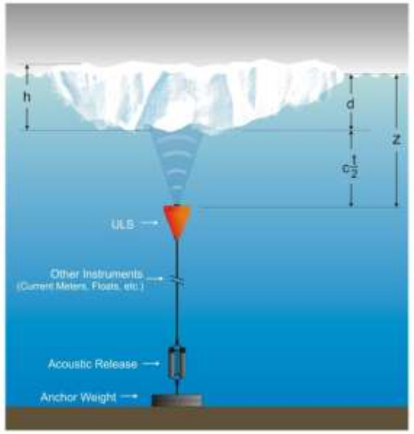
- Correlations above 0.8 with all products (except KaKu UIT abd KaKu UoL)
- Best agreement with LaKu Kacimi, LaKu UiT, AMSR, KaKu LEGOS

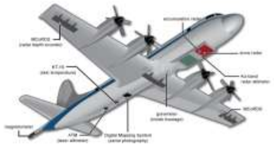
[Carret et al. 2024]

Comparison and validation of the snow depth product

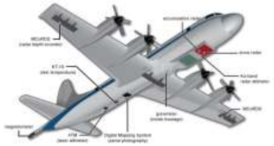
In situ datasets

BGEP
- 4 moorings in the Beaufort Gyre with an upward-looking sonar
- Daily data since 2003
- Variable measured: draft



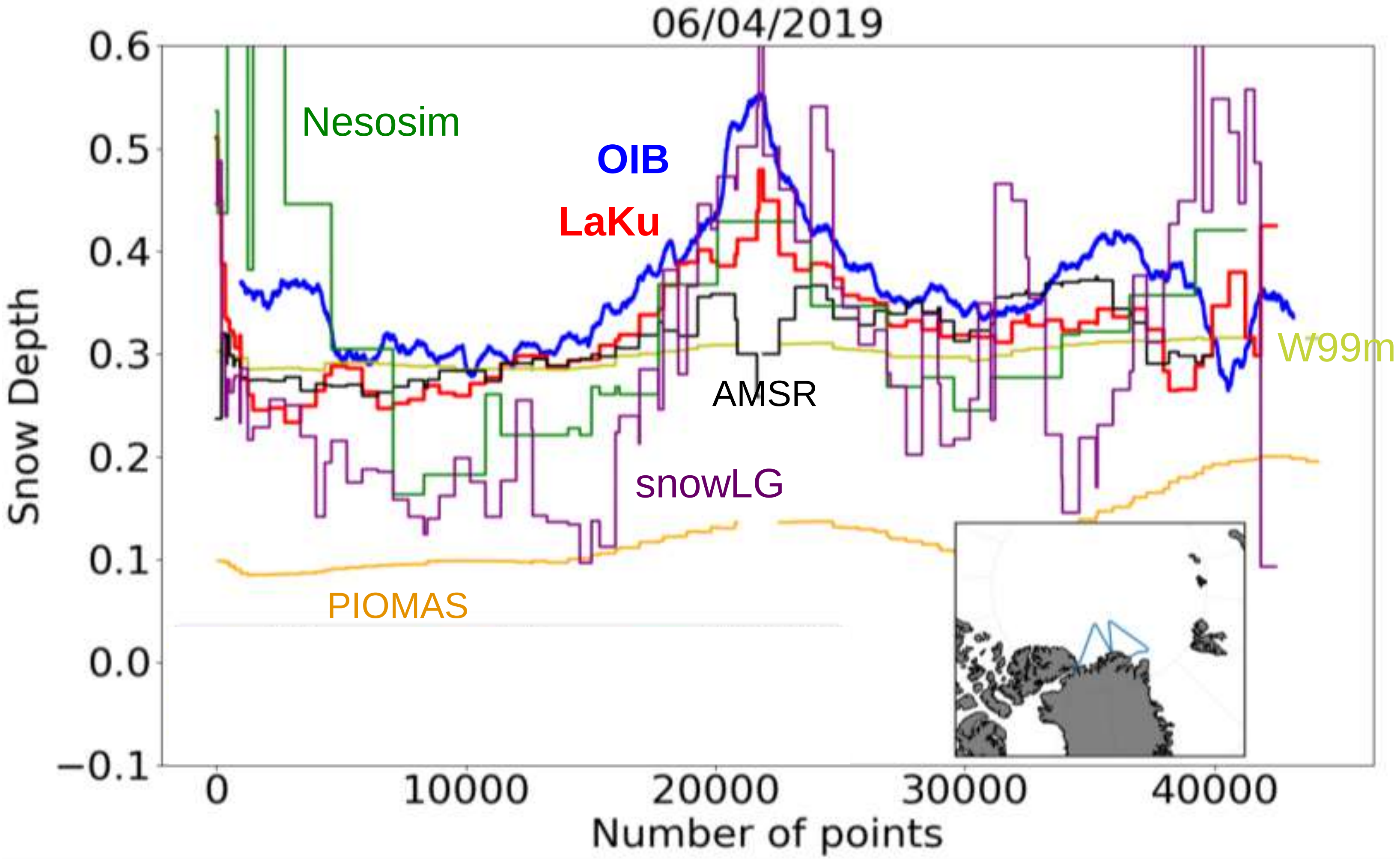


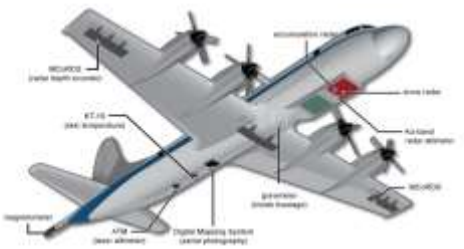
ICEBird
- Airborne survey with an ElectroMagnetic induction
- Campaign in winter and in summer since 2009
- Variable measured: snow depth



Operationnal IceBridge
- 10-year mission to collect polar data between ICE and ICESat-2
- Airborne measurements
- Period of campaign: April 2019
- Variable measured: snow depth

