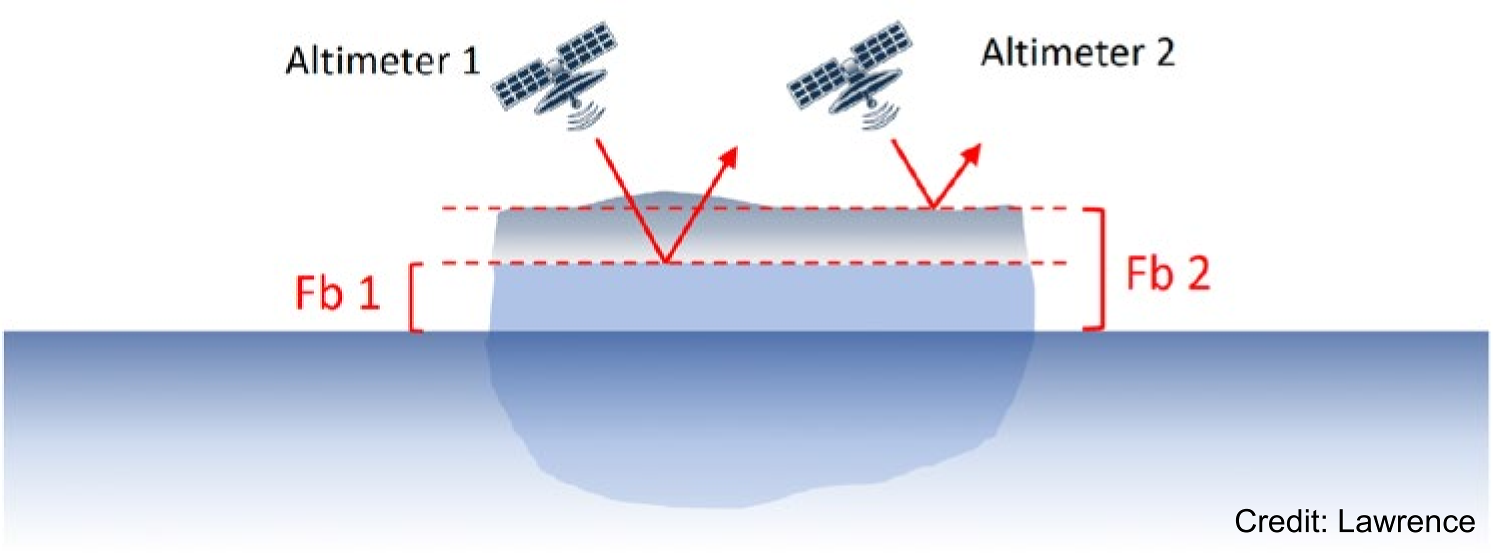
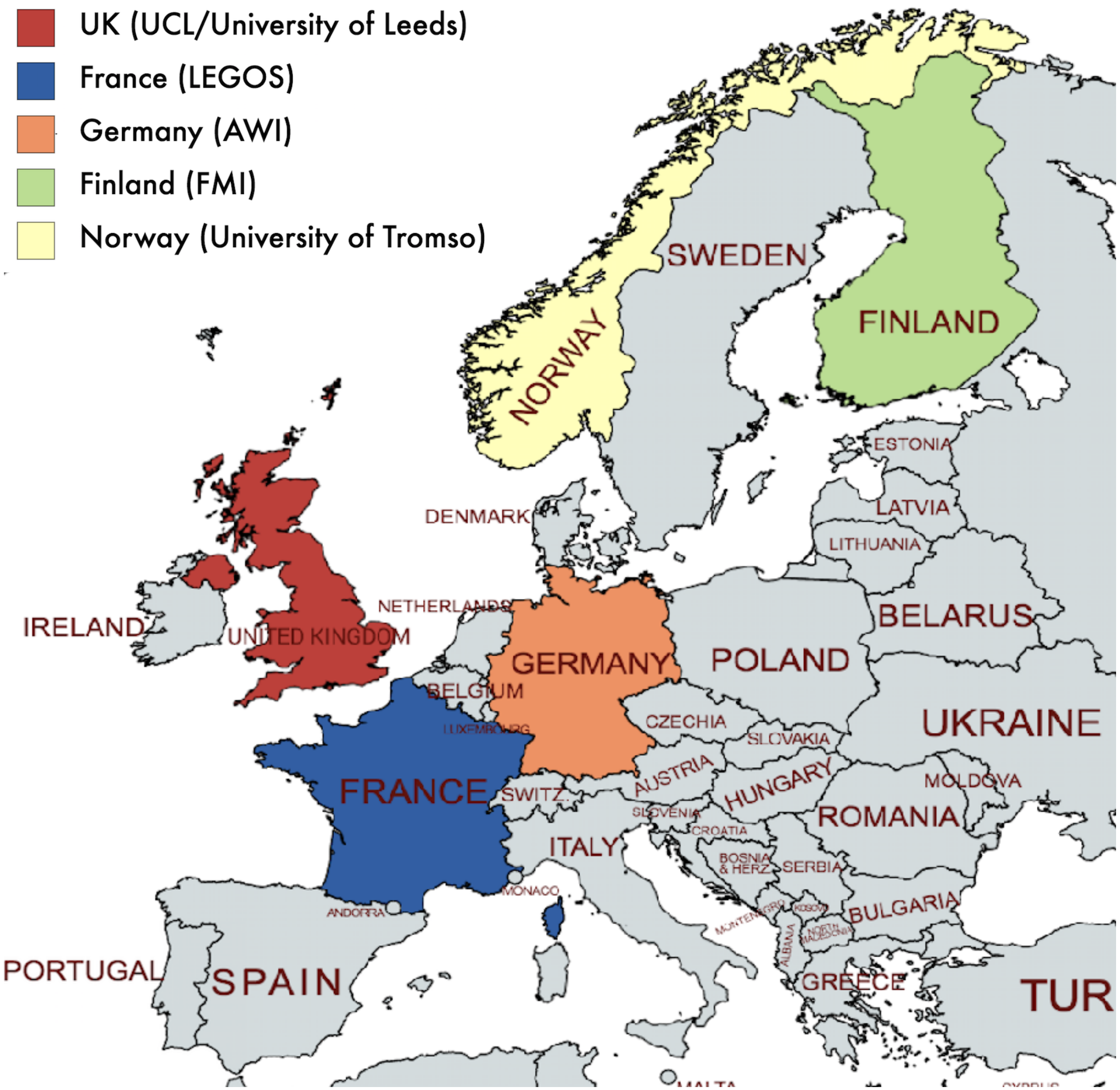
Multi-Frequency Satellite Approaches for Snow on Sea Ice
Challenges and Solutions



Michel Tsamados, Jack Landy + all Polar Snow team

EXPRO+ Snow on Sea Ice

Polar+ Snow



Core partners:

- UCL (ES + MSSL)
- AWI
- FMI
- University of Leeds
- University of Tromso
- LEGOS

Additional partners:

- University of Reading
- University of Helsinki
- Tsinghua University
- NASA Goddard

The Polar+ Snow team

M.Tsamados
Science Lead +
Project manager
R. Willatt + others

S.Fleury
F. Garnier

J. Landy
C. De Rijke-Thomas

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Support project manager
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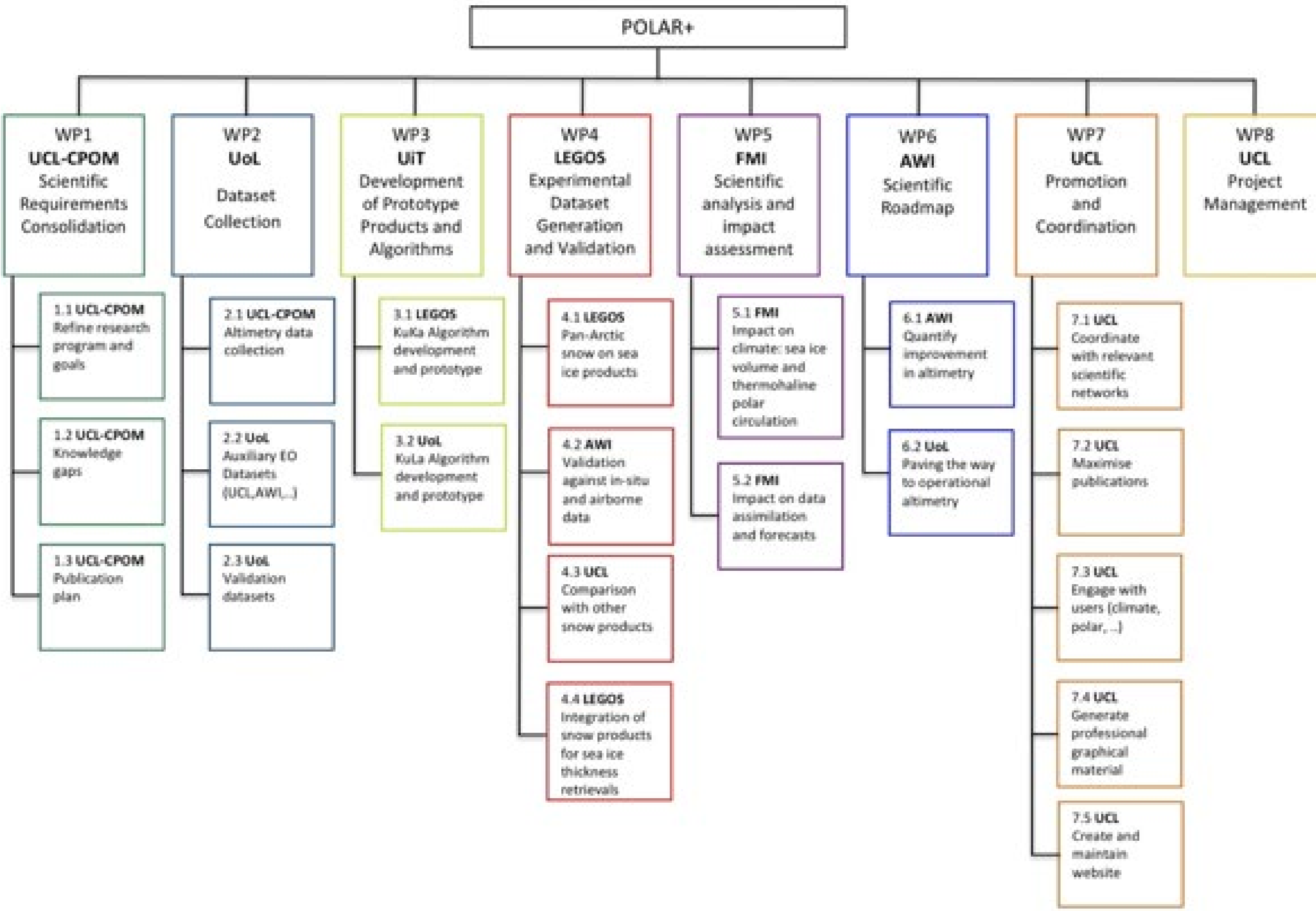
A. Shepherd
I. Lawrence

