Review of

Mapping snow on northern winter roads: A dual-frequency polarimetric radar approach for snow characterization over land, lake and sea ice

by

Stroeve, J., et al.

Summary: This contribution describes measurements, analyses and interpretation of ground-based radar measurements carried out at frequencies in Ku- and Ka-Band, HH and VH polarization, over measurements sites in the Canadian sub-Arctic and Arctic during winter and early spring. The main aim of these radar measurements is to retrieve the snow depth. The radar measurements were carried out along transects over landfast sea ice, lake ice (two lakes), and two different types of tundra, and were accompanied with in-situ observations of relevant snow properties. These latter observations were used to evaluate the retrieved snow depth and to feed physical models used to simulate the expected radar return of the various surfaces to interprete and better explain the results obtained. The results are quite convincing with respect to the snow depth over sea ice and, mostly, also for lake ice, following logically previously published work in this field. The results obtained for the tundra sites are less convincing.

Overall, this contribution is very well written and provides an important addition to our current knowledge in this field. I only have a few specific comments and some suggestions of editoral nature. I also formulated two general comments - which are focusing on editing rather than content.

We thank the reviewer for their useful comments and below we outline how we addressed those comments.

General Comments:

GC1: In the title and the abstract you stress quite a bit that you aim to improve monitoring of winter roads. However, the main content of the paper is basically about snow depth (in general) over various surfaces. Neither do you elaborate on, e.g., roughness issues, aeolian redistribution of the snow, or other factors that might hamper preparation and/or maintenance of a winter road nor do you sufficiently well elaborate on the structural / morphological changes of the snow that forms the winter road, i.e. compaction, etc. Therefore, I have to say, I find it a bit far fetched to use this aim in title, abstract and motivation of this contribution. It could mislead readers.

We appreciate the reviewer’s comment about this. Our original motivation of the study was to see how radar altimetry could map snow depth across different surface types and we realized that this could be useful for winter roads in the north. To address the reviewer’s concern, we have added more to the discussion to bridge this gap and we also modified the introduction slightly.

The introduction now reads: "*Northern winter roads built over landfast sea ice, lake ice, and muskeg (e.g. peatland or bog) are key in providing transportation and connectivity to remote and often isolated regions in the Canadian Arctic and sub-Arctic (e.g. Dong et al., 2025; Barrette et al., 2022). This is because in most northern communities, traditional transportation infrastructure such as highways or railroads is either nonexistent or impractical due to the region's challenging geography and permafrost thaw (e.g. Gheysari and Maghoul, 2024). As a result, roads built over frozen bodies of water or over muskeg often offer the only reliable travel routes during winter. The seasonal viability of these routes will depend on the bearing capacity of the underlying ice and the structural integrity of the snow-fill used to level the driving surface.*

*Mapping winter road conditions presents a range of challenges, driven by dynamic and variable snow accumulation, compaction and melting, as well as the remote and often difficult terrain where these roads are located. Snow depth is a critical variable in the engineering and integrity of winter roads. Since snowfall acts as a thermal insulator which reduces ice growth (e.g. Sturm et al., 1997), in the construction phase, snow must be precisely managed through compaction to increase density and thermal conductivity, ensuring ice thickens sufficiently to support heavy vehicle loads. Heavy snow accumulation on the other hand acts as a static load that can alter the composition and thickness of the ice cover (Brown and Duguay, 2010). If the weight of the snow is sufficient to submerge the ice surface below the hydrostatic water level, lake or sea water infiltrates the snowpack, creating a layer of flooded snow/slush that hinders transport across the ice surface. Once refrozen, this slush forms snow-ice, which is structurally weaker: refrozen snow-ice possesses about 50\% of the load-bearing capacity of the original underlying black ice (Gold, 1971; Michel, 1978). Furthermore, aeolian redistribution can create uneven surface roughness and drifting, which obscures hazardous ice features and complicates maintenance efforts***.**

Remote sensing provides a path forward, offering the capability to map essential variables such as snow depth and ice thickness, at various scales. For example, Zakharova et al. (2021) demonstrated the use of Ku-band backscatter data from Jason-2 and Jason-3 to map river ice thickness needed for the prediction of ice road operations, while Mangilli et al. (2024) used radar altimetry to map lake ice thickness. Over sea ice, approaches…"

The separate discussion section now reads: We hope these additional discussion points will satisfy the reviewer.

"***Bridging snow depth retrievals with winter roads***

Winter roads provide essential connectivity across a heterogeneous landscape in the north. These transport corridors are increasingly vulnerable to warming temperatures and shifting precipitation patterns. Because natural snow accumulation is the primary governing factor for ice growth rates, route viability and road stability, improved methods for mapping snow across these landscapes is an operational necessity. The development of the KuKa dual-frequency polarimetric radar has highlighted how including cross-polarized radar returns offers improved snow depth accuracy compared to dual-frequency co-polarized returns. Our results further highlight that compaction increases the real part of the permittivity e' which would strongly impact the co-polarized returns, so that the HH-VH differencing is operationally superior as the VH signal remains more consistently aligned with the true snow/ice interface. Finally, aeolian *redistribution determines the spatial distribution of snow loading and the formation of impassable drifts along transport routes. While not explored in detail here, being able to identify these high permittivity wind slabs via radar could serve as a proxy for monitoring wind-driven accumulation that causes uneven loading on ice surfaces. Polarimetric satellite missions like the PoSARA concept could provide the foundation for regional snow mapping and operational planning.*

