Correlated Fluctuations in Surface Melting and Ku-band Airborne Radar Penetration in West Central Greenland

Inès Otosaka[1], Andrew Shepherd[1], Tânia G. D. Casal[2], Alex Coccia[3], Malcolm Davidson[2], Alessandro Di Bella[4], Xavier Fettweis[5], René Forsberg[4], Veit Helm[6], Anna E. Hogg[7], Sine Hvidegaard[4], Adriano Lemos[1,8], Karlus Macedo[3], Peter Kuipers Munneke[9], Tommaso Parrinello[10], Sebastian B. Simonsen[4], Henriette Skourup[4], Louise Sandberg Sørensen[4]

eeino@leeds.ac.uk

[1]Centre for Polar Observation and Modelling, School of Earth and Environment, University of Leeds, Leeds, UK.
[2]ESA-ESTEC, Noordwijk, the Netherlands.
[3]Metasensing, Noordwijk, the Netherlands.
[4]Technical University of Denmark, DTU Space, Lyngby, Denmark.
[5]University of Liège, Liège, Belgium.
[6]Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research, Bremerhaven, Germany.
[7]School of Earth and Environment, University of Leeds, Leeds, UK.
[8]Now at University of Gothenburg, Göteborg, Sweden.
[9]Institute for Marine and Atmospheric research Utrecht, Utrecht University, Utrecht, the Netherlands.
[10]ESA-ESRIN, Frascati, Italy.

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Introduction

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Motivation

- **Increased melting** at the surface of the Greenland Ice Sheet[1] has affected the structure of the near-surface firn[2]
- **Radar altimeters** are sensitive to **variations in the firn properties** as the radar signal penetrates in the snowpack[3,4]
- This presents challenges for satellite radar altimeters, e.g., for converting volume change into mass change[5]

Objectives

- Investigate spatial and temporal variations in the firn stratigraphy and radar altimetry echoes from a combination of firn cores and modelled densities with seven years of airborne radar data collected during field campaigns in West Central Greenland
- Investigate the potential of higher frequency radar (Ka-band) to mitigate firn density fluctuations
- Assess the impact of radar penetration fluctuations on the retracked heights

Study area: the EGIG line

- The Expéditions Glaciologiques Internationales au Groenland (**EGIG**) extends from the ablation zone at the Western margin of the ice sheet, across the dry snow zone to the Summit, and further towards the Eastern margin[6]

- We use data collected between 2006 and 2017 over a ~675km transect of the EGIG line as part of ESA's CryoSat validation experiment (**CryoVEx**)