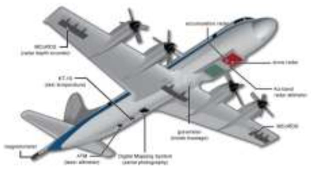
Comparison with OIB snow radar

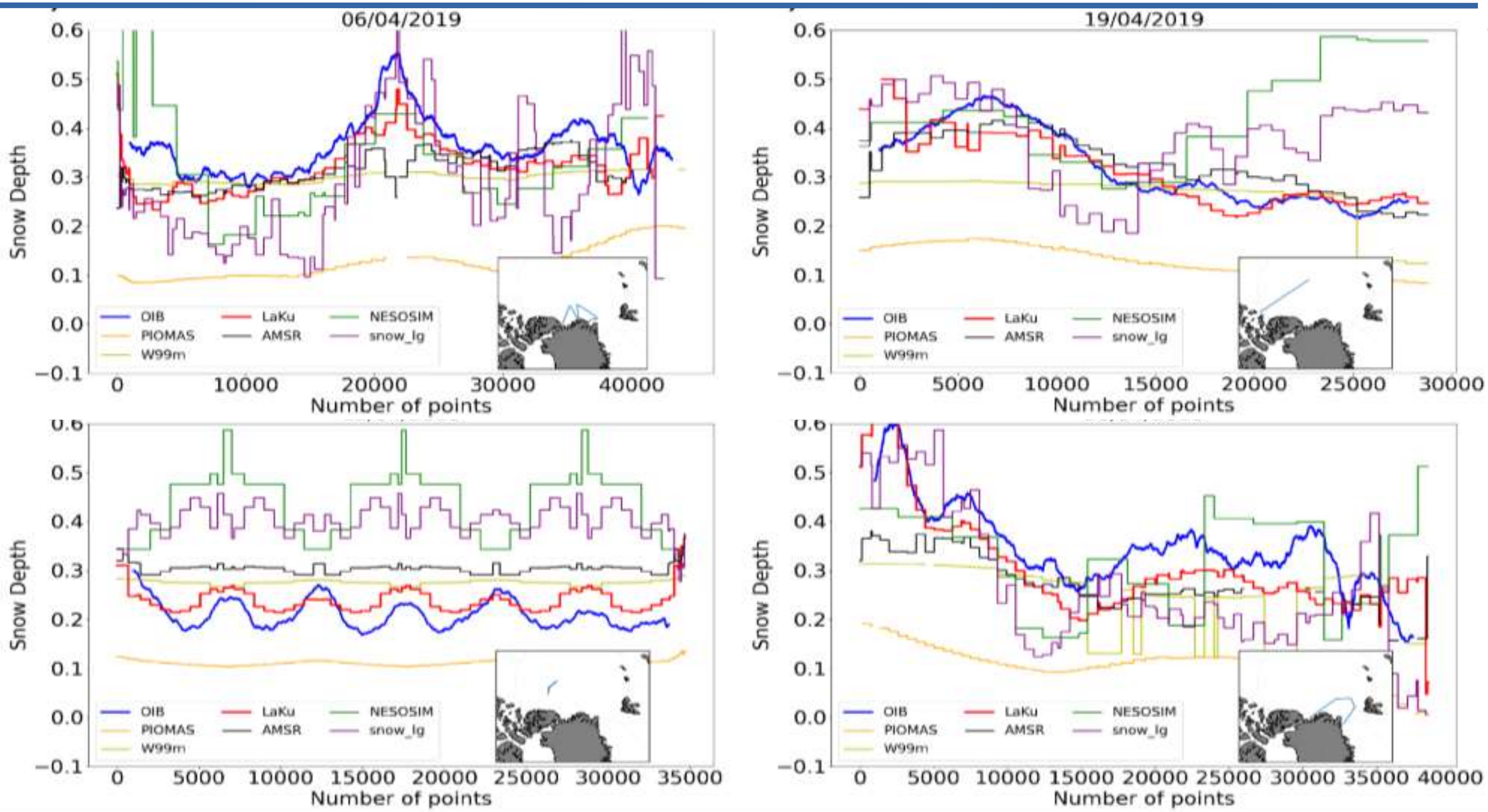




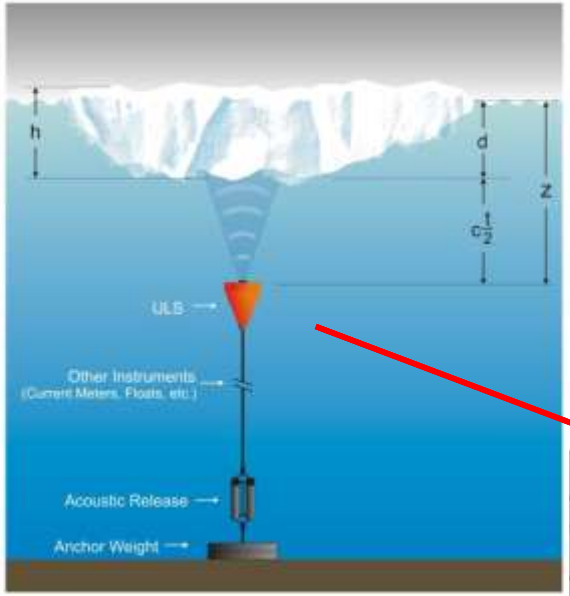
[Carret et al 2024]

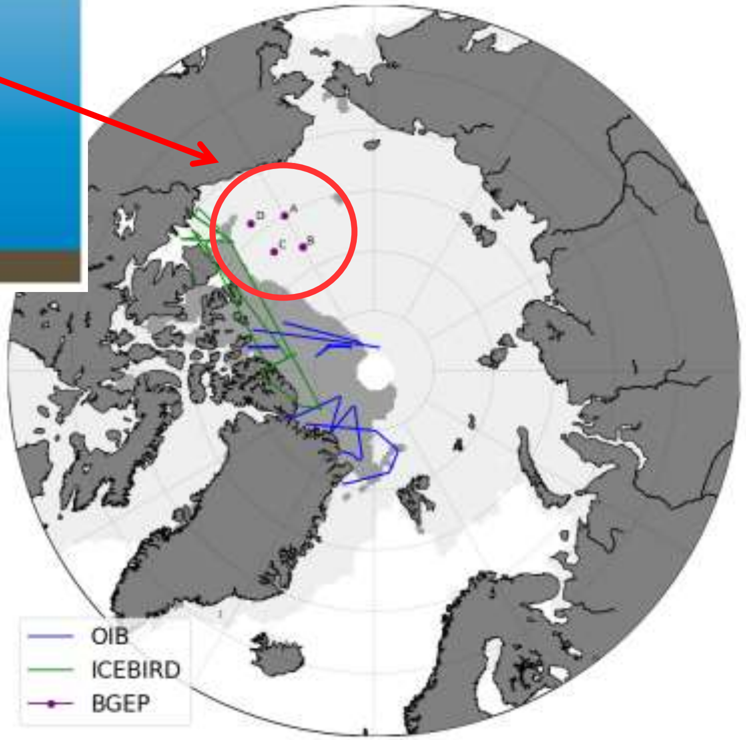
Comparison with OIB snow radar





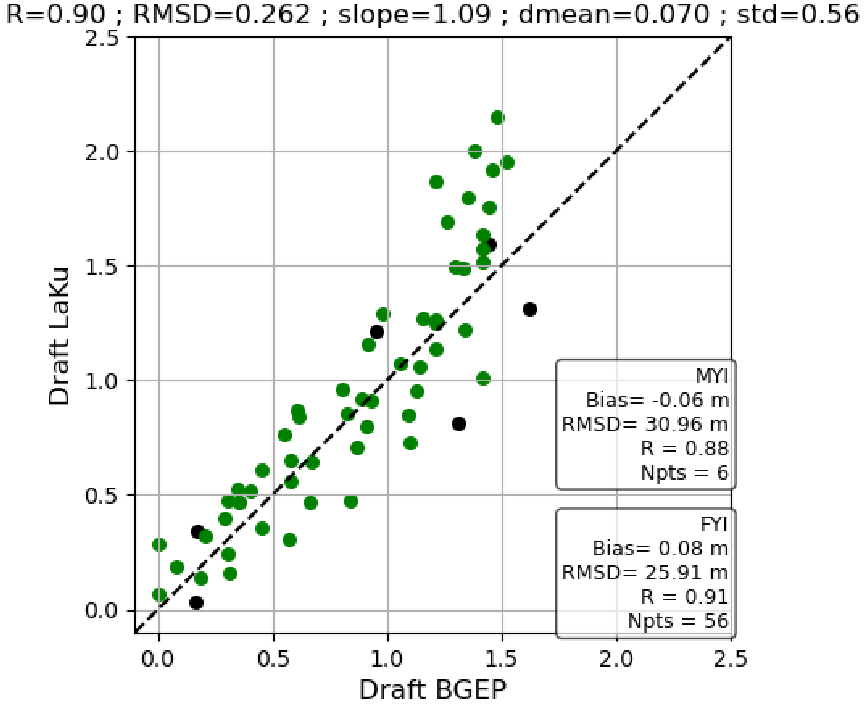
Comparison with BGEP moorings !?



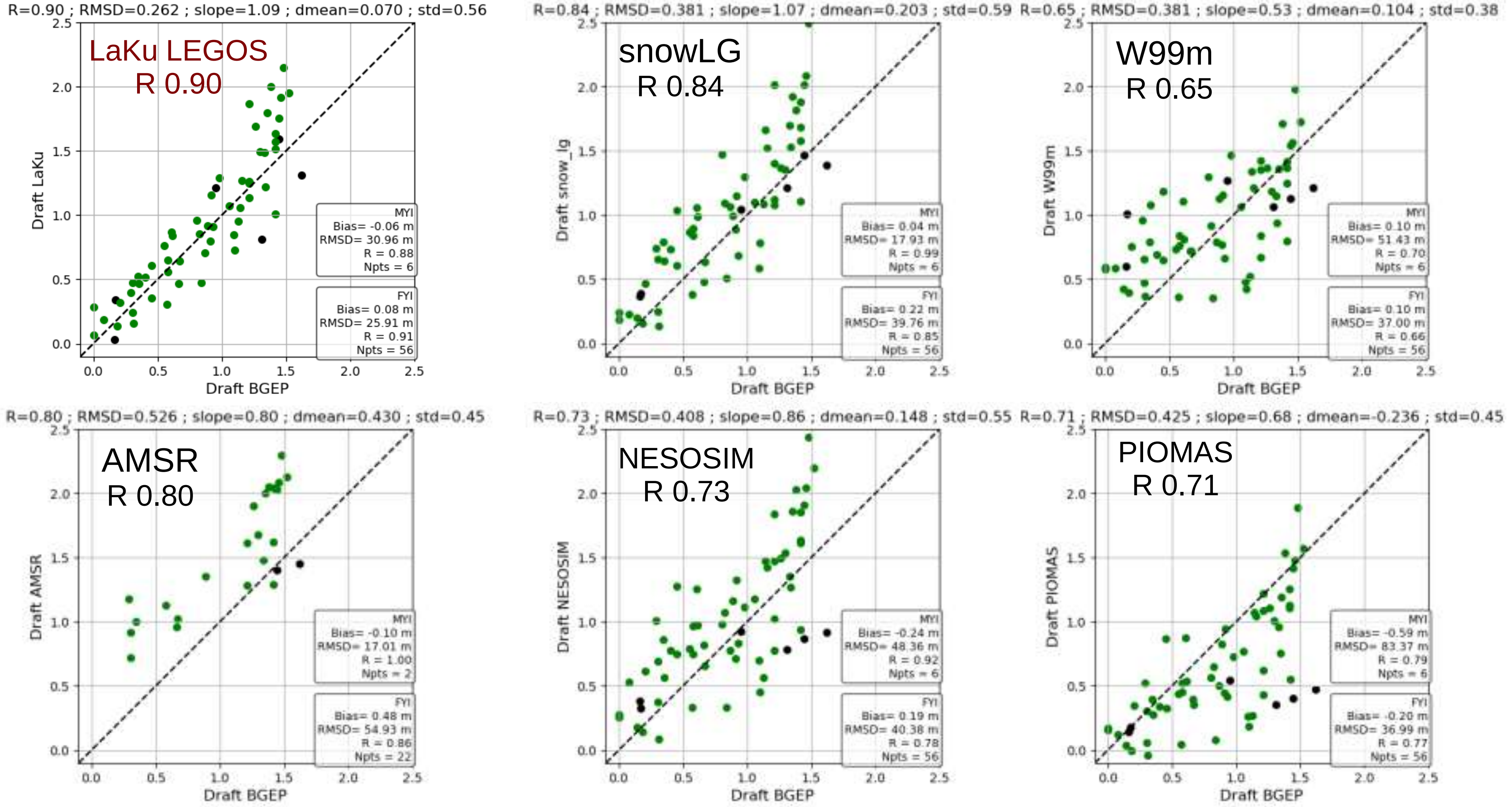


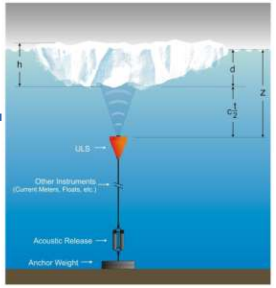
radar freeboard FB_{ku} + snow depth SD => Draft