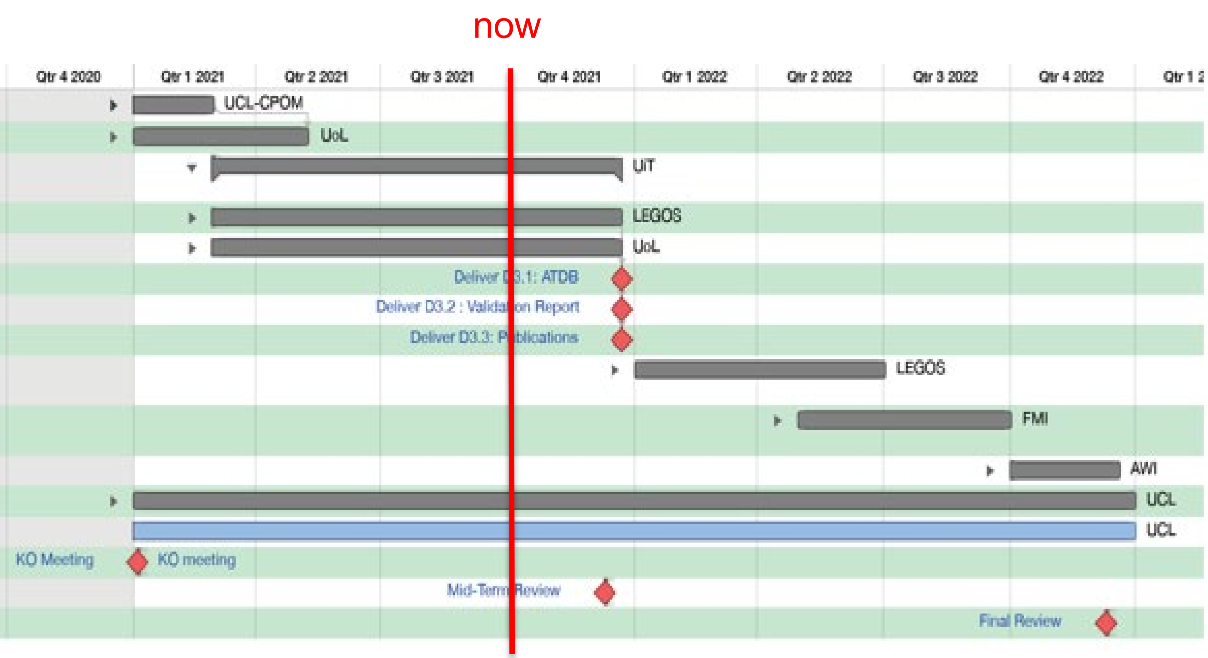
Collaborating Partners. NASA Goddard: N. Kurtz, A. Petty, R. Tilling Tsinghua University: S. Xu, L. Zhou Reading: D. Feltham, D. Schroeder Helsinki: P. Uotila

Work Packages

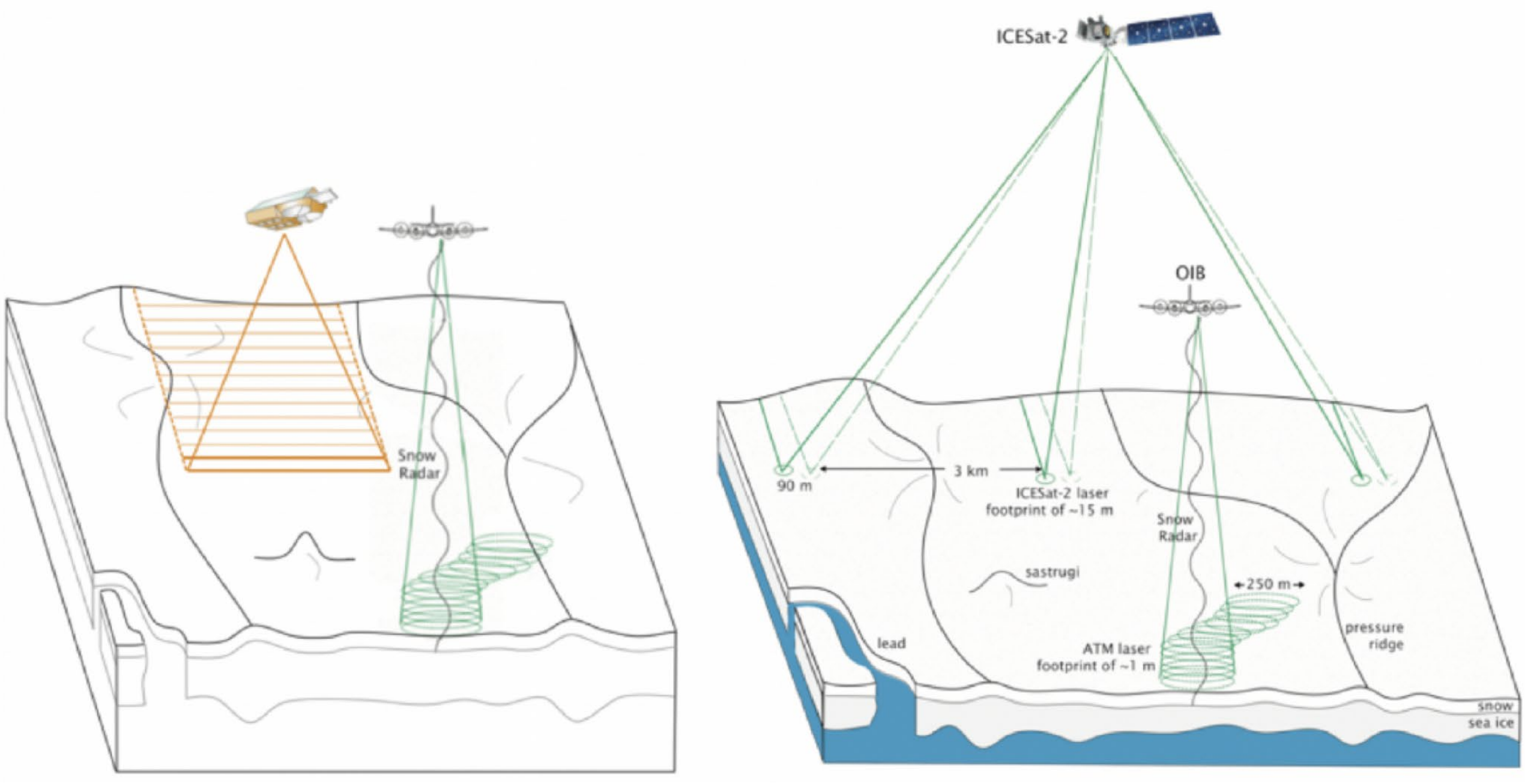


Gantt chart

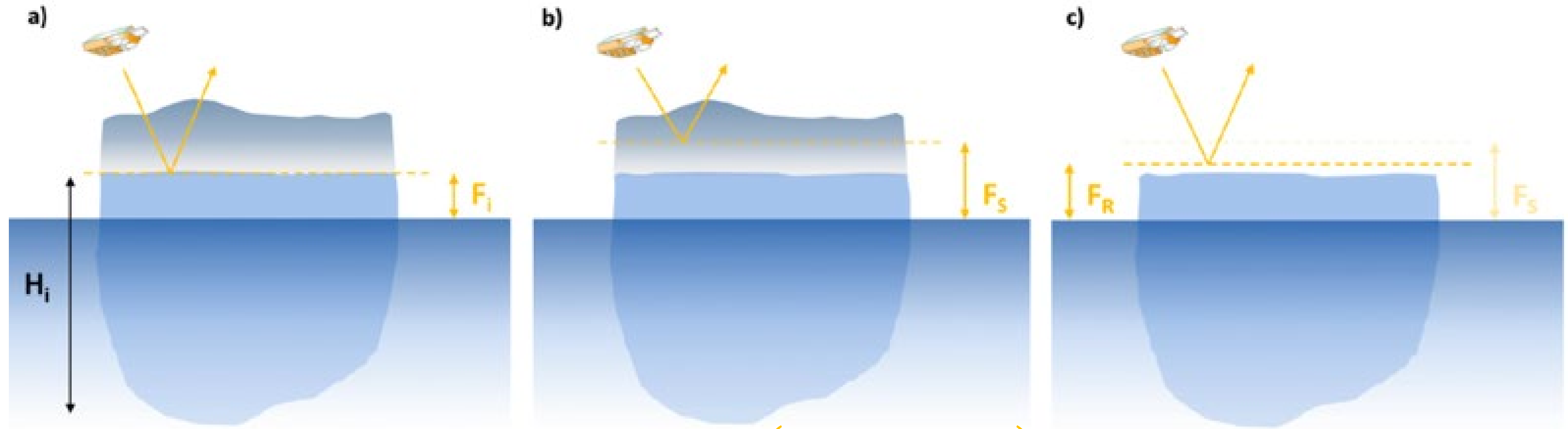
Title	Start	End
1) WP1 Scientific Requirements Consolidation	01/01/2021	01/03/2021
2) WP2: Dataset Collection	01/01/2021	07/05/2021
3) WP3: Development of Prototype Products and Algorithms	01/03/2021	22/12/2021
3.1) WP3.1: KuKa Algorithm development	01/03/2021	22/12/2021
3.2) WP3.2: KuLa Algorithm development	01/03/2021	22/12/2021
3.3) Deliver D3.1: ATDB	22/12/2021	22/12/2021
3.4) Deliver D3.2 : Validation Report	22/12/2021	22/12/2021
3.5) Deliver D3.3: Publications	22/12/2021	22/12/2021
4) WP4: Experimental Dataset Generation and Validation	03/01/2022	01/07/2022
5) WP5: Scientific analysis and impact assessment	02/05/2022	30/09/2022
6) WP6: Scientific roadmap	03/10/2022	20/12/2022
7) WP7: Promotion and coordination	01/01/2021	30/12/2022
8) WP8 Project management	01/01/2021	30/12/2022
9) KO Meeting	05/01/2021	05/01/2021
10) Mid-Term Review	10/12/2021	10/12/2021
11) Final Review	12/12/2022	12/12/2022