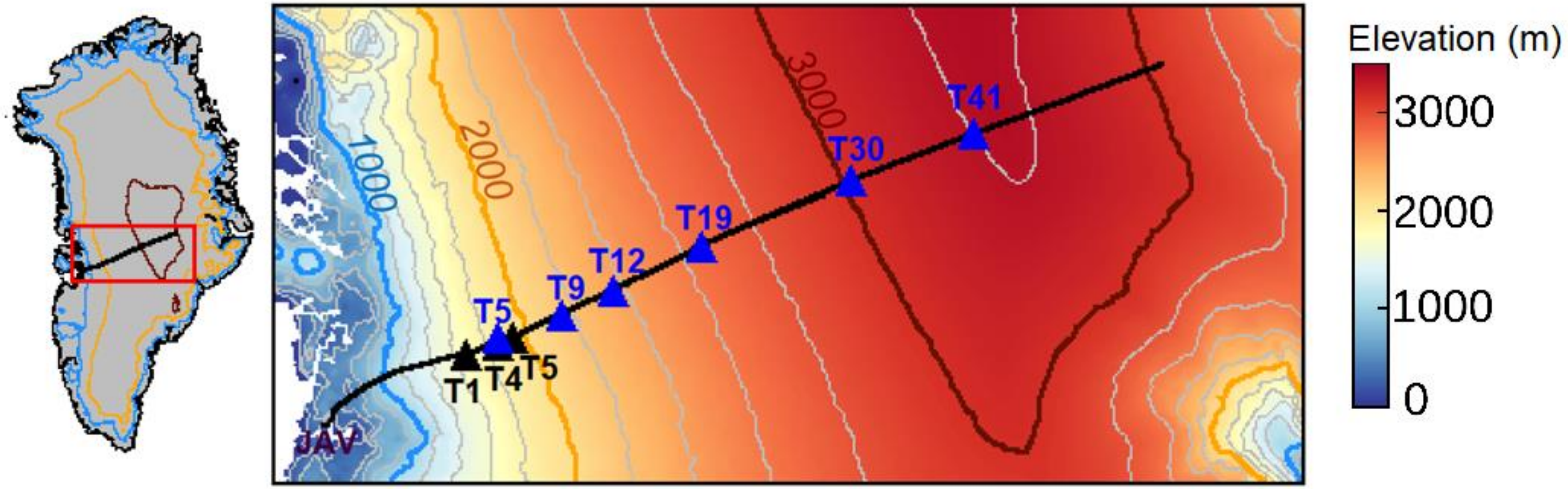

Figure 1. *The EGIG line transect and T-sites at which shallow firn cores were collected in* ***2016*** *and* ***2017***

Data and Methods

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From **7 CryoVEx field campaigns**:

- Airborne Ku-band radar ASIRAS (13.5 GHz) – 2006, 2008, 2010, 2011, 2012, 2014, 2016, 2017
- Airborne Ka-band radar KAREN (34.5 GHz) – 2016, 2017
- Airborne laser scanner ALS – 2006, 2008, 2010, 2011, 2012, 2014, 2016, 2017
- Shallow firn cores (depth < 6 m) – 2016, 2017

Firn densification models:

- IMAU-FDM (2016, 2017)
- MAR-FDM (all years)

