Review: Characterization of Ice Features in the Southwest Greenland Ablation Zone Using Multi-Modal SAR Data

Sara-Patricia Schlenk et.al.

This study investigates ice features in the ablation zone of SW Greenland by using airborne SAR data in different frequency bands. SAR polarimetry, interferometry, tomography, and modeling is employed to characterize the features. Temporal stable low backscattering areas named as radar dark features are found, especially in the low frequency (L,P-band) domain which are interpreted as a weathering crust containing residual liquid water. Radar bright features are characterized by volume scattering and the presence of a subsurface scattering layer is found along the transect.

In general, the paper is well written, clearly structured and the presented data set and methods to characterized ice features in the ablation zone and its interpretation is worth to be published in TC. Equations used are correct and figures are of good quality while mostly supporting the analysis. As the focus of the paper is a detailed interpretation of the data as well as to find a possible explanation of the origin of the radar dark features, I miss some more qualitative analysis of the data itself as well as the use of available external data sets.

General points:
The paper is a continuation of results presented in Parella et.al. (2021) and of the EUSAR conference paper of Pardini et.al. (2016) where the radar dark features were already described and Tomograms presented. I miss the reference to this paper as well as any discussion of those findings.
As mentioned above, I recommend to make use of the extensive data set of Operation Icebridge. CRESIS accumulation radar, which was used e.g. by Jullien et.al. (2023) to identify ice slab thickening, are available for 2010 and 2011 in the Russell glacier area and should be used in combination with the P-Band sounder data as it seems that the vertical resolution of the sounder data is not as good as the CRESIS accumulation radar. This could help to identify layers or inclusions in the upper 10m where the origin of the source of the radar dark features as well as to better explain the origin and regional extent of the deeper layer found in 20 to 50m depth.

All figures, where image data is shown are too small. I would recommend to use the full width of a page and high resolution to be able to zoom in.

When looking at the Radarsat compilation (20m C-Band, Joughin et.al. (2016)) one can already see the dark features (see figure 1 below - The blue lines show as an example some of CRESIS flight lines acquired on 8th April 2011)). To me it seems that some of those dark features are correlated with across flow surface crevasses. The circular features, which move with the ice as the authors explain, are situated in the middle of Russell glacier, and are maybe connected to a river network up slope and therefore are maybe relicts of drained lakes.

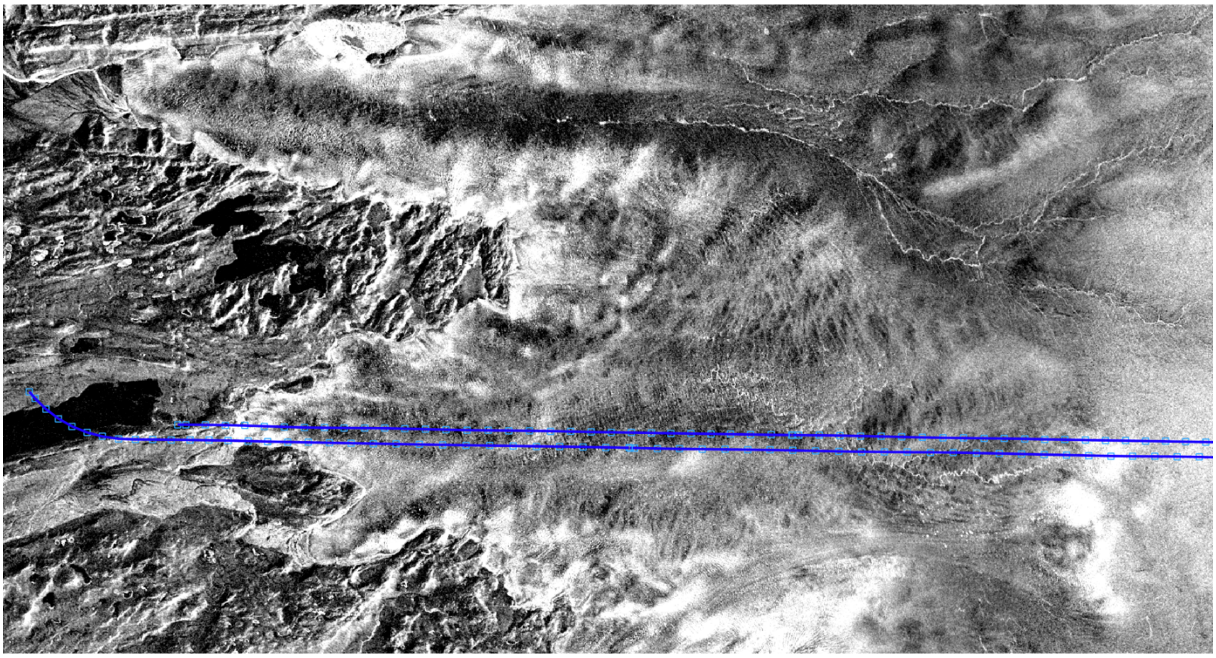
Figure 1 RadarSat compilation with two CRESIS_accum profiles on top