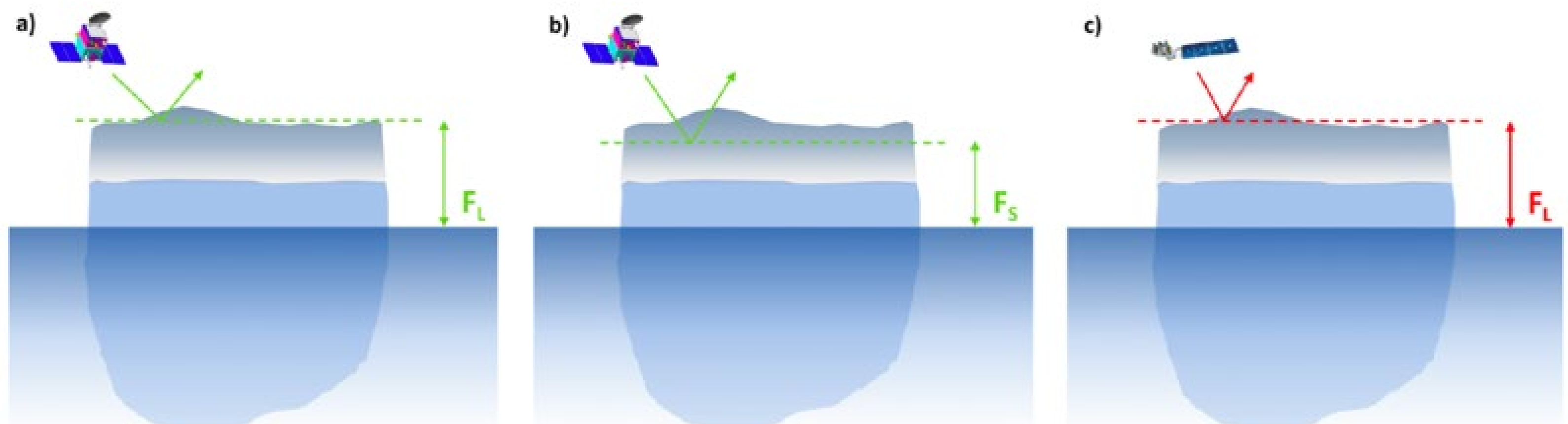
CryoSat-2, ICESat-2 and airborne



Different Freeboards



$$F_R^{CS2} = F_I + \left(1 - \alpha^{CS2}\,\frac{c}{c_S}\right) H_S$$

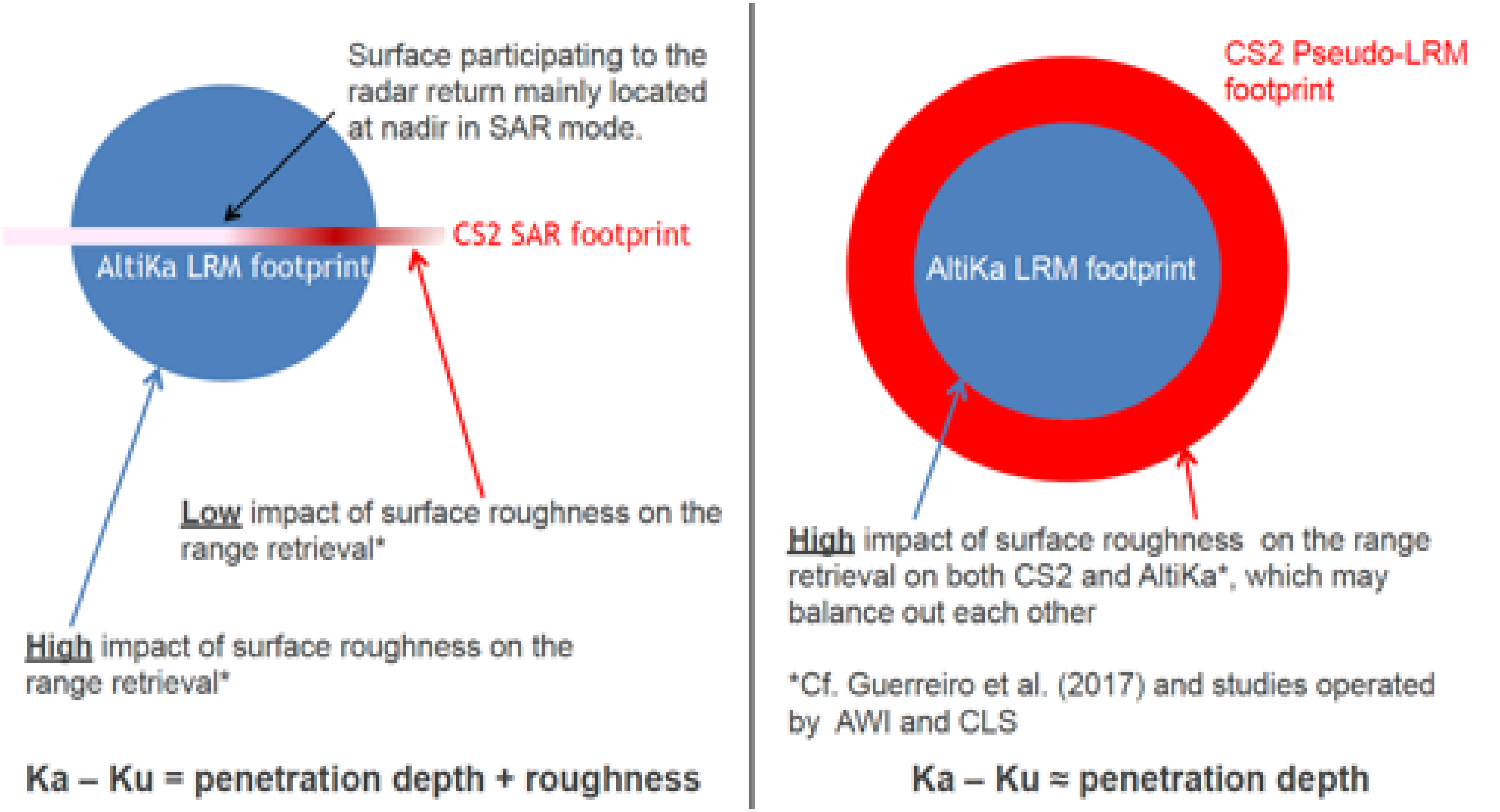


$$F_R^{AK} = F_I + \left(1 - \alpha^{AK}\,\frac{c}{c_S}\right) H_S$$

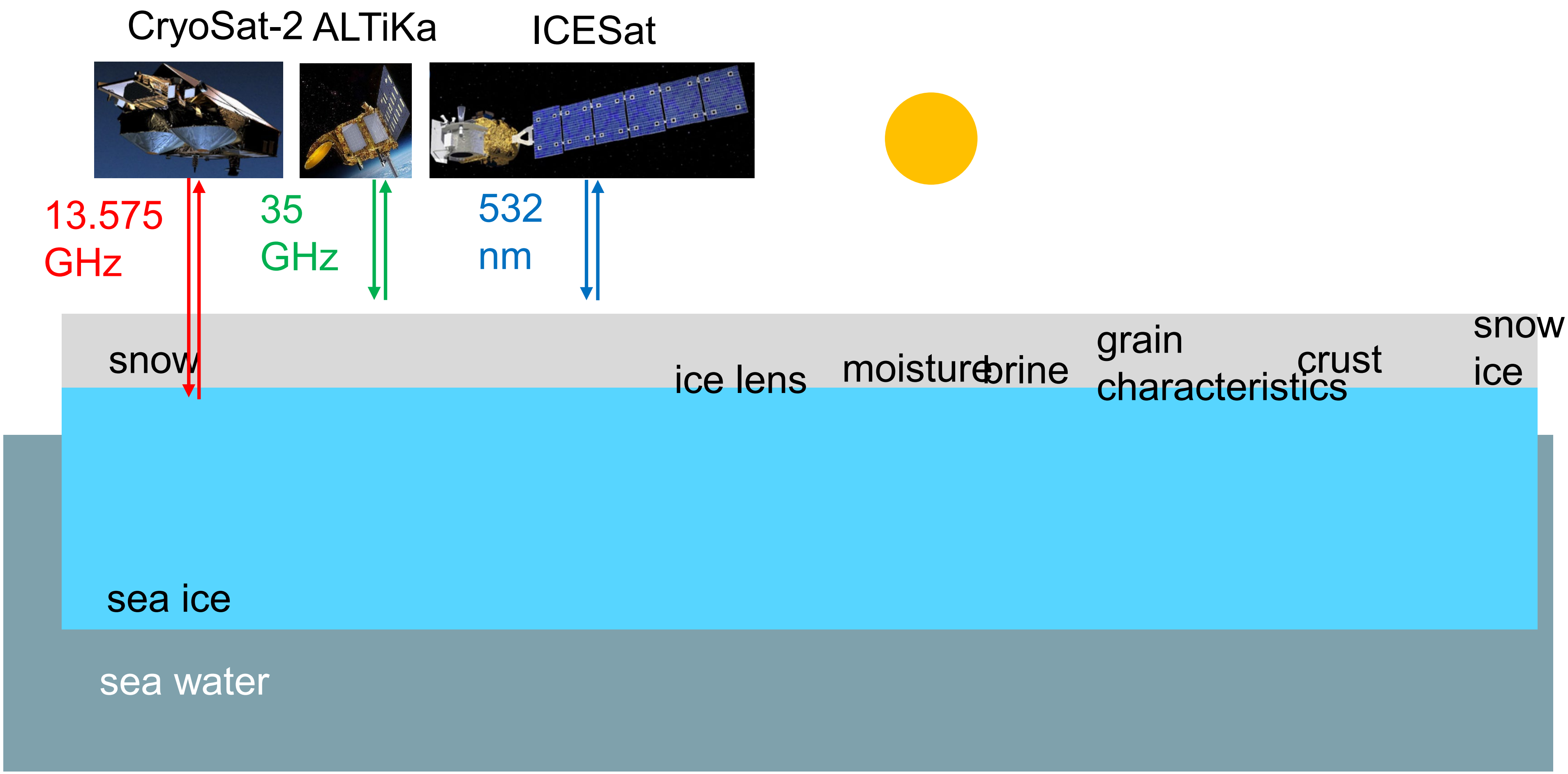
$$F_R^{AK} = F_I + H_S$$

Role of roughness and footprint

Credit: Cryo-SEANice project / Robert Ricker



Role of snow – light interaction



Credit: Rosie Willatt

WP3: Development of Prototype Products and Algorithms

WP3 Lead: UiT (Jack Landy)

Tasks

3.1) KuKa Algorithm development (Lead: LEGOS)

3.2) KuLa Algorithm development (Lead: UoL)