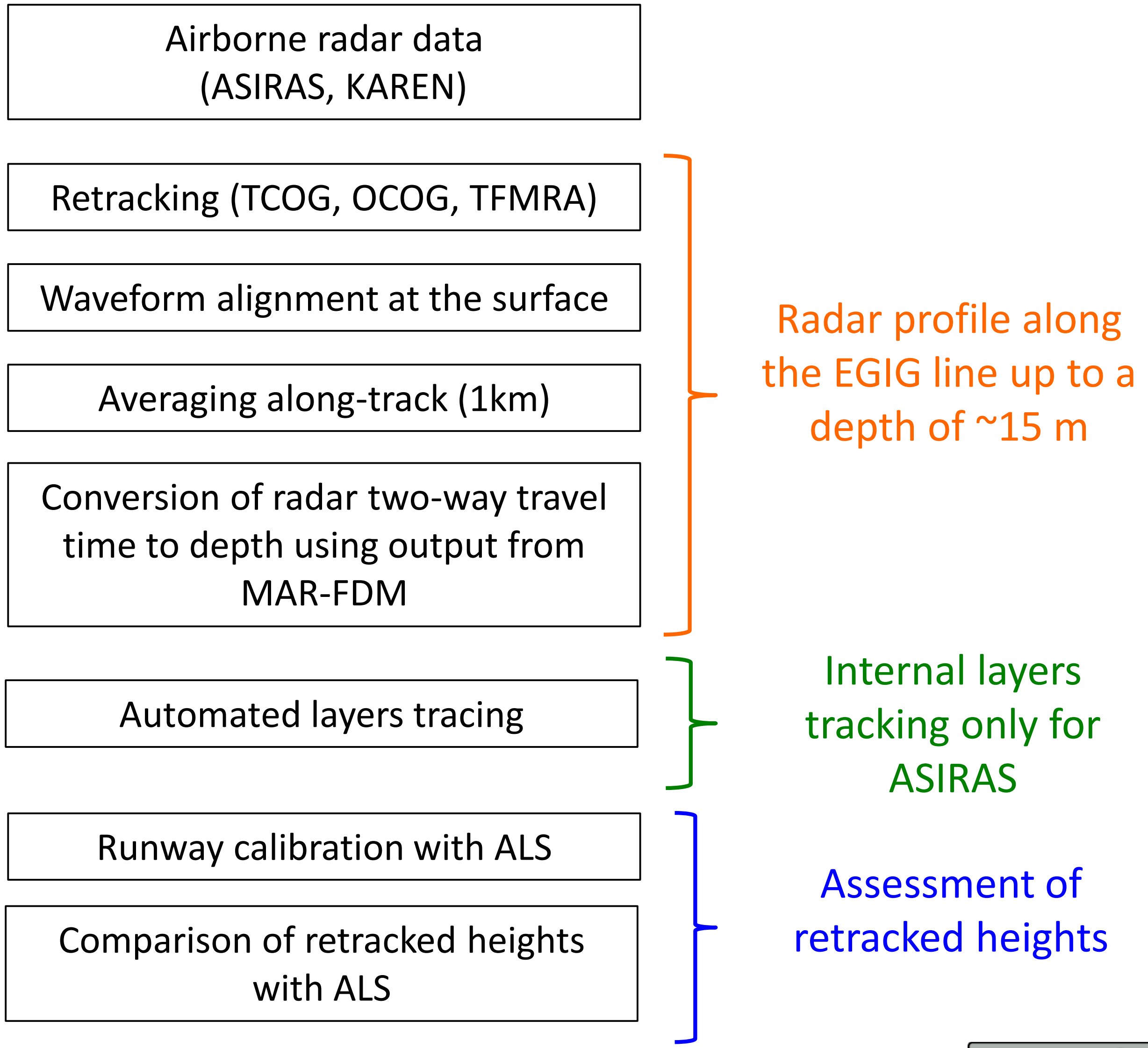

Figure 2. *Methodology applied to radar data*

Validation of firn models with in-situ data

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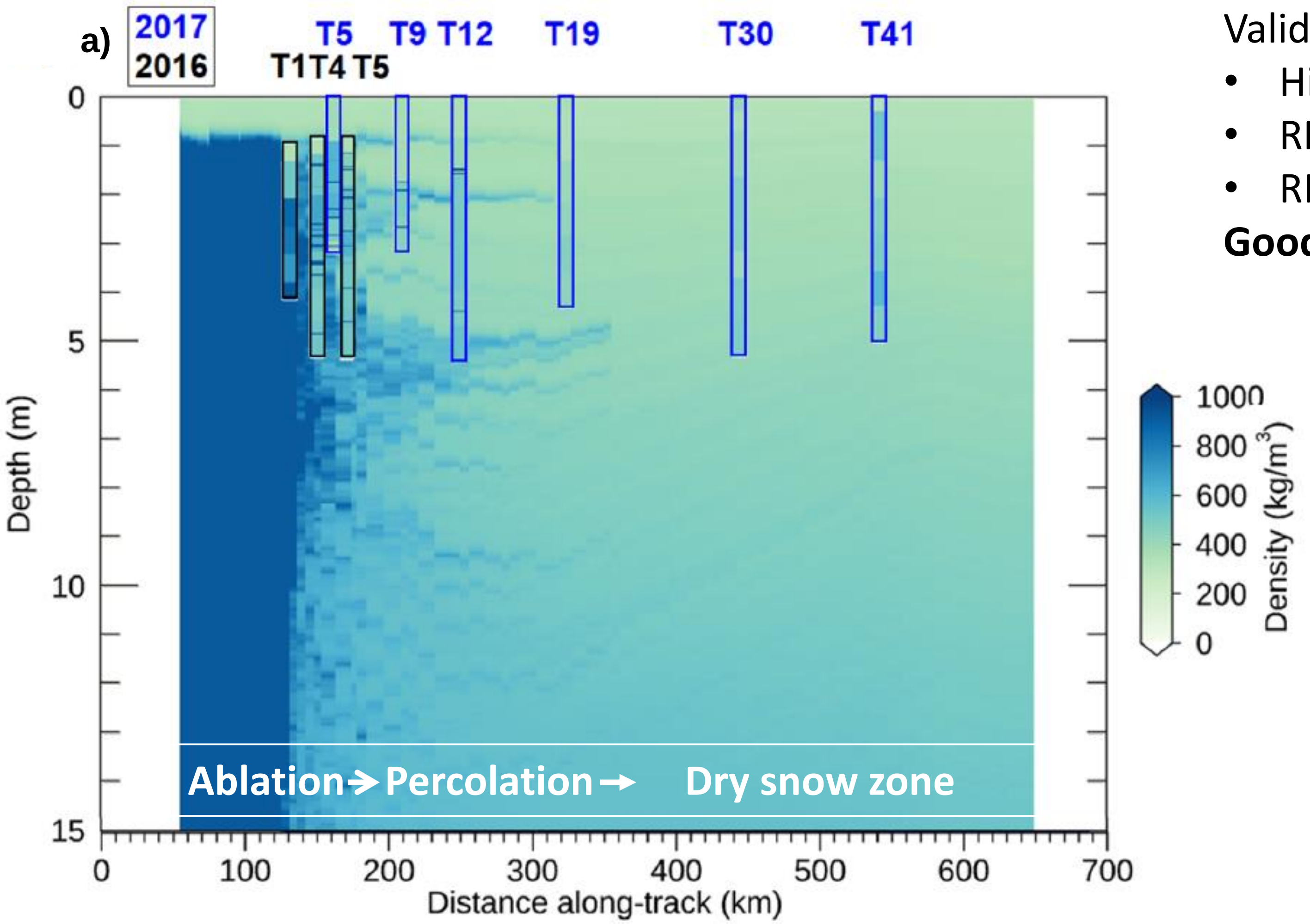

__Figure 3a.__ IMAU-FDM 2017 density profile along the EGIG line

Validation of firn models using in-situ firn densities:

- High correlation between models and observations
- RMSD(IMAU) = 64 $kg.m^{-3}$
- RMSD(MAR) = 73 $kg.m^{-3}$

Good agreement between modelled and in-situ densities