$$Draft = \frac{\rho_i\ FB_{ku} + \rho_i * ((1 + U\rho_s)^{1.5} - 1)\ SD + \rho_s\ SD}{\rho_w - \rho_i}$$

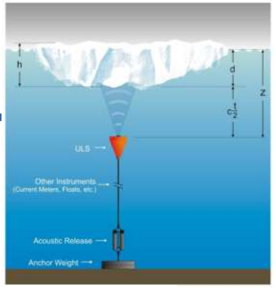


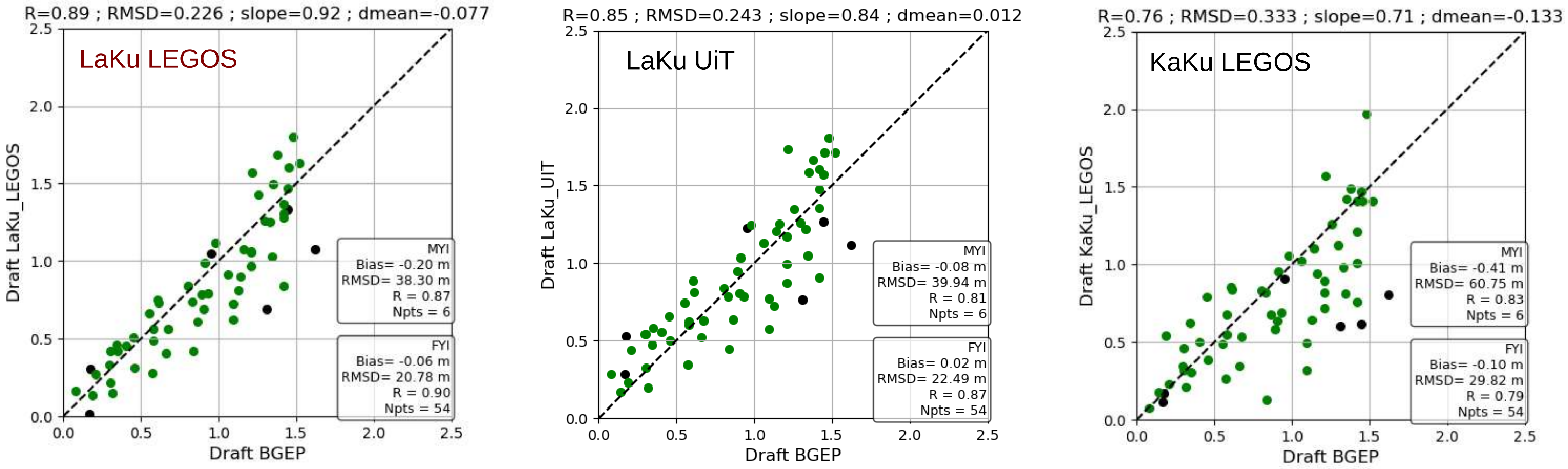
Comparison with BGEP moorings





Comparison with BGEP moorings



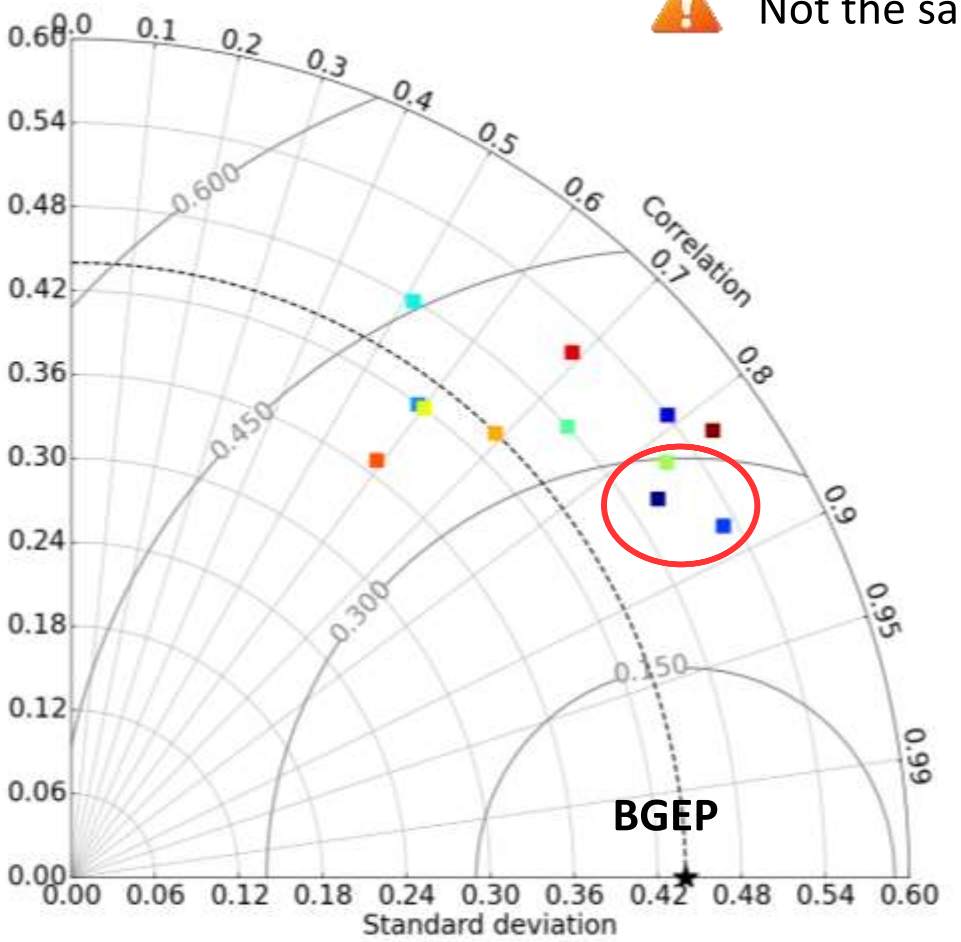


Very close results between the 2 LaKu solutions whereas using different processing for the FBs

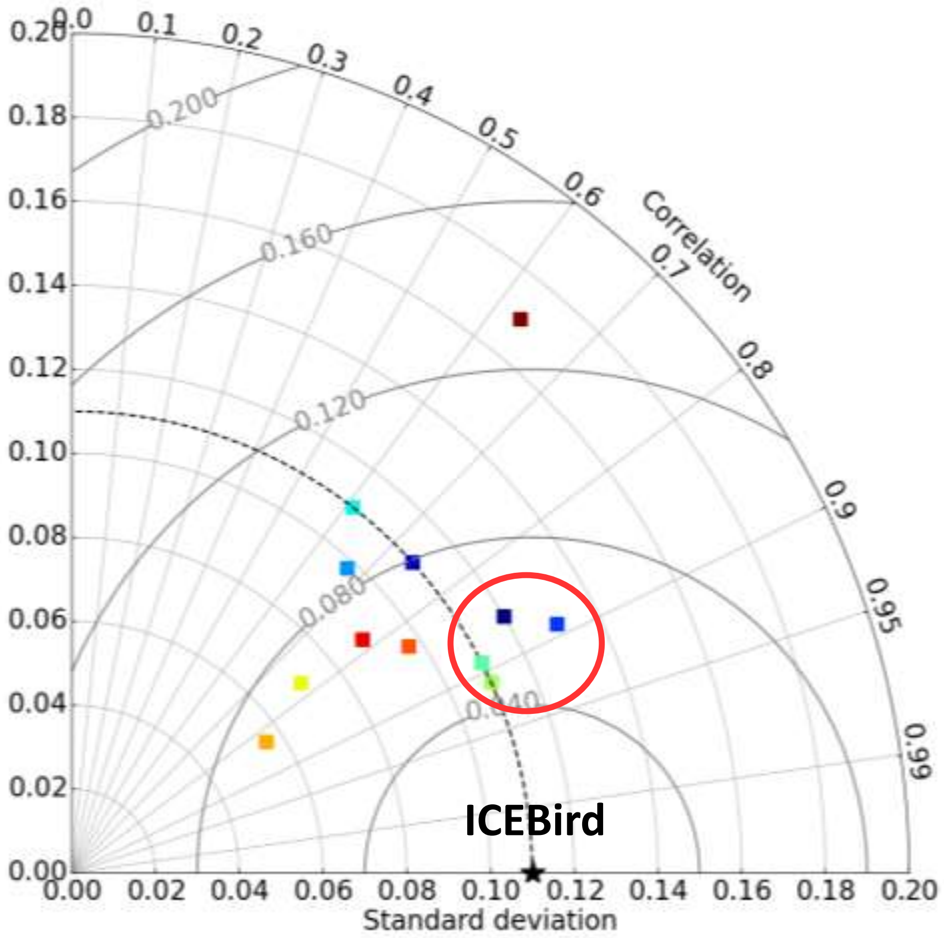
KaKu less good but not far

Comparison with BGEP and ICEBird

Not the same scale (draft vs FB)