Could you please show an extra figure with a summer SENTINEL2 or Landsat image without snow cover as well as backscatter images of all three frequency bands, to be able to see surface crevasses (the airborne radar data is of higher resolution and should resolve the crevasses better than RadarSat). The crevasses would allow water to penetrate deeper than just the shallow weathering crust. In my opinion if water is present in the weathering crust you should also see dark features in X-Band as the weathering crust is usually less then 0.5m thick and the origin of the strong attenuation of L and P band seems to be deeper. How thick is the winter snow layer on top of the previous summer layer? Is there any information of the typical winter snow accumulation from the AWS nearby?

Specific remarks:

L85: ACTIC15 → ARCTIC15
Why don't you include C-Band as Parrela et.al. 2021?

Table1: Please specify the bandwidth of each system and add the wavelength lambda. This would help to understand to which surface roughness the different bands are sensitive.

L115 Fully focused SAR processing of sounder data. How was this achieved and is there a reference to be cited?

L125: Additional data sets:
As mentioned above, please make use of CRESIS accumulation radar for the top 80m

L223: Analysis of data
As mentioned above, please add backscatter images of all Bands and a summer optical image for crevasse detection.

Figure 3: Can you please mask the optical image in the same way as the radar images. This would make it easier to visually compare the images.

In your analysis you mention H and alpha. Please also show an extra figure with images of H, alpha, Anisotropy and add P and phi as images as well as in your analysis similar to Parella (2021). In addition, please generate the DEM gradient from your F-SAR DEM and include this as well. It would be interesting to see where surface depressions are located. Maybe a hillshade of the high-resolution DEM overlaid by a transparent DEM is also worth to show.

Table 4 and Table 5: Please include mean and standard deviation. Just showing the range is not really enough.

Can you please add a figure, were you show a scatter plot of H versus HH or HV Power as well as alpha vs power for all frequency band, as this seems to be correlated.
Please add a similar scatter plot with the phase center heights to illustrate the drastic change of phase center heights for L and P band in the radar dark areas.

Figure 4.
Again, too small. Why don't you show the DEM transparent on top of a hillshade. ATM data is not really telling me something here. To my opinion you can skip it. Insteade, please add also the DEM slope image or the slope image of the smoothed FSAR DEM which is used to detrend. Maybe surface depression can be seen, which are removed by the de-trended DEM.

Section 4.3
Figure 6. Is the sounder data depth scale converted to ice velocity?

Can you please create a similar figure as fig 6 but zoom in into the upper 10m or 20m ? As in this depth you expect the occurrence of the weathering crust containing liquid water, correct? Please extract H and /or HH,HV power along the flight track and plot this as extra subfigure in this new Figure. This would allow to directly align the dark features with the Tomograms.

For the Tomogram please don't use a spectral color scale. The scale should follow guidelines for color blind people . Please use the same color scale for the Tomograms and the Sounder radargram. Can you please add a similar figure for X and L Band (maybe in the appendix).

Can you please explain in more detail why this matrix filter to suppress surface scattering contribution picks up a layer in 30 to 50m depth, where no energy content was seen before? I'm wondering why the power level in subfigure f) after applying the matrix-filter is similar to the power level in areas where the deeper layer was seen before. Can you explain this?

In addition, please include CRESIS accumulation radargrams to compare with the p-band sounder data (see figure 2 below). Do you see a strong deep reflector in the same depth, and can you resolve strong near surface reflections in areas of the radar dark features? Is such a strong near surface reflector (if present) missing in the radar bright areas?

