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

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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.

- 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

From 7 CryoVEx field campaigns:

- Airborne Ka-band radar KAREN (34.5 GHz) – 2016, 2017
- Shallow firn cores (depth < 6 m) – 2016, 2017

Firn densification models:

- MAR-FDM (all years)

Figure 2. Methodology applied to radar data

- Airborne radar data (ASIRAS, KAREN)
- Retracking (TCOG, OCOG, TFMRA)
- Waveform alignment at the surface
- Averaging along-track (1km)
- Conversion of radar two-way travel time to depth using output from MAR-FDM
- Automated layers tracing
- Runway calibration with ALS
- Comparison of retracked heights with ALS

Radar profile along the EGIG line up to a depth of ~15 m

Internal layers tracking only for ASIRAS

Assessment of retracked heights
Validation of firn models with in-situ data

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

**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\textsuperscript{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)

\textbf{ASIRAS internal layers correspond to isochrones}

\textit{Figure 4. ASIRAS 2017 profile and IMAU-FDM isochrones in black}
**ASIRAS Radar profiles**

**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.

*Figure 5. ASIRAS profiles a) 2012, b) 2014, c) 2016, d) 2017 and waveform example taken at 400 km along-track*
Fluctuations in the degree of radar penetration

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

- 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)?

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

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!

References