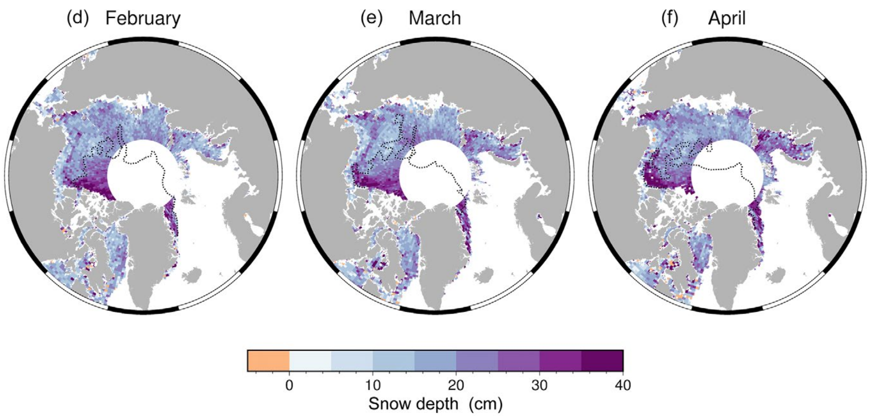
Deliverables

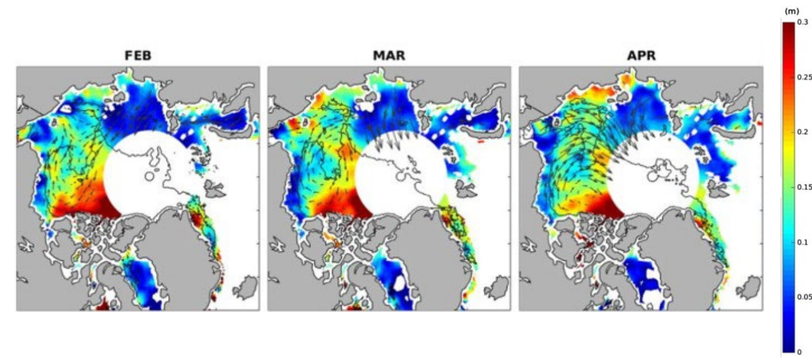
3.3) Algorithm theoretical baseline development

3.4) Validation

3.5) Publications, presentations or other dissemination

WP3: Development of Prototype Products and Algorithms





Calibration method: DuST (Lawrence et al., 2018)

- CryoSat-2 and AltiKa calibrated to snow-ice and air-snow interfaces, respectively, using airborne data from OIB
- Accounts for penetration and/or roughness biases

Bias correction method: ASD (Guerreiro et al., 2018; Garnier et al., 2021)

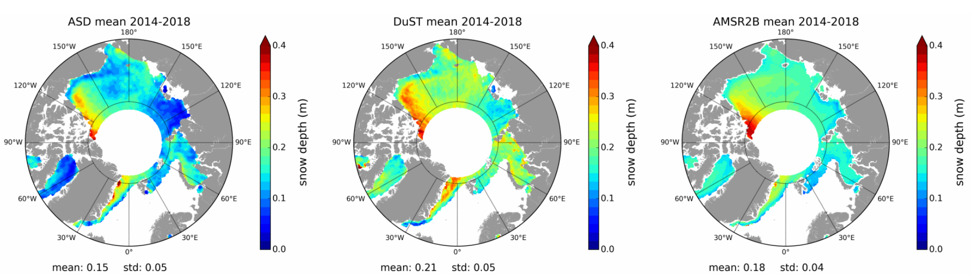
- CryoSat-2 converted to pseudo-LRM before comparison to AltiKa LRM
- Accounts for footprint-related roughness biases

WP3: Development of Prototype Products and Algorithms

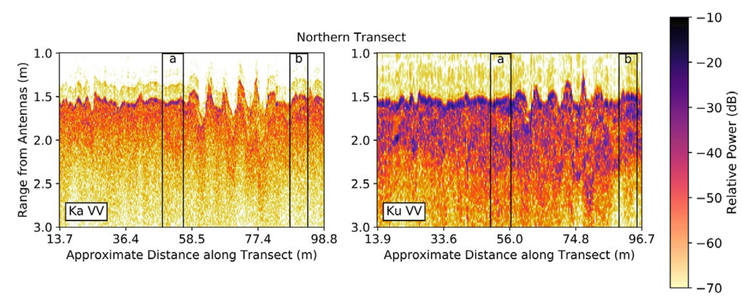
3.1) KuKa Algorithm development

Publications:

- Garnier et al 2021 (LEGOS, UCL, ESA) “Advances in altimetric snow depth estimates using bi-frequency SARAL/CryoSat-2 Ka/Ku measurements”. Under review in TCD.
- Gregory et al 2021 (UCL, UoL) “A Bayesian approach towards daily pan-Arctic sea ice freeboard estimates from combined CryoSat-2 and Sentinel-3 satellite observations”. Published in TC.
- Stroeve et al 2020 (UCL, AWI, UiT) “Surface-based Ku- and Ka-band polarimetric radar for sea ice studies”. Published in TC.



Garnier et al, TCD, 2021



Stroeve et al, TC, 2020

WP3: Development of Prototype Products and Algorithms

3.1) KuKa Algorithm development

Presentations at the CryoSat-2 10th Anniversary Conference:

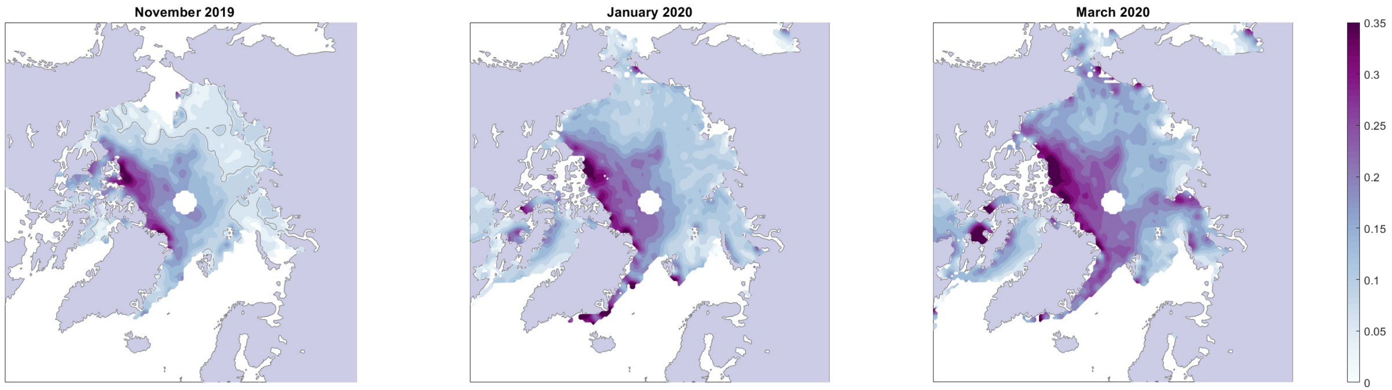
- Willatt et al "Investigating Ku- and Ka-band radar penetration and scattering in an evolving snow pack during MOSAiC"
- Garnier et al "Assessment of Ka-Ku altimetric snow depth on sea ice product"
- Landy et al "How do surface roughness and radar penetration affect pan-Arctic snow depths derived from multi-sensor altimetry? Physical waveform modelling applied to CryoSat-2 and AltiKa SARAL, with comparison to ICESat-2"
- Lawrence et al "A merged CryoSat-2 Sentinel-3 freeboard product, its sensitivity to weather events, and what it can tell us about Ku-band radar penetration"
- Cipollini et al "Multi-band altimetry of the cryosphere: status and outlook"
- Sallila et al "The impact of snow products on detecting trends in sea ice thickness during the CryoSat-2 era"
- Fleury et al "Arctic Sea Ice Thickness and Sea Level Anomaly from CryoSat-2 and Physical Retracker"
- Laforge et al "Evaluation of CryoSat-2 sea-ice products in the light of the CS2/IS2 tandem phase opportunity"

WP3: Development of Prototype Products and Algorithms

3.2) KuLa Algorithm development

Publications:

- Kwok et al (NASA) “Arctic snow depth and sea ice thickness from ICESat-2 and CryoSat-2 freeboards: a first examination”
- Glissenaar et al (UoB, UiT, UCL) “Impacts of snow data and processing methods on the interpretation of long-term changes in Baffin Bay sea ice thickness”. Under review in TCD.
- Fredensborg Hansen et al (ESA, FMI) “Estimation of degree of sea ice ridging in the Bay of Bothnia based on geolocated photon heights from ICESat-2”. Published in TC.



Landy et al, CS2 Anniversary Conference, 2021

WP3: Development of Prototype Products and Algorithms

3.2) KuLa Algorithm development

Presentations at the CryoSat-2 10th Anniversary Conference:

- Farrell et al "The Golden Era - Advances in Mapping Sea Ice Thickness by Combining CryoSat-2 and ICESat-2 Retrievals"
- Landy et al "How do surface roughness and radar penetration affect pan-Arctic snow depths derived from multi-sensor altimetry? Physical waveform modelling applied to CryoSat-2 and AltiKa SARAL, with comparison to ICESat-2"
- Laforge et al "Evaluation of CryoSat-2 sea-ice products in the light of the CS2/IS2 tandem phase opportunity"

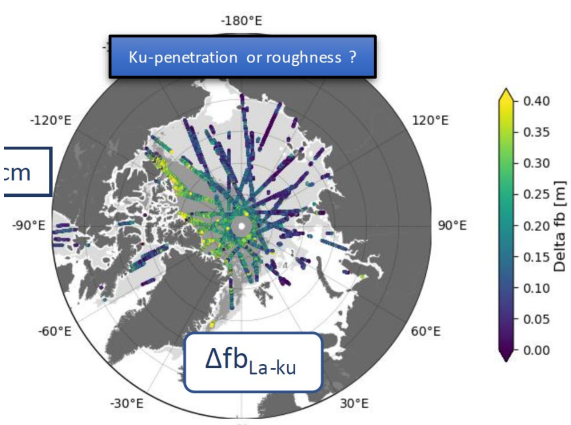
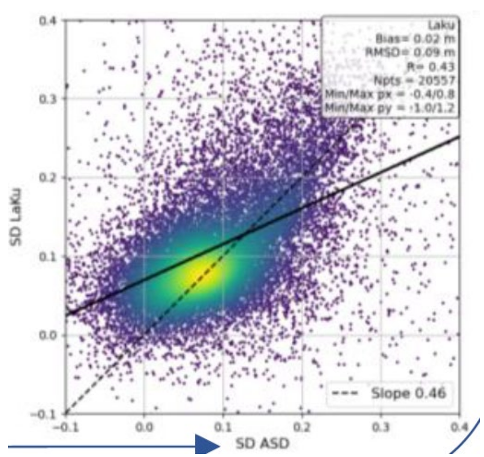


Fig. 4 $\Delta fb_{La\text{-}ku}$ for collocated tracks [Nov-Dec 2020]



How can we separate the impact of roughness from the penetration to measure the snow depth from La-Ku bi-sensor approach ?