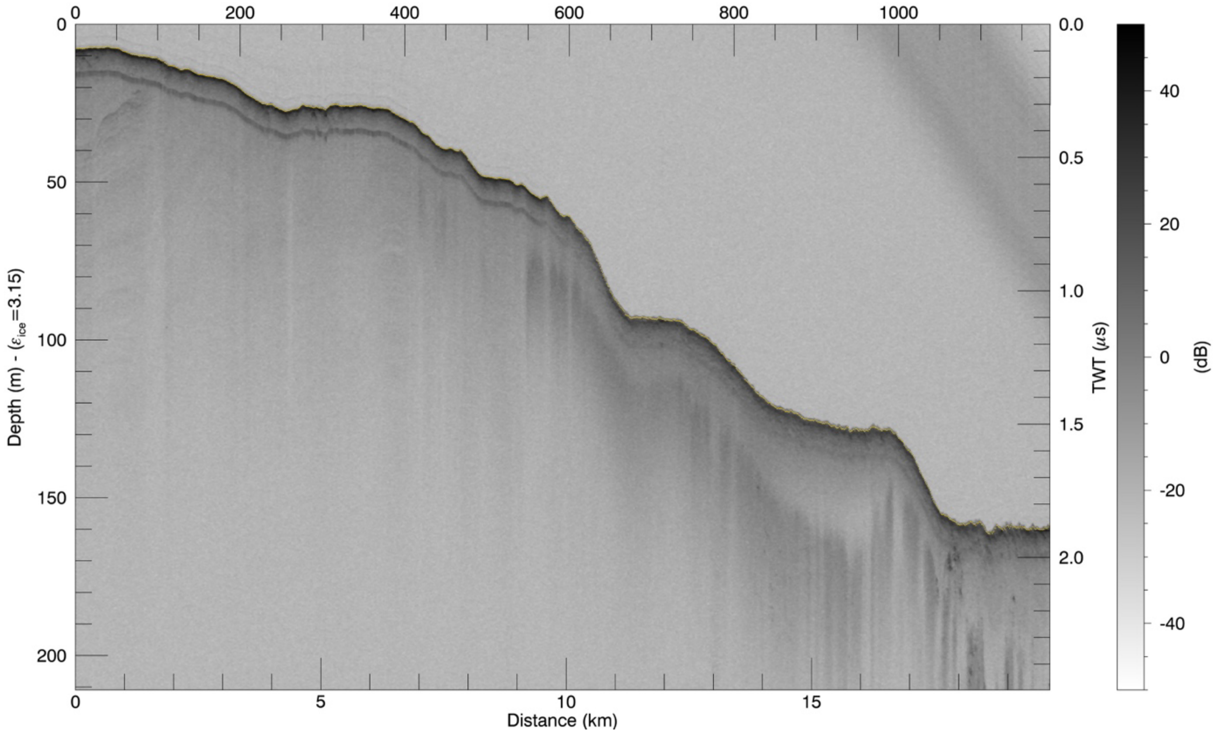

Figure 2 Radargramm of CRESIS_accum (20110408_01_158). Trace 0 to 550 strong layer in roughly 10m - related to side lobe as surface return is very strong. From 550 onward dark reflection band similar to P-band sounder visible. This seem to be corelated with rough crevassed surface (surface clutter????)

L355

I personally, don't agree that a thermal boundary is the main driver for the subsurface scattering layer in depth between 15 to 50m. The temperature wave is strongly suppressed with depth and should reach a value which corresponds to the annual mean surface temperature. This, is indicated in your plot, where the temperatures reaching -5°C in 10m depth. How should a temperature boundary layer develop further down and how should this be responsible for a spatial varying reflection in 20 to 50 m depth? This idea needs more explanation!

I personally think, that this lower reflector could be related to radar clutter from near surface crevasses across track or the dark radar features itself, which the radar picks up from the side. At least this could explain the high spatial variability. Can you please make use of the dense grid of the CRESIS accumulation radar data to track this deeper layer and try to relate this to surface features across track. The CRESIS data would also allow to support your theory of the presence of a layer across the entire test site as stated in L485 (an example of the CRESIS data is given in figure 2).

Fig 8. And Fig 9

Please enlarge the labelling of axis.

Fig. 10

Please include in e,f,g the extent of the area as extra axis label right and top of each figure. This would allow to visually estimate the distance between the moved features and compare it to the average ice flow velocity.

L440 I think the water body needs to have a certain thickness to fully absorb the signal. This is related to the frequency. Even in areas of firn aquifer sometimes the bedrock is visible (see Horlings 2022).

L 432 and discussion later on

No link to surface roughness or topography …. I don't fully agree. See above – I think there is a link to crevasses as seen in Radarsat or maybe also to surface depressions. Those depression can be situated up slope. The circular features seem to be relicts of old lakes which were drained. As impurities are collected in lakes, they can later act (after lake drainage) to intensify the formation of a weathering crust allowing water to infiltrate the subsurface or enhance melting between grain boundaries. This argument you discuss later in L 465 ff but you mentioned that no direct evidence was found. For what evidence you were looking for and how do you rule this argument out? I think you need to look in a spatially larger area.

Maybe its worth to have a look on an optical image during the melt season in the drainage catchment of Russell glacier. Where are lakes formed up slope and where do you see a denser river network? I could imagine that more water is present in the radar dark areas than in the bright areas during the melt season and maybe this kind of network is connected to lakes upslope. The band of radar dark features is also situated in the main trunk of Russell glacier where ice velocities are slightly larger. The glacier north of Russell (see figure above) shows even less backscatter in Radarsat more concentrated in the fast-flowing main trunk. Similar processes should be expected there to allow liquid water to penetrate and be present in the near surface layers. I fully agree that the dark features are related to liquid water content but I would not completely rule out a topographic driver.

Additional, as rocks are nearby more impurities can be expected in the ice matrix or between grains which were transported by water. Impurities enhance sub grain melting as well as the attenuation and might play a role here as well.