- Correlations above 0.6 for all products for ICEBird
- The 3 best solutions are LaKu products
- Only one has yet been published



[Carret et al. 2024]

Uncertainty on Sea Ice Thickness

SIT Equations

$$SIT\,(FB_{Ku}, SD) = \frac{\rho_w}{\rho_w - \rho_i} FB_{Ku} + \frac{\rho_w (1 + T\rho_s)^{1.5} - \rho_w + \rho_s}{\rho_w - \rho_i} SD \qquad \text{(Equ. 1)}$$

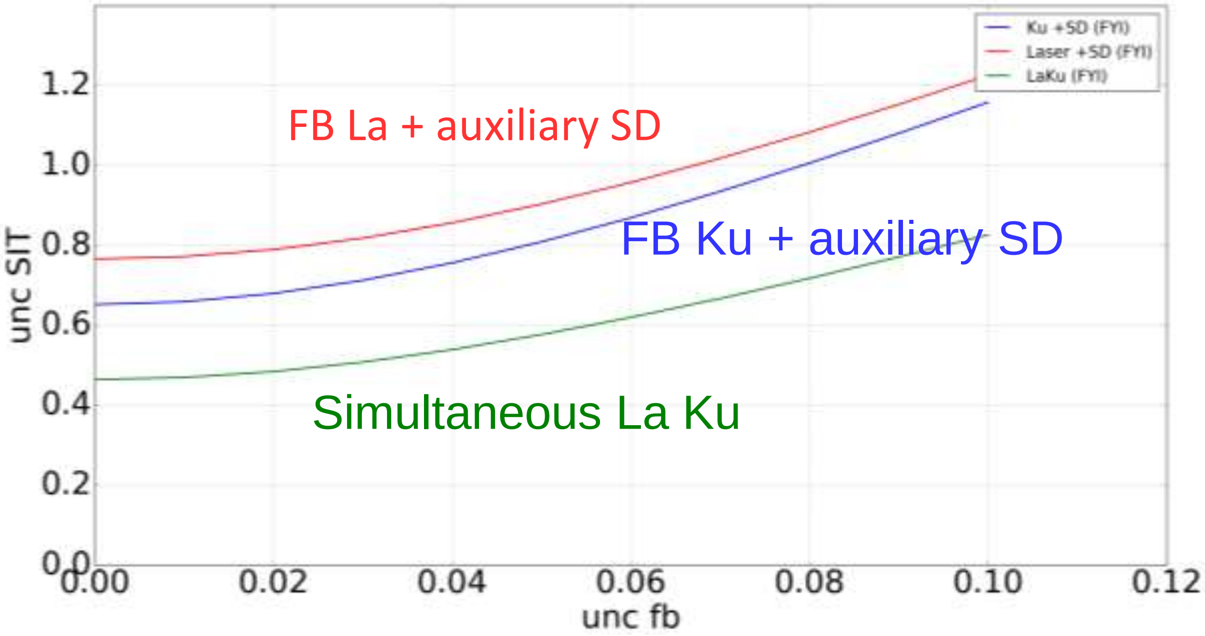
$$SIT\,(FB_{La}, SD) = \frac{\rho_w}{\rho_w - \rho_i} FB_{La} + \frac{\rho_s - \rho_w}{\rho_w - \rho_i} SD \qquad \text{(Equ. 2)}$$

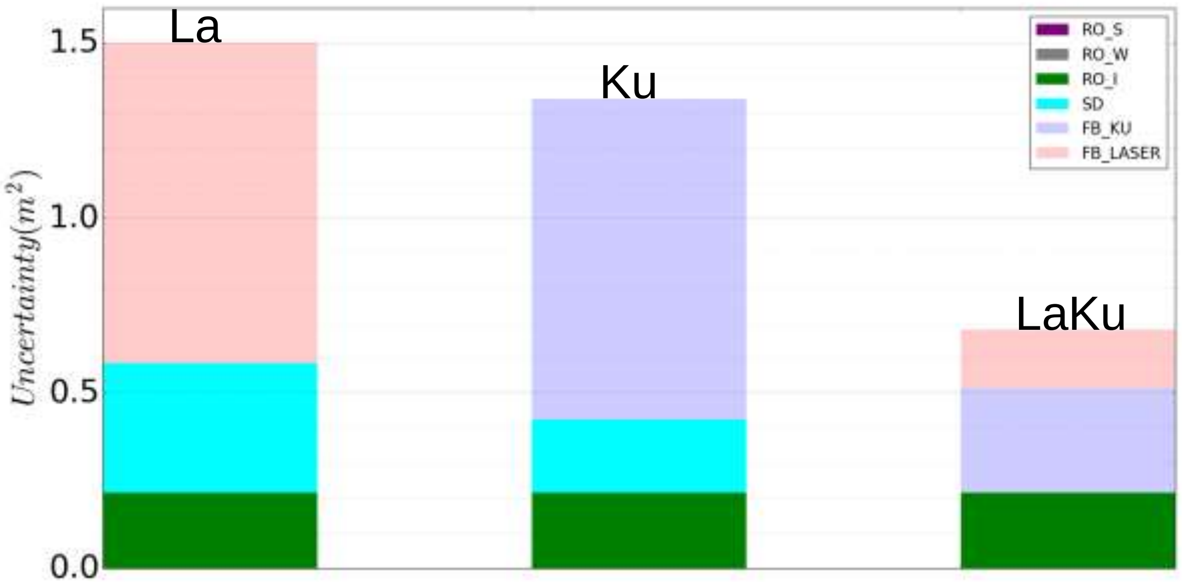
$$SIT\,(FB_{Ku}, FB_{La}) = \frac{\rho_w}{\rho_w - \rho_i} FB_{La} + \frac{\rho_s - \rho_w}{\rho_w - \rho_i} (1 + T\rho_s)^{1.5} (FB_{La} - FB_{ku}) \qquad \text{(Equ. 3)}$$

Error propagation equation (case 3)

$$u_{SIT}^2 = u_{FBKu}^2 \left[\frac{-\rho_w - (\rho_s - \rho_w)/c/c_s}{\rho_w - \rho_i}\right]^2 + u_{FBLaser}^2 \left[\frac{\rho_w + (\rho_s - \rho_w)/c/c_s}{\rho_w - \rho_i}\right]^2 +$$
$$u_{\rho s}^2 \left[\frac{FB_{Laser} - FB_{Ku}}{\rho_w - \rho_i} (1 - (\rho_s - \rho_w) 0.000765 (1 + 0.00051 \rho_s)^{-1})\right]^2 +$$
$$u_{\rho w}^2 \left[\frac{-\rho_i FB_{Laser} + (\rho_i - \rho_s)(FB_{Laser} - FB_{Ku})/c/c_s}{(\rho_w - \rho_i)^2}\right]^2 + u_{\rho i}^2 \left[\frac{f}{(\rho_w - \rho_i)^2}\right]^2$$