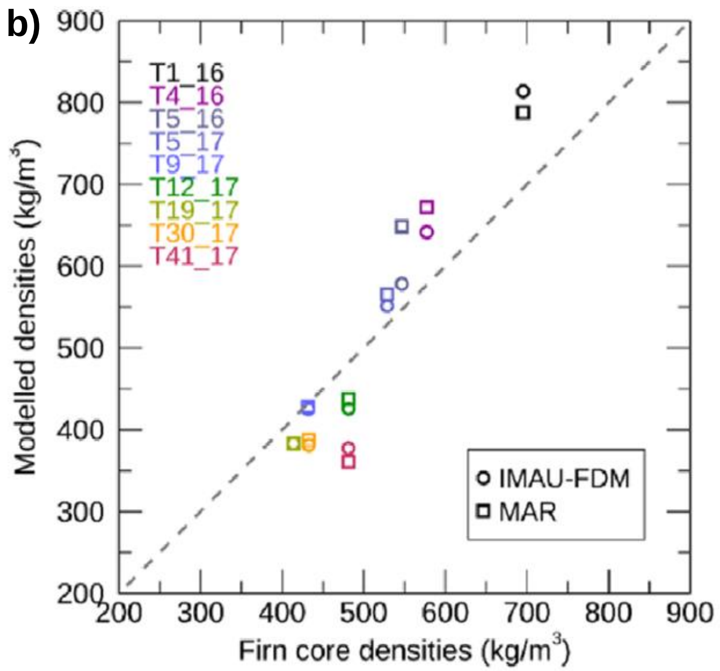

__Figure 3b.__ Scatterplot modelled densities VS firn core densities

Comparison of Ku-band radar and IMAU-FDM

- Clear sequence of internal layers in ASIRAS radar profile, attributed to the annual cycle of summer melt and densification and winter snowfall[7,8,9]
- Comparison of ASIRAS internal layers distribution and sequence to IMAU-FDM isochrones
- High correlation between ASIRAS layers and IMAU-FDM isochrones (r=0.99)