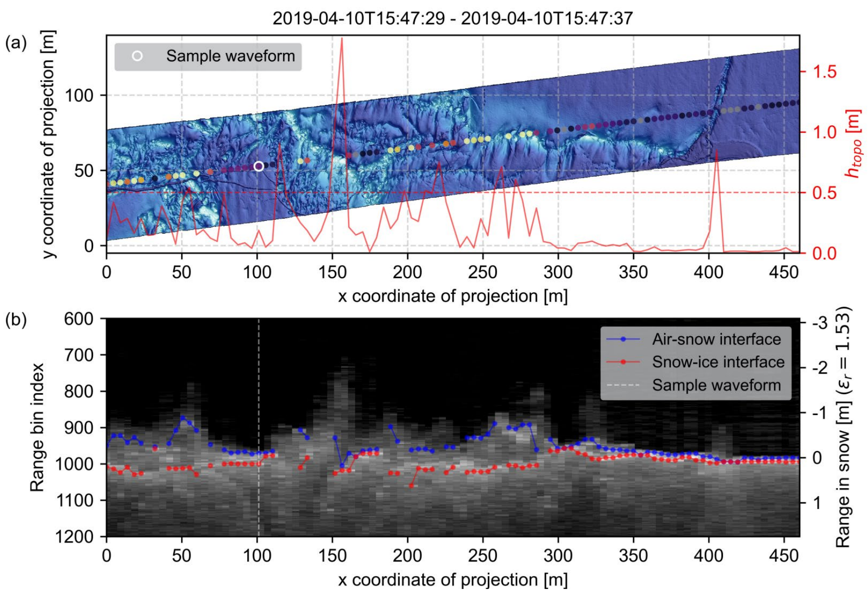
Laforge et al, CS2 Anniversary Conference, 2021

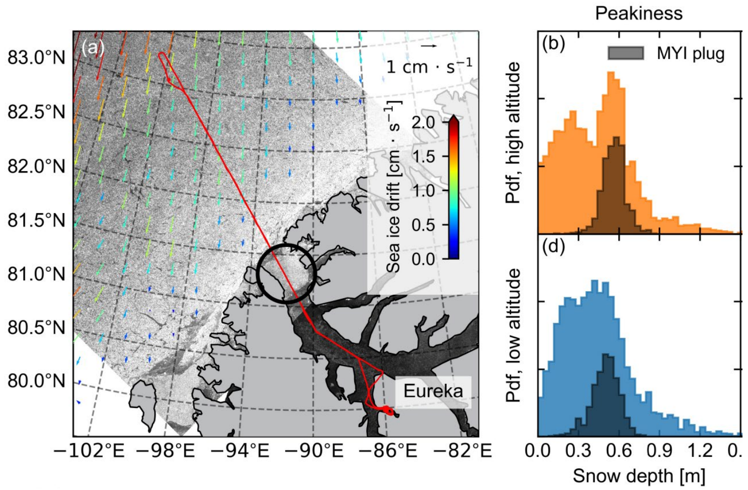
WP3: Development of Prototype Products and Algorithms

3.4) Validation

Publications:

- Jutila et al 2021 (AWI). ‘High-Resolution Snow Depth on Arctic Sea Ice From Low-Altitude Airborne Microwave Radar Data’. Published in TGARS.
- Jutila et al 2021 (AWI). ‘Retrieval and parametrisation of sea-ice bulk density from airborne multi-sensor measurements’. Under review in TCD.





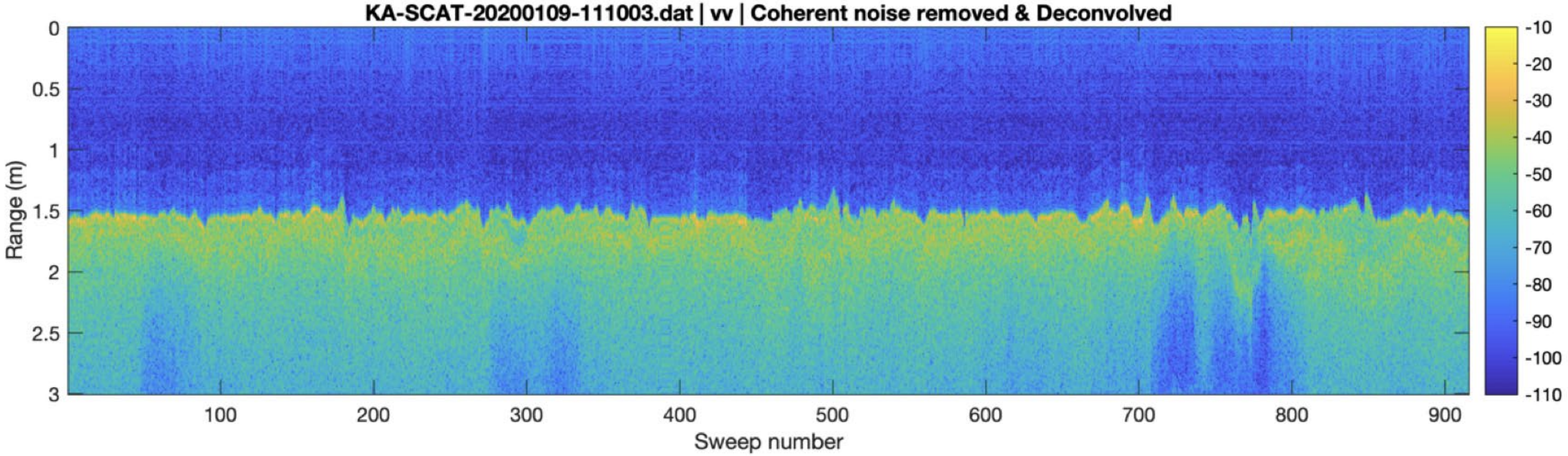
Jutila et al, TGARS, 2021

WP3: Development of Prototype Products and Algorithms

Polar+ Snow

Remaining Questions

- How do we reconcile KuKa and KuLa snow depth products? Physically, empirically
- How do we improve satellite algorithms with new understanding from ground-based or airborne Ku/Ka/La studies?
- What are the relative roles of roughness vs radar penetration on biases in Ku-band/Ka-band freeboards?

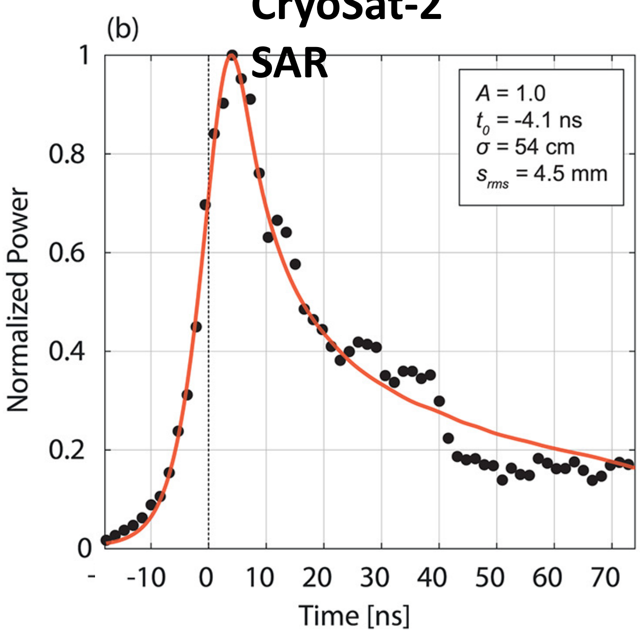


WP3: Ongoing activities

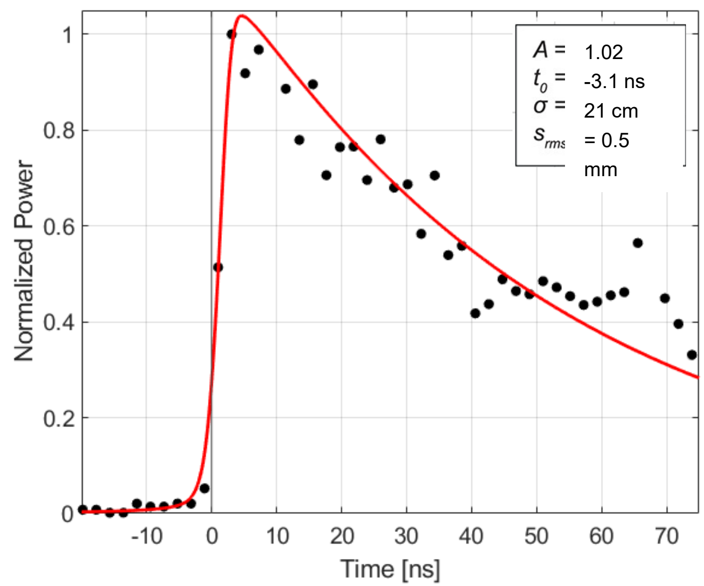
University of Tromsø/Bristol Ongoing Activities

Radar echo simulations for CryoSat-2 (SAR) and AltiKa (LRM) performed with FBEM (Landy et al., TGARS, 2019)