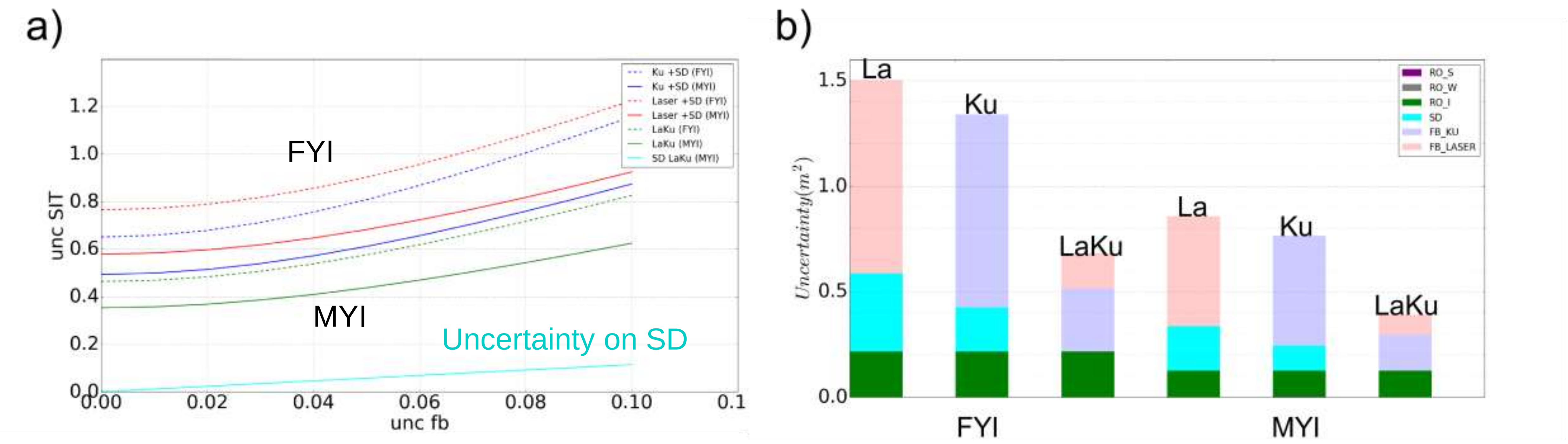
Uncertainties





- For a fix value of uncertainty: larger impact of FBlaser to the total SIT uncertainty
- Simultaneous laser and Ku measurements → reduction of SIT uncertainties + estimation of Snow Depth

Uncertainties



- ➔ For a fix value of uncertainty: larger impact of FBlaser to the total SIT uncertainty
- ➔ Combining laser and Ku measurements → reduction of SIT uncertainties + estimation of Snow Depth

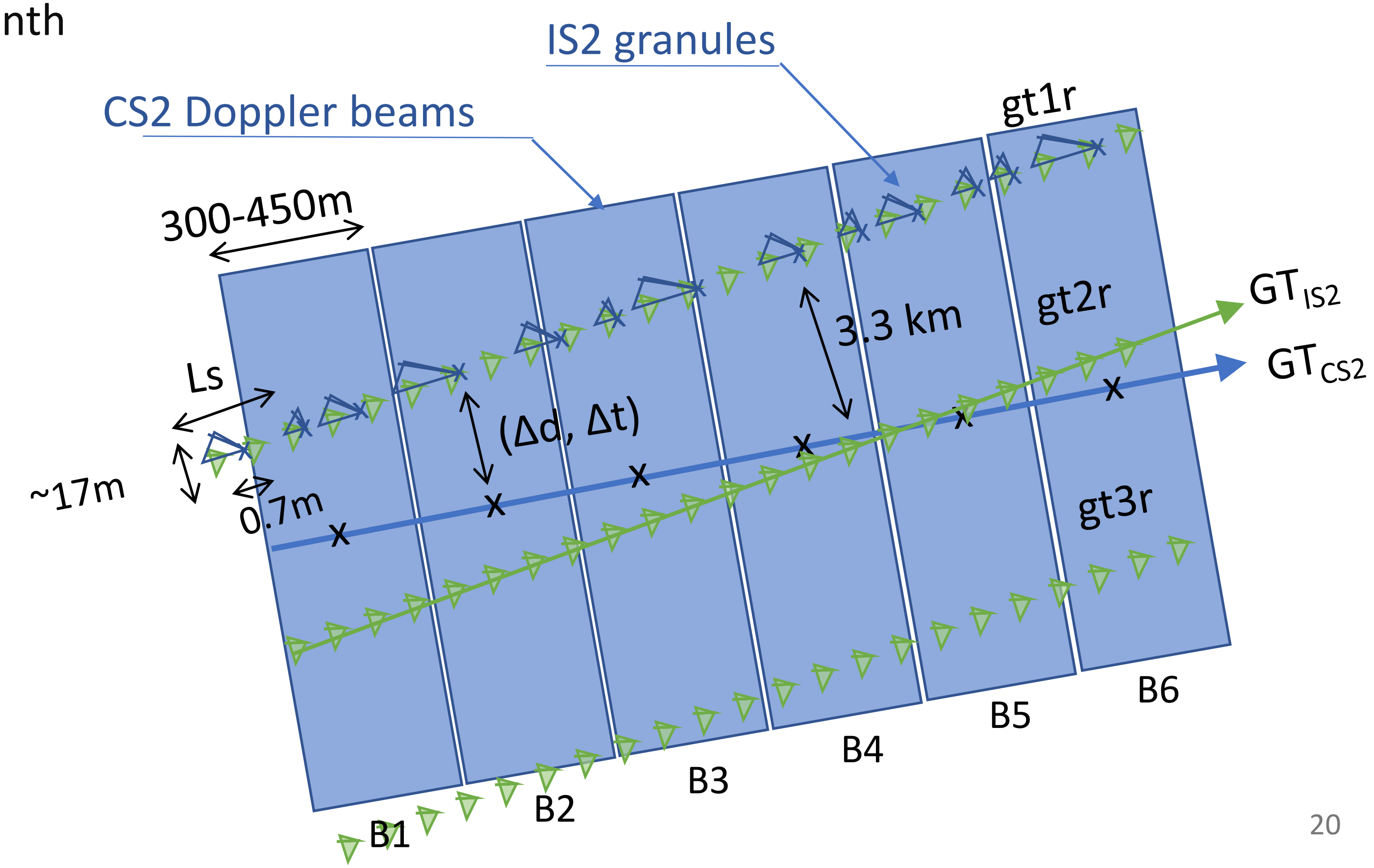
CRYO2ICE

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).

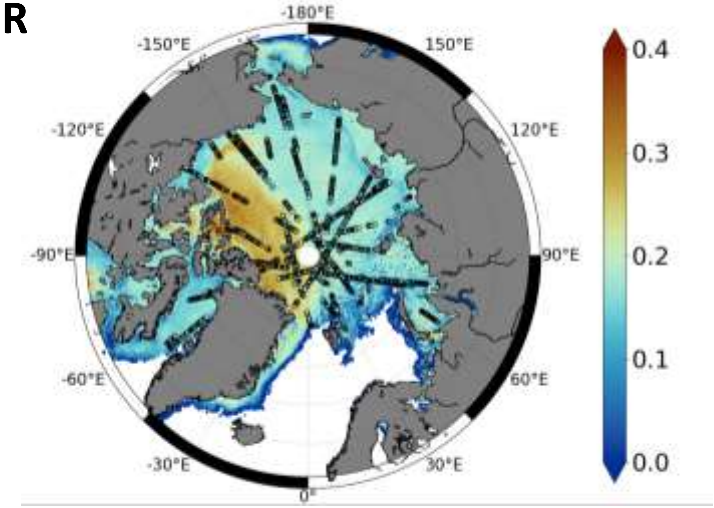
- 20 tracks of coincidental measurements per month
- With a 2-3 hours delay
- Thousands of kilometers transects

Satellite footprints:

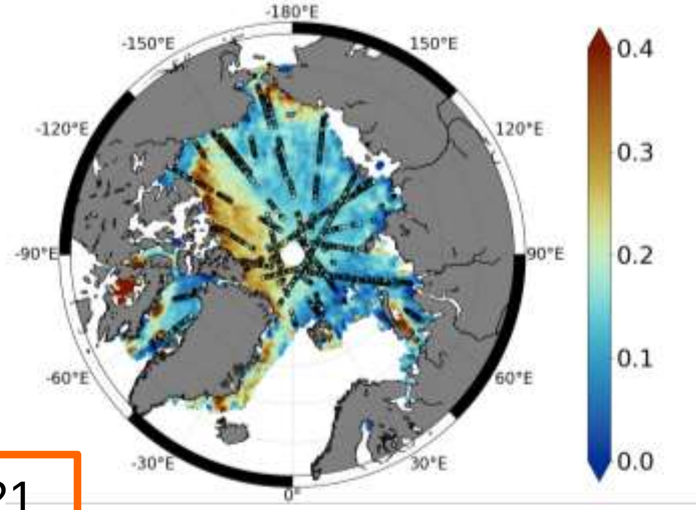
- **CryoSat-2:**
  - Doppler beam: (300-450)m x 1.5 km
- **IceSat-2:**
  - Granules: Ls x 17m , Ls ϵ [10m,150m]
  - Swath: 6.6 km x 10 km