ASIRAS internal layers correspond to isochrones

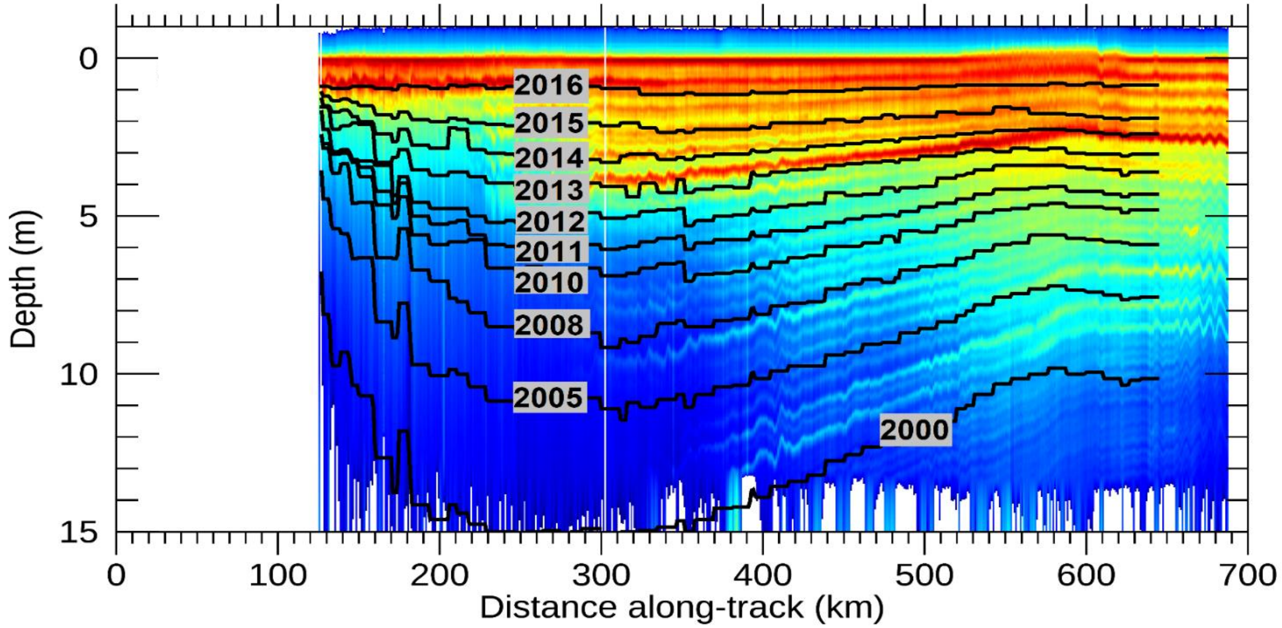

Figure 4. *ASIRAS 2017 profile and IMAU-FDM isochrones in black*

ASIRAS Radar profiles

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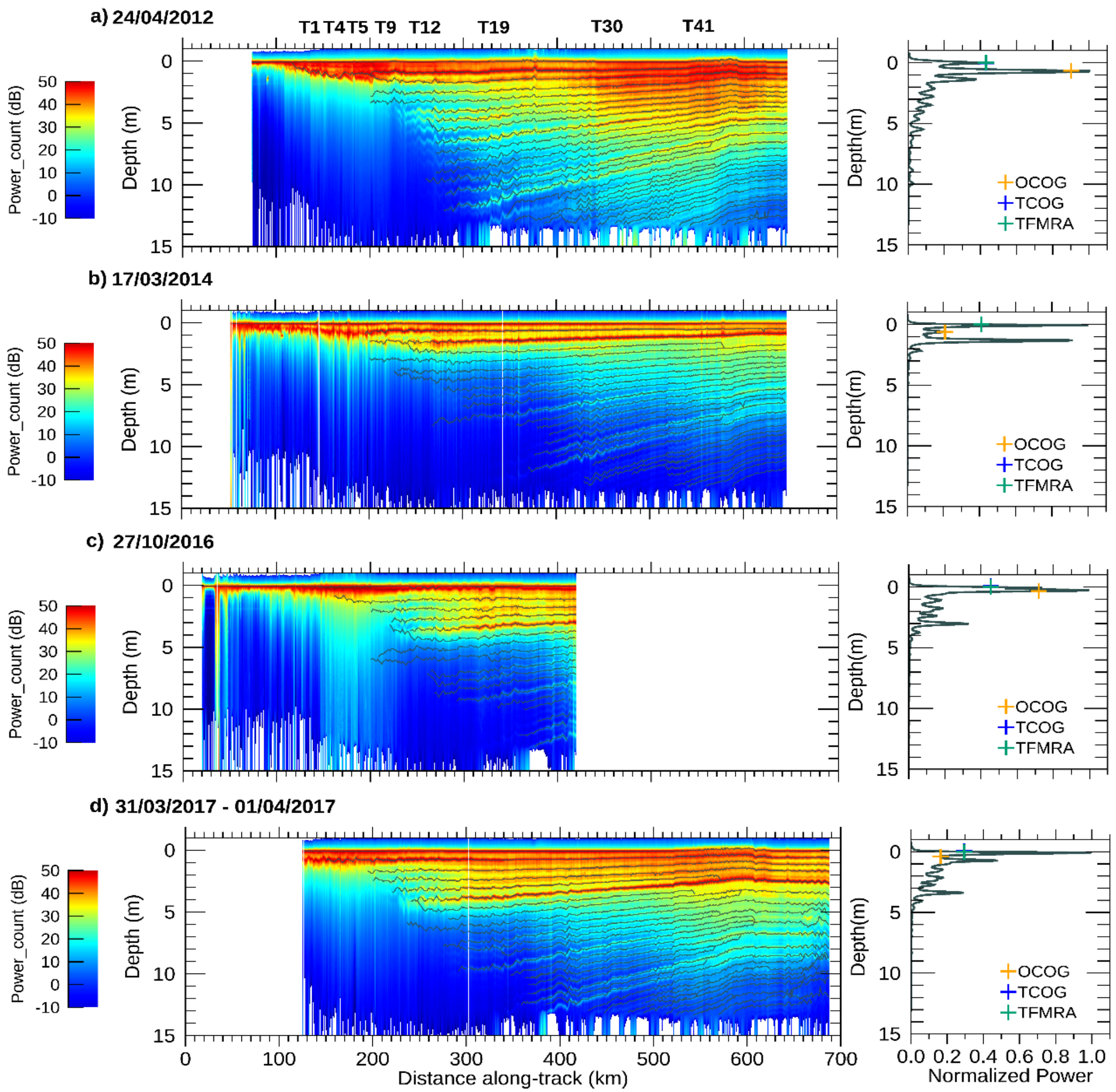

Figure 5. *ASIRAS profiles a) 2012, b) 2014, c) 2016, d) 2017 and waveform example taken at 400 km along-track*

Spatial variations

- Few internal layers in the ablation/percolation zones (until ~250 km along-track), after which their abundance begins to increase with surface elevation as the firn density falls

Temporal variations

- Marked inter-annual variability
- Change in the backscatter energy distribution after 2012: strong dielectric contrast of the 2012 melt layer reducing the energy transmitted to the deeper firn column

Fluctuations in the degree of radar penetration

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Quantification of the degree of penetration into the near-surface firn through three parameters:

- Width of the waveform (OCOG width)
- Number of layers above 10% of max surface return power
- Depth at which power falls below 1% of max surface return

Exceptional nature of the 2012 melt event[10]

- **Large fluctuations in the degree of radar penetration,**
  - 63% decrease in the OCOG width
  - 68% decrease in the number of layers
  - 5.9 ± 2.3 m decrease in radar penetration depth
- **Linked to the 2012 melt layer**
  - 1 cm ice lens found at a depth of 4.4 m at site T12 in 2017
  - High density peak after 2012

Despite large fluctuations in penetration, there is a **good agreement of Ku-band retracked heights with ALS** (difference within 16.5 cm)

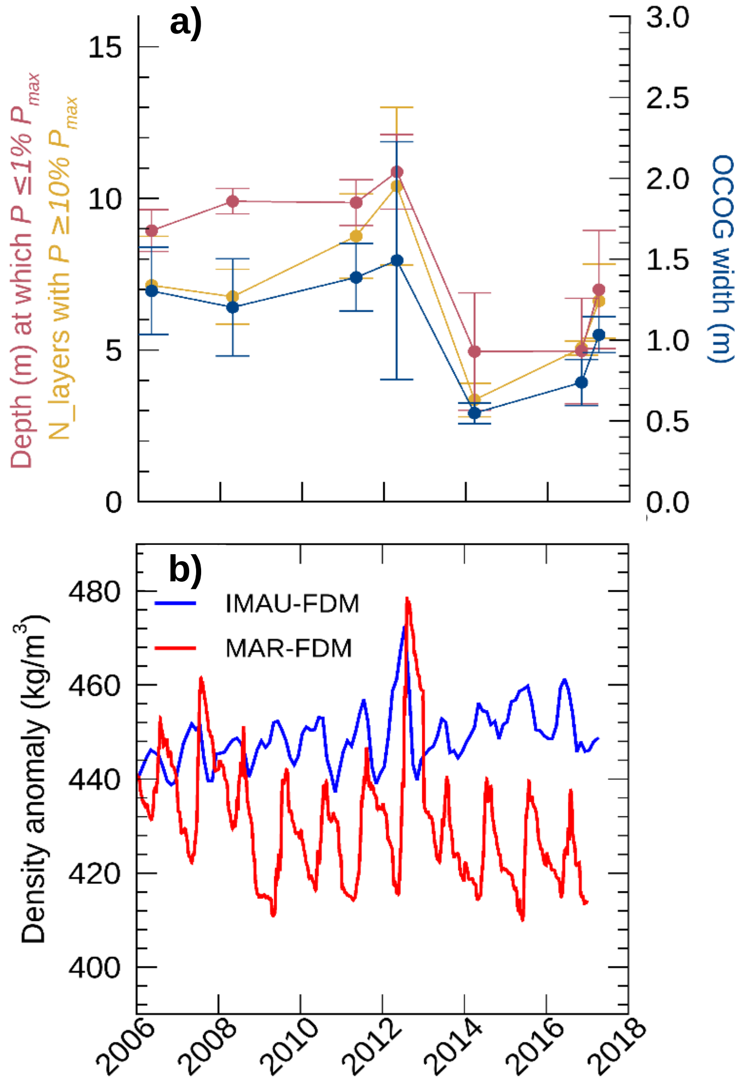

***Figure 6.** a) Temporal variations in radar-derived parameters, b) Density anomaly*

What about at a higher frequency (Ka-band)?