CryoSat-2 SAR

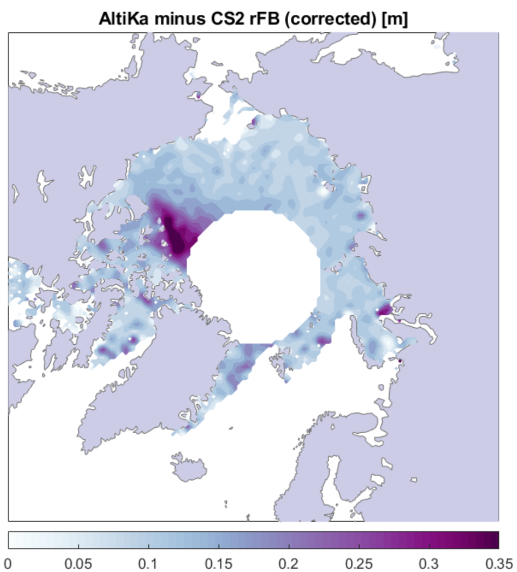


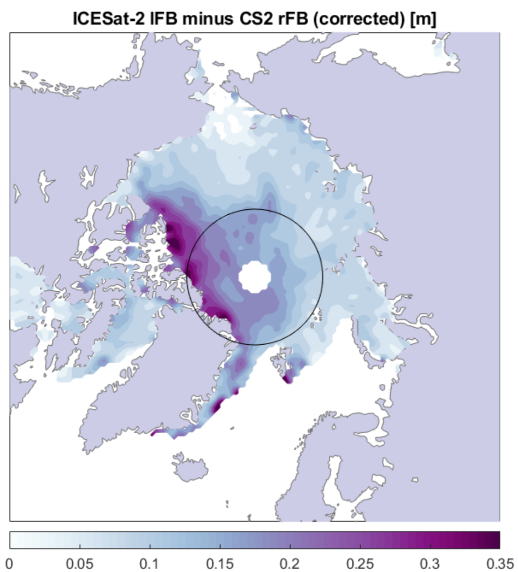
AltiKa LRM

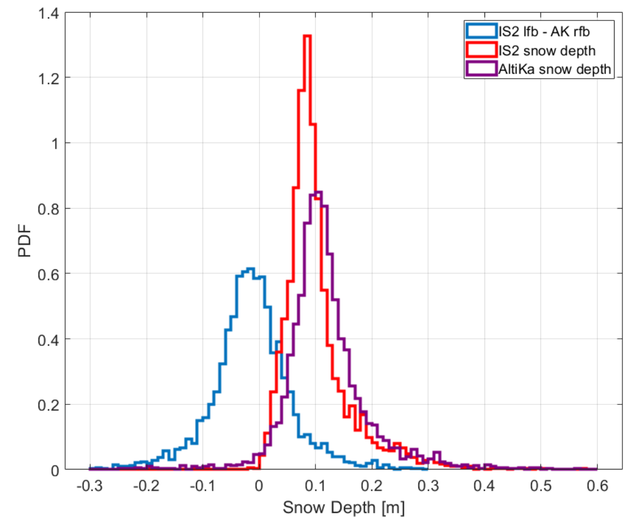


University of Tromsø/Bristol Ongoing Activities

Intercomparison of retracked CS2, AK, and IS2 freeboard observations:



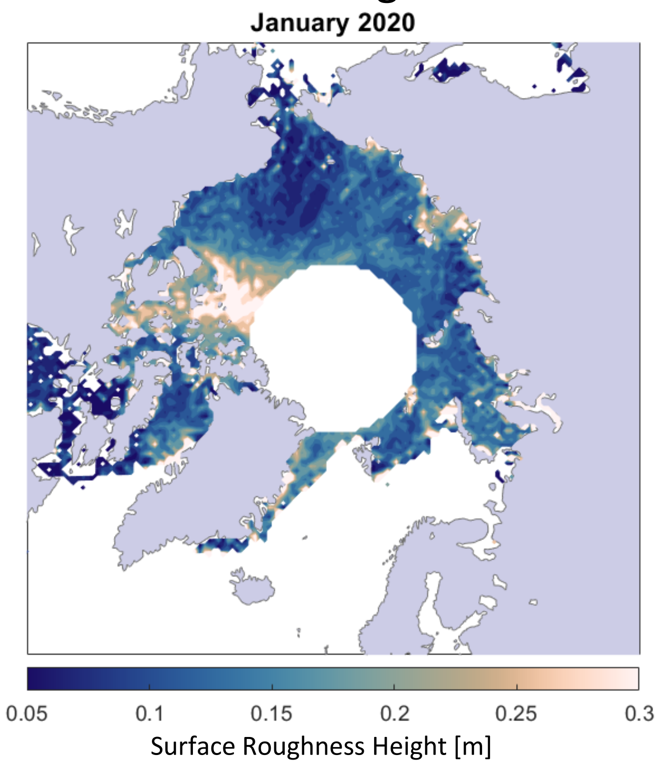


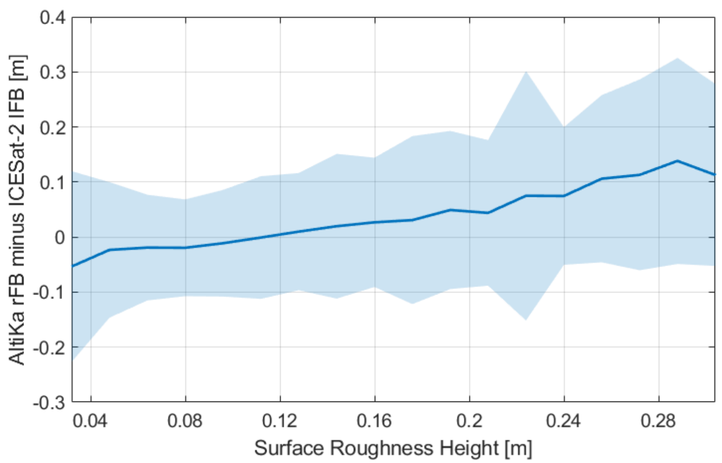


December 2019

University of Tromsø/Bristol Ongoing Activities

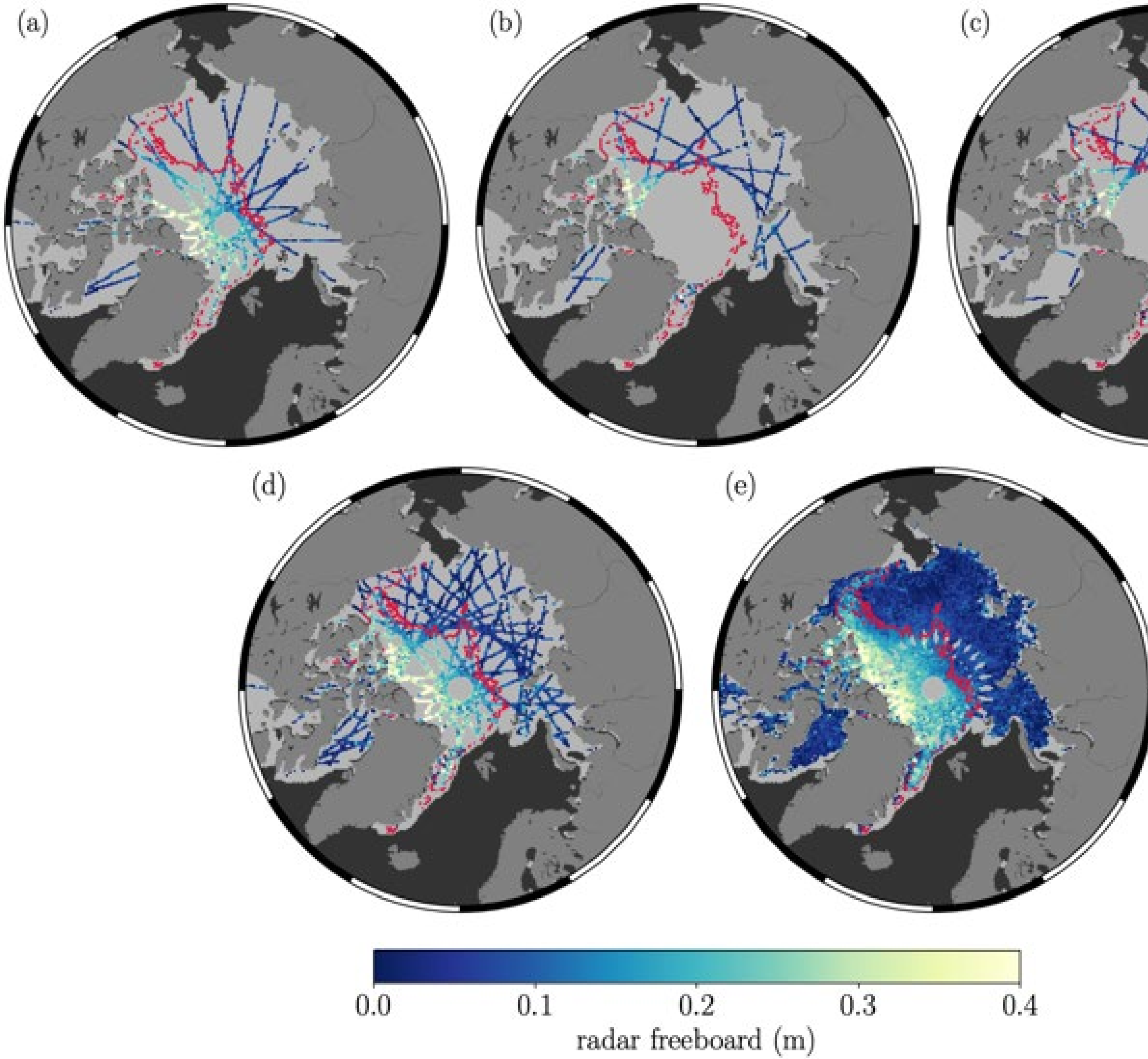
Role of surface roughness:



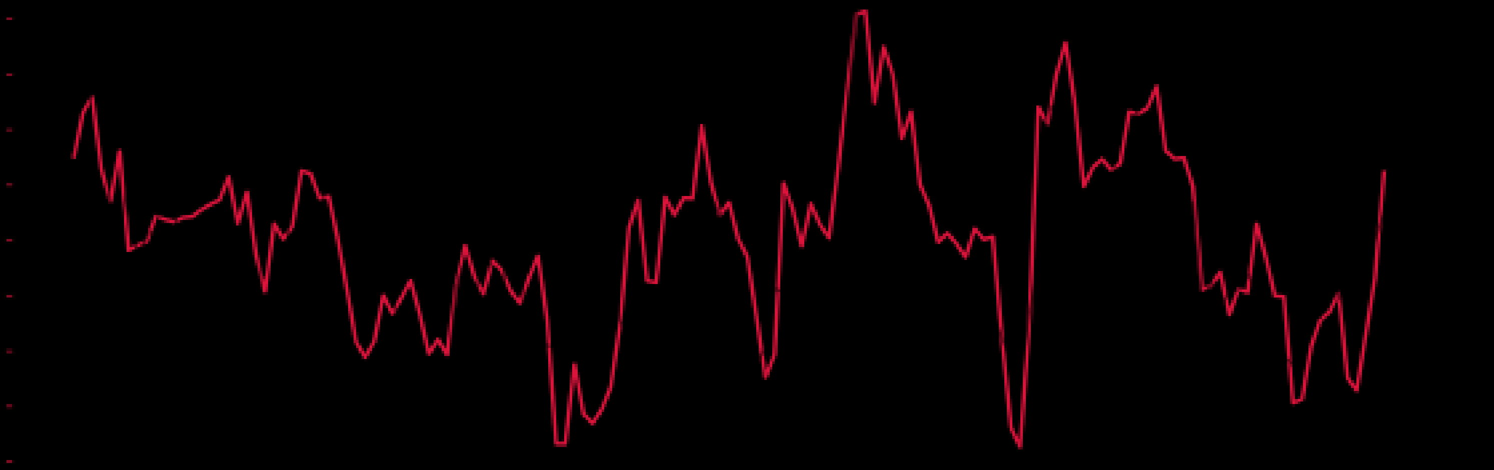


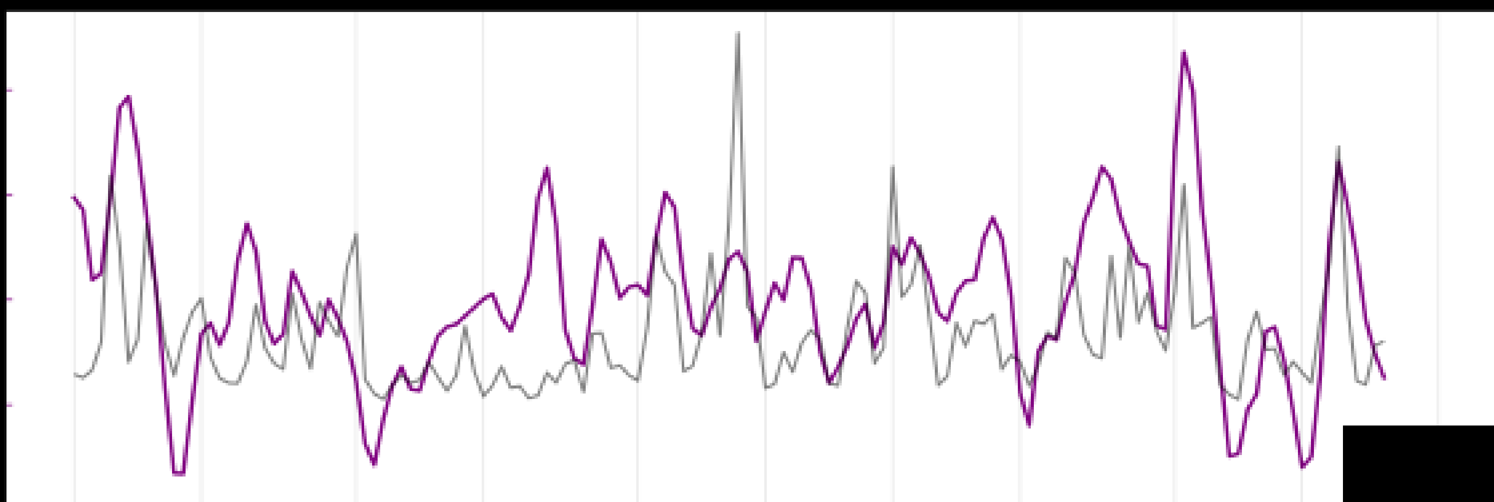
- Clear relationship between surface roughness derived from AltiKa and bias between AK & IS2 freeboards
- Need for improvements in waveform retracking or classification schemes? Possibility to bias correct?

WP3: Data fusion algorithms (i.e. with S3, IS2…)



Gregory et al, TCD 2021





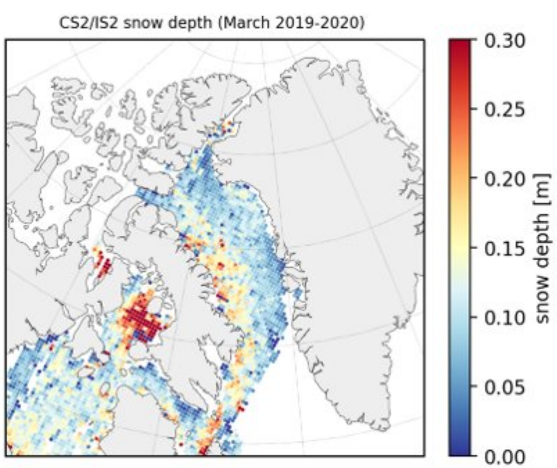
[redacted]

Early validation and comparison work

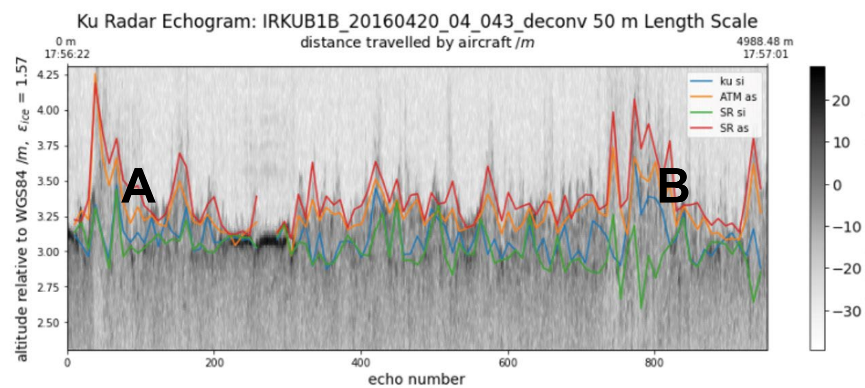
University of Tromsø/Bristol Ongoing Activities

- Claude De-Rijke Thomas (PhD Student, Bristol) analysis and modelling of Ku-, Ka-, and Snowradar (S- to C-) band echoes from OIB and CryoVex, to examine coincident penetration and roughness biases

- Isolde Glissenaar (PhD Student, Bristol) used Baffin Bay as a test case to reconcile long-term seasonal sea ice thickness from different sensors (radar altimetry, laser altimetry, radiometry, CIS charts)

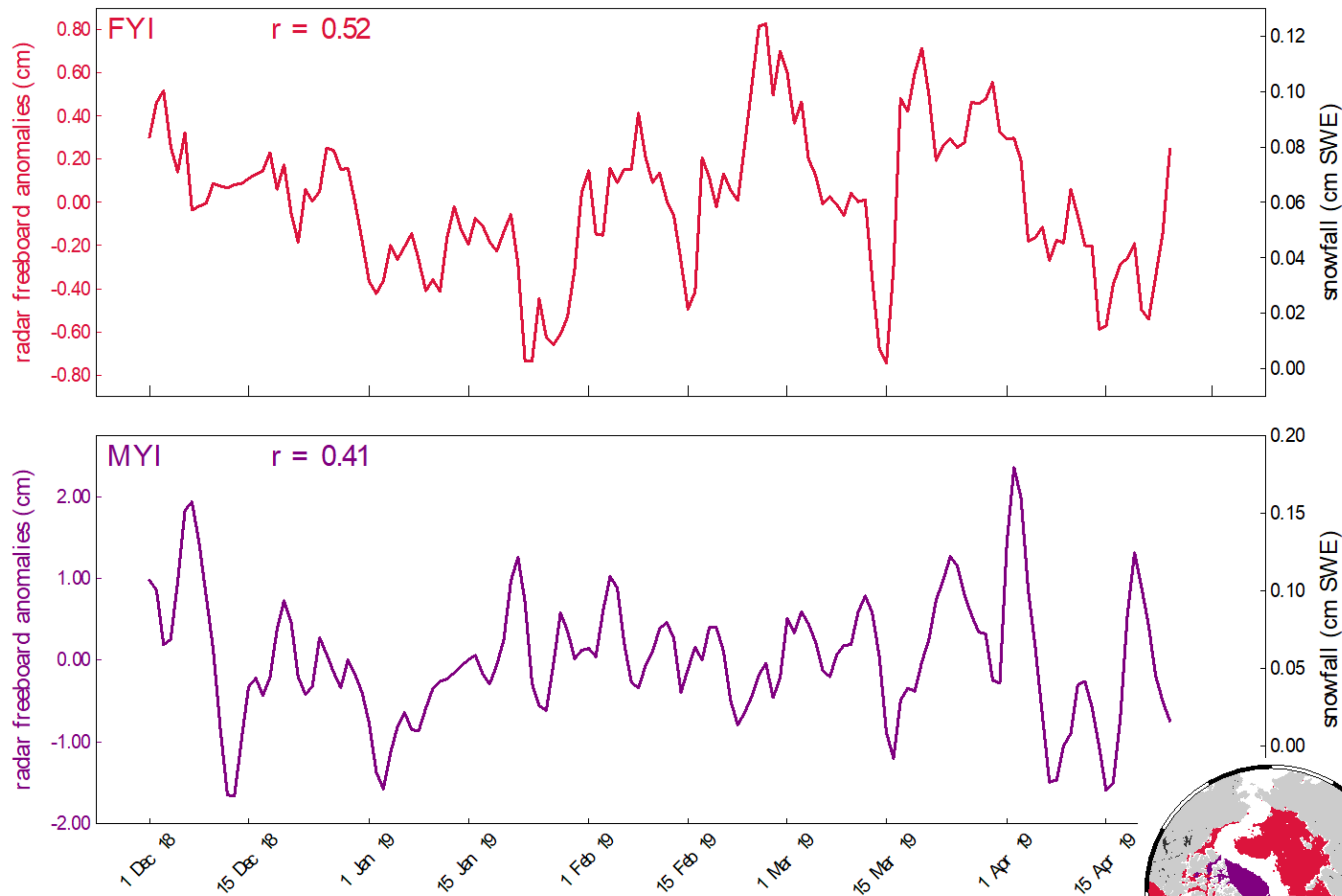


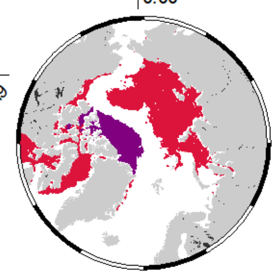
Glissenaar, Landy, Petty, Kurtz, Stroeve “Impacts of snow data and processing methods on the interpretation of long-term changes in Baffin Bay sea ice thickness”. Under review in TCD.

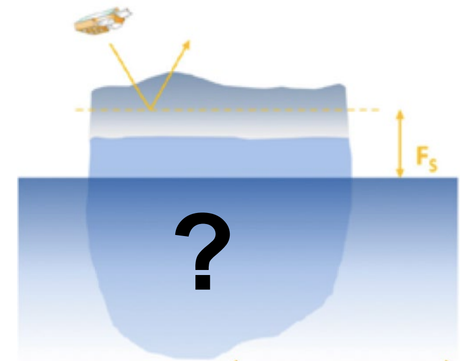


De-Rijke Thomas, Landy, King, Tsamados “A comparison between coincident laser and Ku radar versus S- to C-band ‘snow radar’ data for airborne retrievals of snow depth on sea ice”. EGU Presentation.