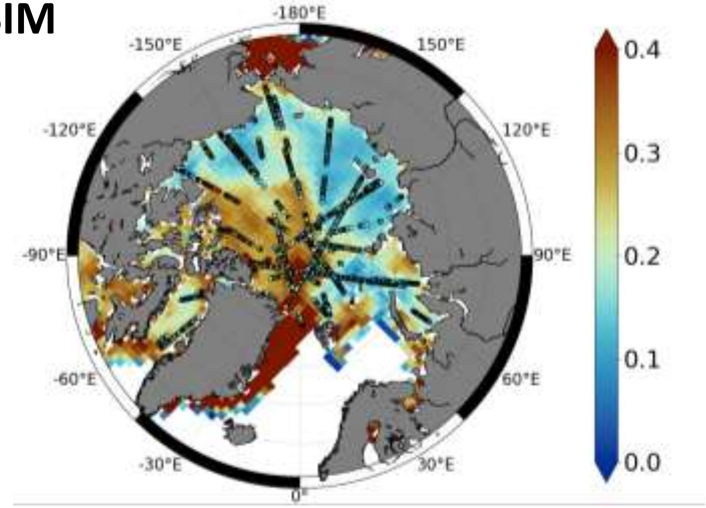
AMSR



LaKu

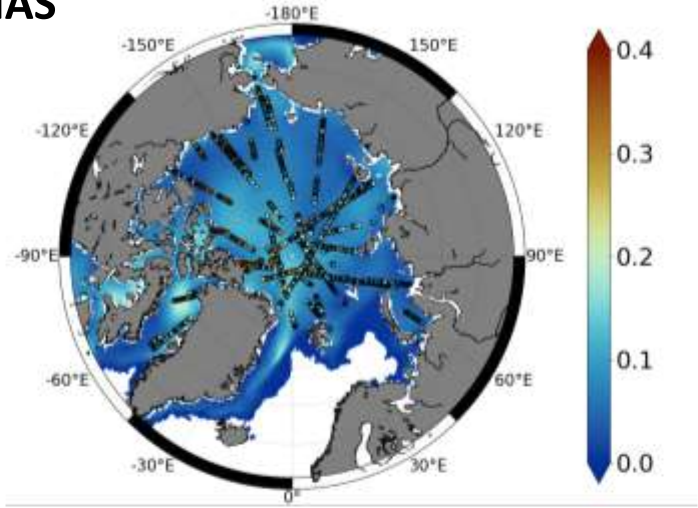


NESOSIM

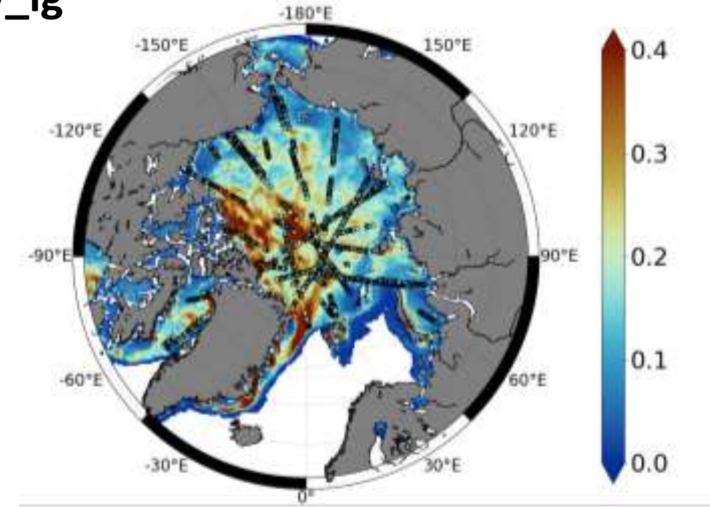


04/2021

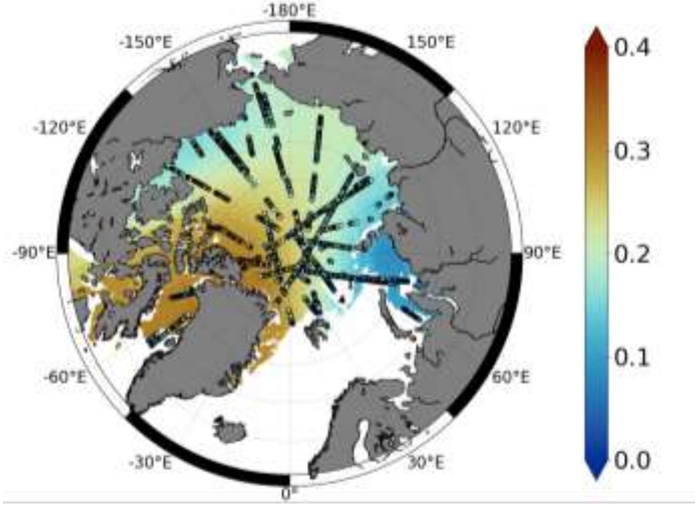
PIOMAS



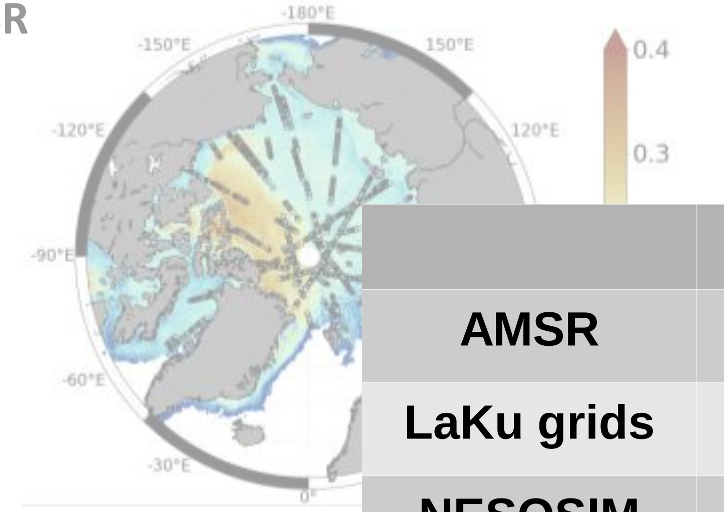
snow_lg



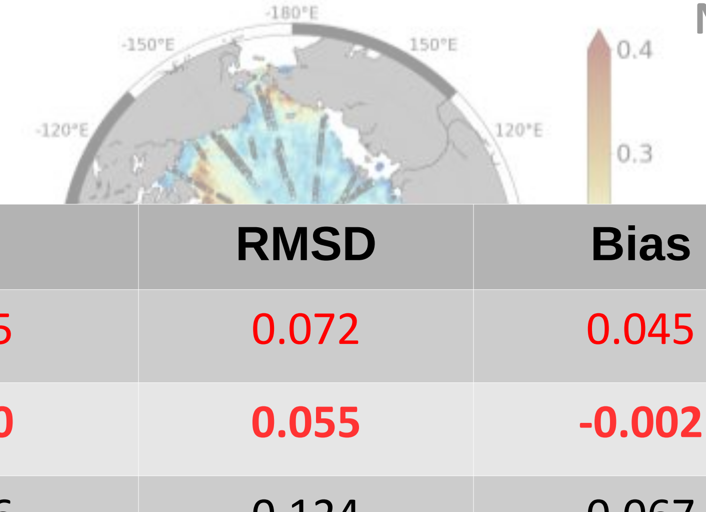
W99



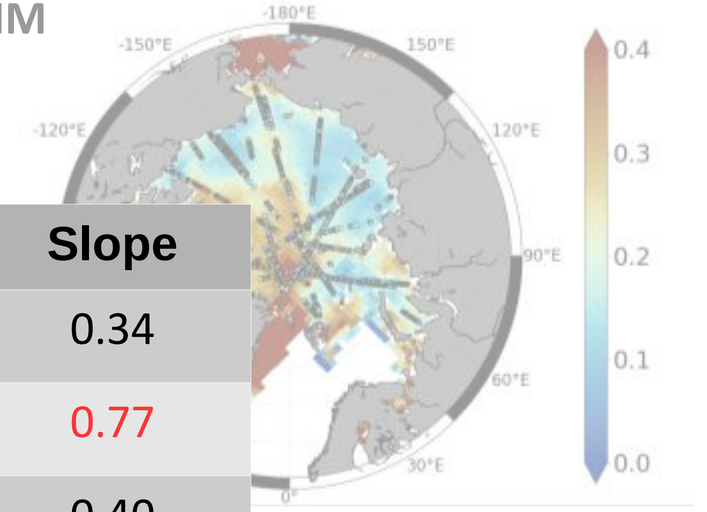
AMSR



LaKu

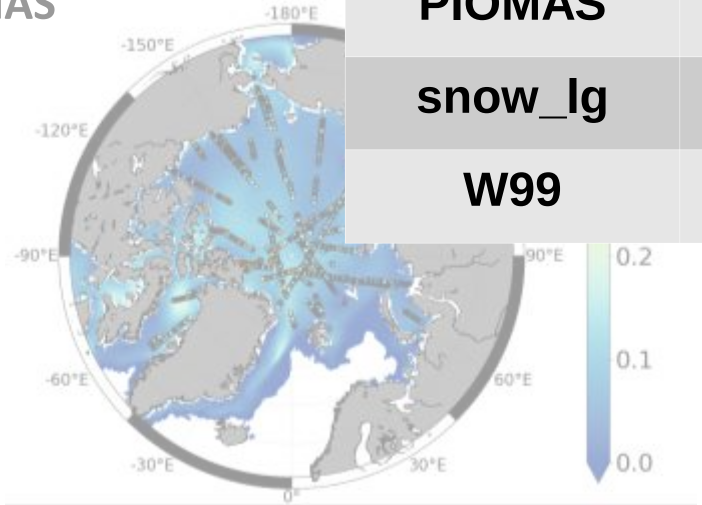


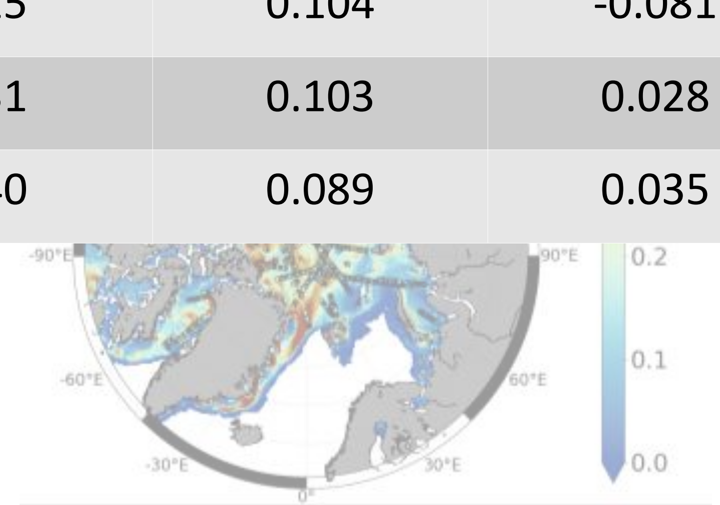
NESOSIM

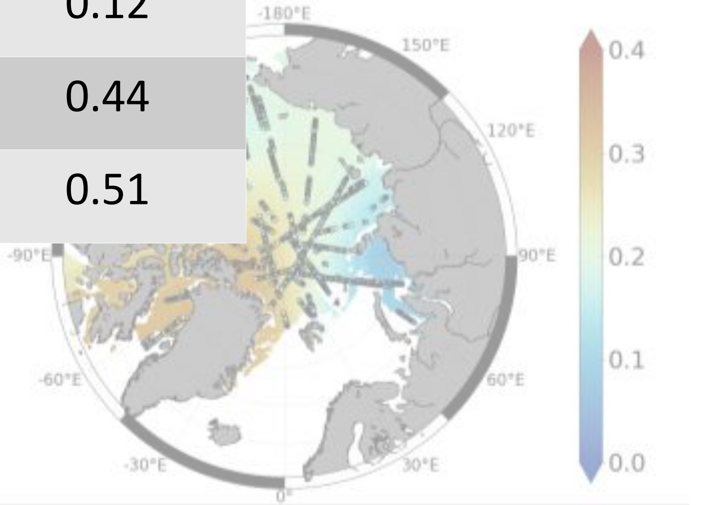


	R	RMSD	Bias	Slope
AMSR	0.55	0.072	0.045	0.34
LaKu grids	**0.70**	**0.055**	**-0.002**	0.77
NESOSIM	0.26	0.124	0.067	0.40
PIOMAS	0.25	0.104	-0.081	0.12
snow_lg	0.31	0.103	0.028	0.44
W99	0.40	0.089	0.035	0.51