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New Ka-band radar added to the CryoVEx campaigns in 2016 and 2017 to study differences between Ku- and Ka-bands

- **Surface scattering** is dominant in the Ka-band waveforms
- Due to the reduced bandwidth of KAREN compared to ASIRAS, the internal layering cannot be resolved
- **Reduced Ka-band penetration** compared to Ku-band by ~50%
- Good agreement of Ka-band retracked heights with ALS data, with a difference between 12.5 cm – 16.0 cm

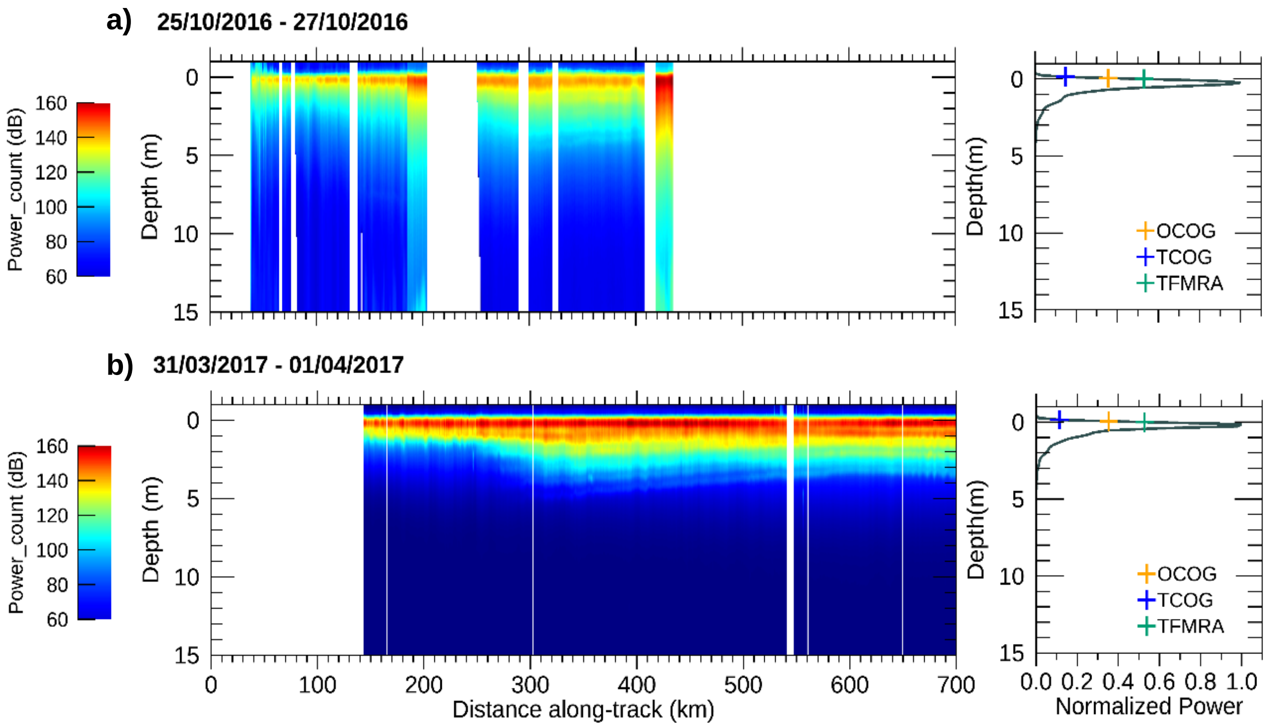

Figure 7. *KAREN profiles a) 2016, b) 2017 and waveform example taken at 400 km along-track*

Summary and Conclusions

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1. We present an extensive and coincident set of **near-surface firn density** and **airborne radar and laser** measurements acquired between 2006 and 2017 along the EGIG line - a 675 km long transect across **West Central Greenland**

2. We trace **firn annual stratigraphy** from **Ku-band** data to 15 m depth, but **a ~1 cm ice lens reduces the degree of penetration by 5.9 ± 2.3 m** after the 2012 intense melt event

3. **Echo retracking compensates for the effects of penetration**, leading to surface heights that agree with laser data to within 13.9 cm

4. **Ka-band is less sensitive to volume scattering than Ku-band** as power above 1 % of the maximum surface return reaches depths ~50 % lower

Thank you to all the CryoVEx team members!

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