The puzzle







Credit: Gregory et al, 2021c

www.cpom.ucl.ac.uk/snow-on-sea-ice/

Polar+ Snow

UCL LEGOS UNIVERSITY OF TROMSØ AWI FINNISH METEOROLOGICAL INSTITUTE UNIVERSITY OF LEEDS

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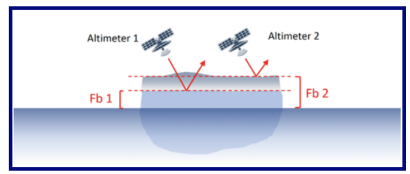
Polar+ Snow

Polar+ Snow on Sea Ice

Polar+ Snow on Sea Ice is part of ESA's Scientific Data Exploitation element of the Earth Observation Envelope Program (EOEP-5). The Scientific Data Exploitation element aims at responding to the needs of the EO and Earth system science communities in terms of innovative methods, novel products, open science tools and new Earth science results.



Study Objectives

The primary objective of this project is to investigate multi-frequency approaches to retrive snow thickness over all types of sea surfaces in the Arctic and provide a state-of-the-art snow product. The recommendations are to:

- Better understand the snow depth penetration from laser, Ka and Ku band radar altimetry measurements as a function of the snow characteristics
- Collect, analyse and exploit the most extensive source of in-situ and airborne datasets
- Generate improved multi-sensor snow depth products over the Arctic sea ice
- Demonstrate the impact of these products for climate and operational applications
- Produce a scientific roadmap for ESA's future EO satellite mission to help address the scientific challenges and knowledge gaps of snow on sea ice

Contact details

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Email: m. tsamados@ucl.ac.uk

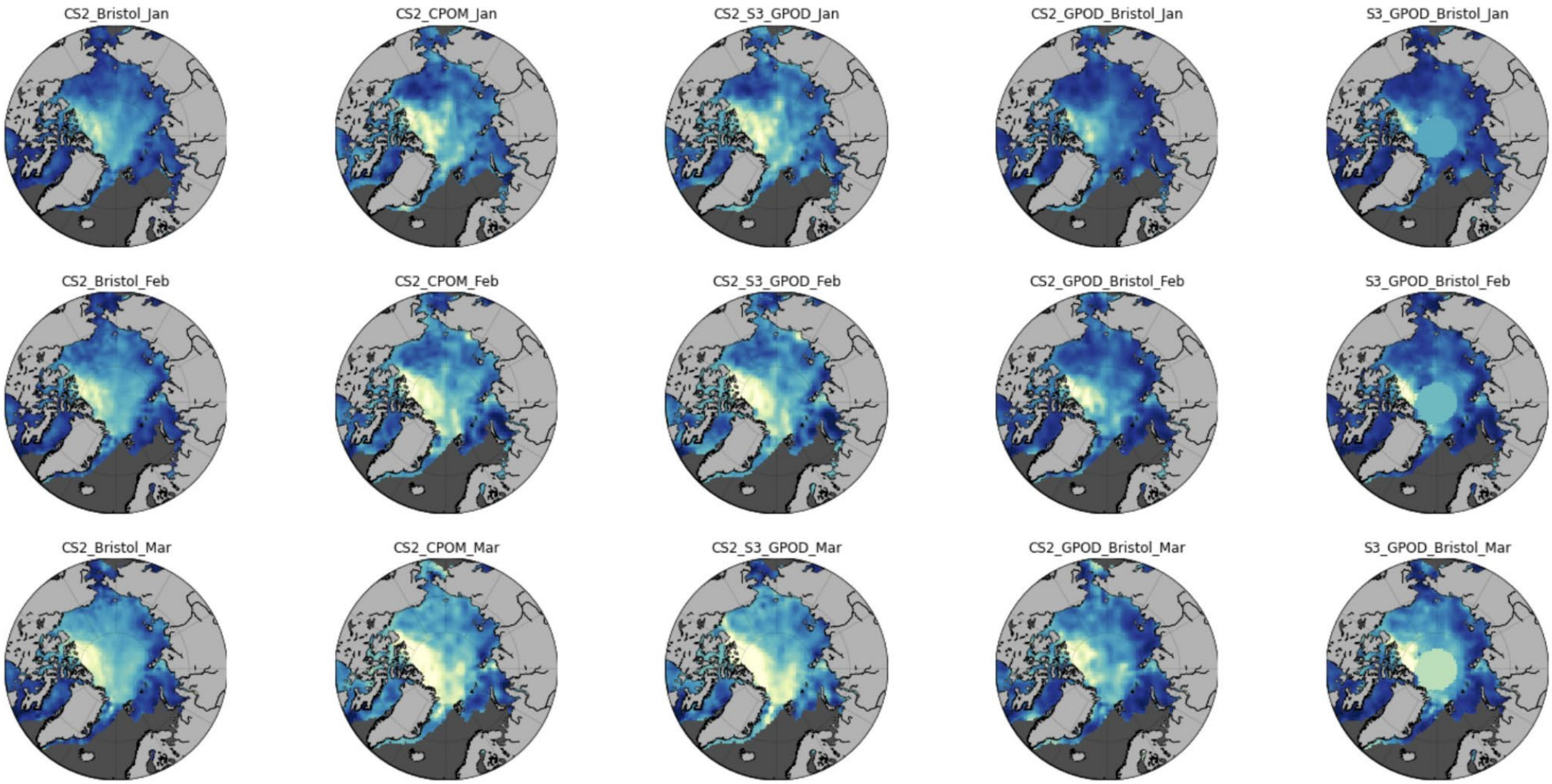
Website : a.muir@ucl.ac.uk

Challenges and Solutions

- Accurate radar and laser retracking accoiunting for surface heterogeneity
  - ✓ Physical retrackers and corrected empirical retrackers
  - ✓ Direct facet based models / simulators
- Detecting the ice-snow and snow-air interfaces
  - ✓ Understanding the snow-light interactions
  - ✓ Physical models (SNOWPACK…)
  - ✓ Radiative models (SMRT…)
- Validation / calibration with in-situ and airborne campaigns
  - ✓ MOSAiC
  - ✓ KaKu radar
  - ✓ Future dedicated airborne campaigns (OIB, IceBird, CryoVex, Karen)
- Innovative fusion and AI algorithms
  - ✓ Optimal interpolation
  - ✓ AI based surface and snow characterization
  - ✓ Multi-mission synergies
- Uncertainty quantifications
  - ✓ Inversion approaches, Monte-Carlo, physical models
  - ✓ Data assimilation in state of the art models
  - ✓ Error propagation to sea ice thickness

CS2 + AK (KuKA)

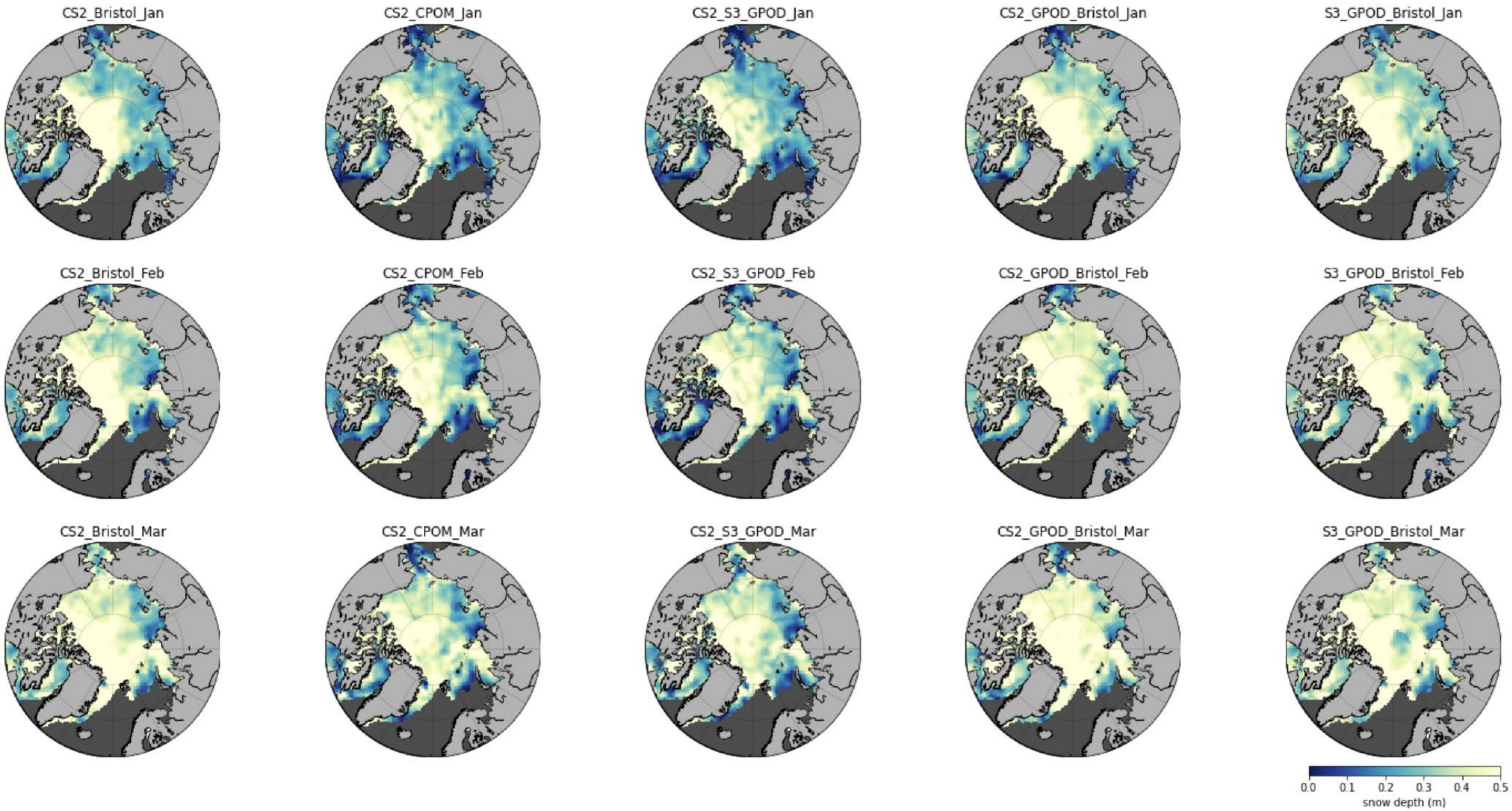
Polar+ Snow



$$F_R^{CS2} = F_I + \left(1 - \alpha^{CS2}\,\frac{c}{c_S}\right) H_S \qquad F_R^{AK} = F_I + \left(1 - \alpha^{AK}\,\frac{c}{c_S}\right) H_S$$

Credit: Carmen Nab

CS2 + IS2 (KuLA)



$$F_R^{CS2} = F_I + \left(1 - \alpha^{CS2}\,\frac{c}{c_s}\right) H_S$$

$$F_R^{IS2} = F_I + H_S$$

Credit: Carmen Nab