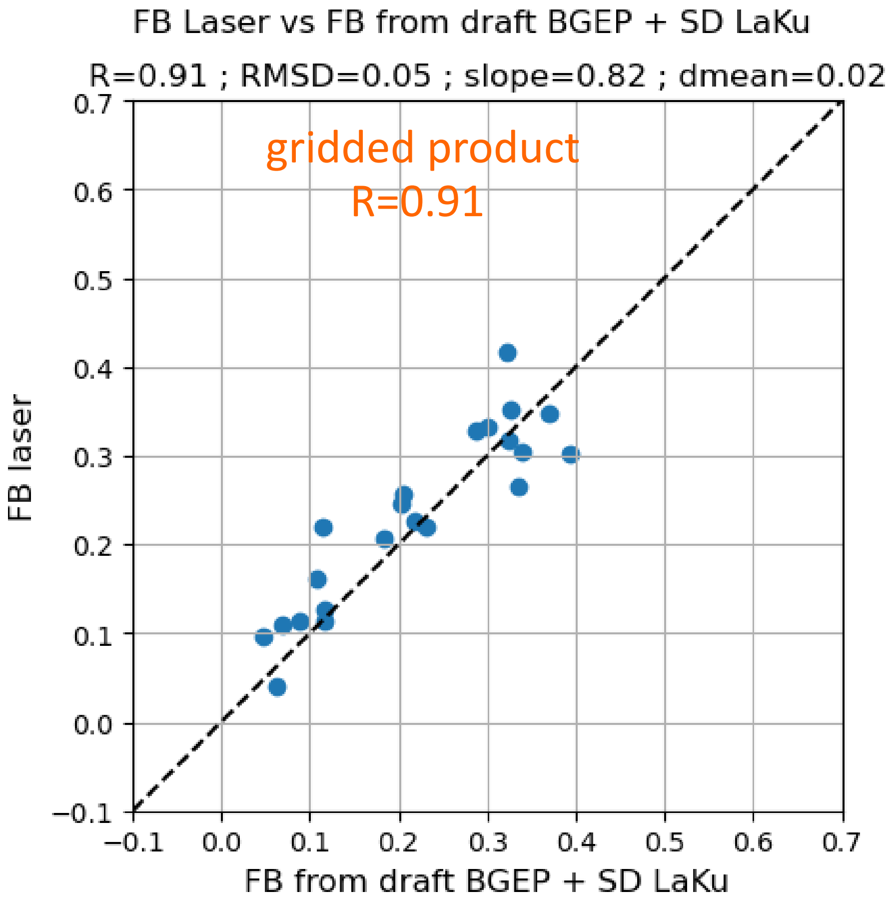
PIOMAS

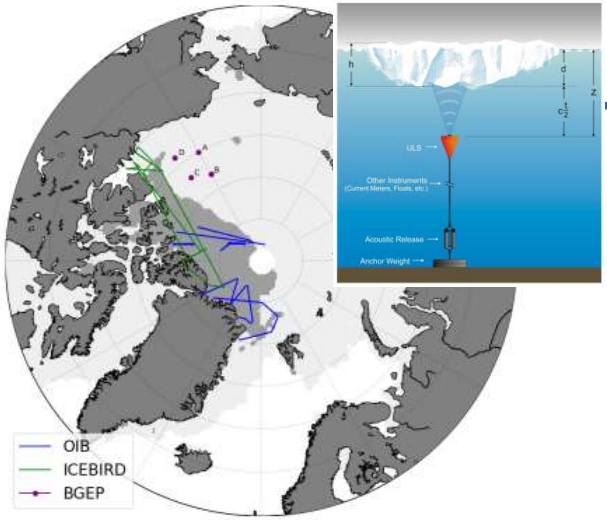




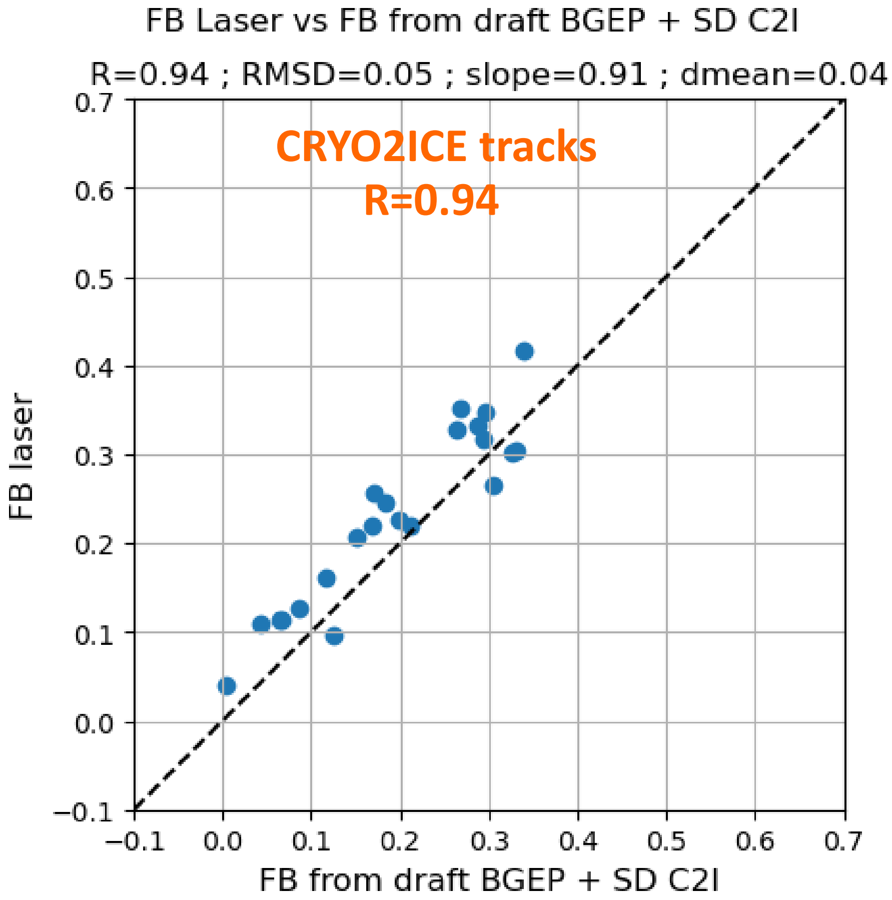


CRYO2ICE





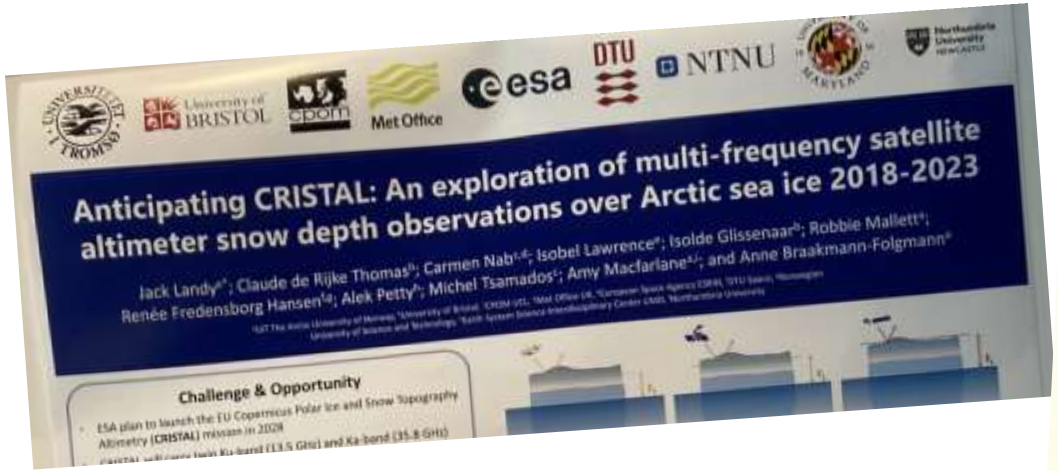
The CRYO2ICE tracks passing in the vicinity of the mooring provide slightly higher correlation (0.94 vs 0.91) than the monthly gridded product at the mooring point although the bias is a little higher (0.04 vs 0.02)



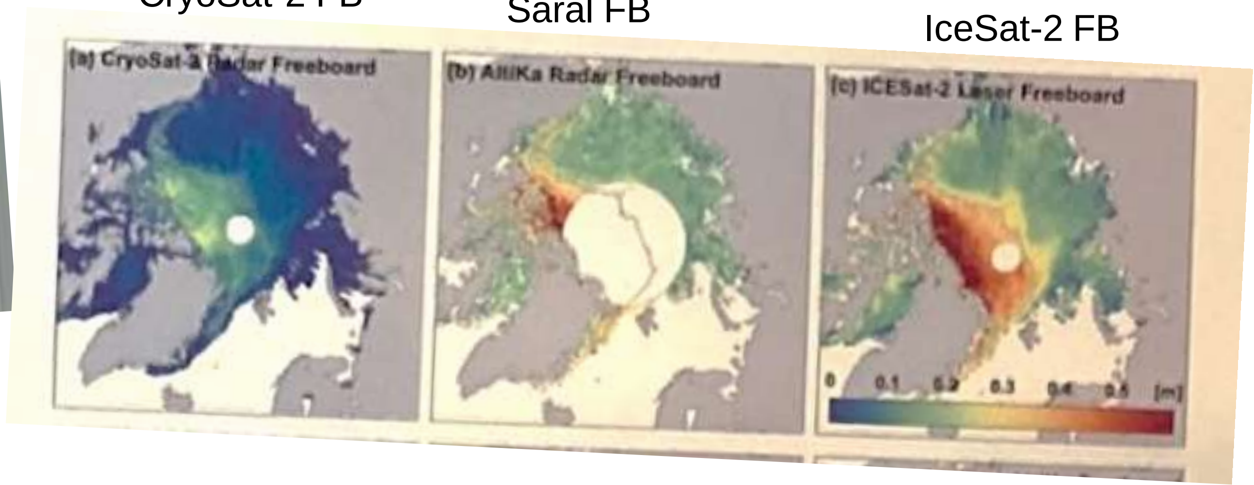
Conclusions

- Good agreement between the LaKu snow depth product and the in situ data
- The different LaKu snow depth solutions are very coherent -> stable solution
- SAR Ku processing based on physical model retracker provide better solutions (tested with TFMRA50)
- The KaKu solution is less efficient but close to LaKu. Recall: LRM versus SAR/Lidar!

See also the amazing results about LRM Ka processing shown in a poster from [Landy et al] !



CryoSat-2 FB Saral FB IceSat-2 FB



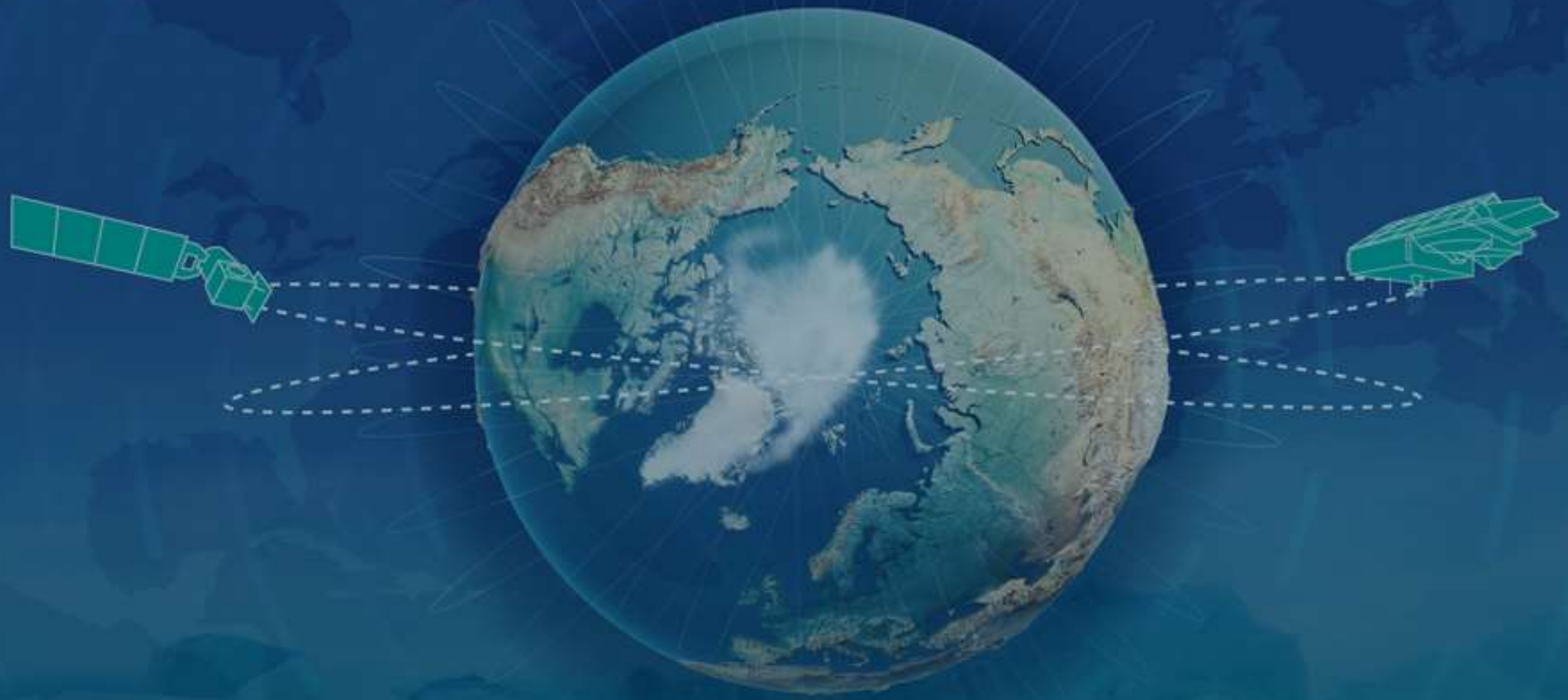
Conclusions

- Good agreement between the LaKu snow depth product and the in situ data
- The different LaKu snow depth solutions are very coherent -> stable solution
- SAR Ku processing based on physical model retracker provide better solutions (tested with TFMRA50)
- The KaKu solution is less efficient but close to LaKu. Recall: LRM versus SAR/Lidar!

  See also the amazing results about LRM Ka processing in a poster from [Landy et al] !
- Simultaneous bi-frequency measurements lower SIT uncertainties.
- The CRYO2ICE project is an opportunity to demonstrate it
- Results very promising for CRISTAL (and CIMR) …

  … but still work to do : Ku penetrations, ice and snow densities, Ka processing

  … and need for in-situ snow depth measurements !
- Results published soon in [Carret et al., Scientific Data 2024]



Thanks for your attention