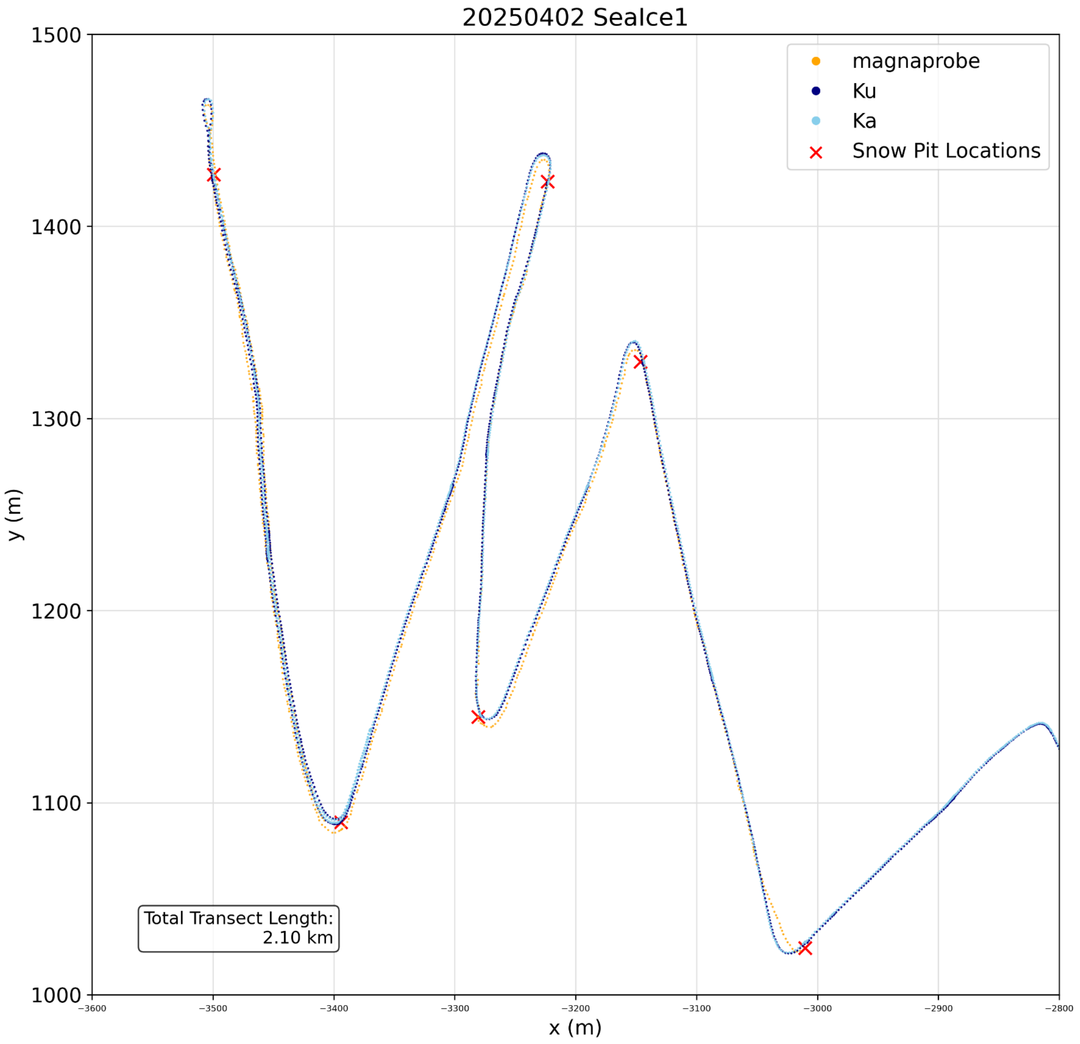
While we did not specifically address the role of permafrost thaw, an evaluation of snow cover impacts on permafrost stability near a highway embankment in the Northwest Territories demonstrated enhanced permafrost thaw with snow accumulation, and recommended mechanical snow removal and/or snow compaction as mechanisms to encourage permafrost stability (O'Neill and Burn, 2017). Snow depth mapping using radar altimetry would help identify regions of snow accumulation and priority zones for snow removal/compaction to ensure stable northern infrastructure over permafrost.

As shorter winter road seasons demand alternative, permanent (all-season) transportation and connectivity infrastructure options, accurately characterizing snow depth and ice thickness to inform the engineering and design of remote transportation corridors constructed over a variety of land and icescapes will be increasingly important. Ground based radar altimetry expanded to aerial and satellite coverage used to map snow depth can inform near real time interventions that will mitigate snow load impact on infrastructure stability and meet the needs of communities that rely on these connections for safety, security and equitable access to services."

We hope these additional discussion points will satisfy the reviewer.

GC2: I find the description of the experiments a bit light. One needs to read through 90% of the paper to finally learn how long the transects actually were. Also an illustration how the various in-situ measurements are located relative to the radar transects is missing and would be very nice to better understand the experiments as a whole.

Thank you for this comment and we have added figures to the appendix that show the location of the snow pits relative to the transects and include the length of each transect in the figure caption and within the main body text. Unfortunately lat/lon locations were not stored for Churchill so we cannot show the location of the snow pits for that field campaign. An example of the Resolute figures added is below:



Specific Comments:

L17-26: Little is said in this paragraph about muskeg and the impact of vegetation. Also, the role permafrost desintegration has on such roads and their monitoring is not laid out sufficiently well.

We decided to keep the introduction brief but we expanded in a discussion section (see above). However, we did also add a little more in the introduction (see above edits). While we recognize that permafrost degradation is important as well, we are focused on mapping snow depth in this study and added a paragraph in the discussion section about this (see above edits). We hope these additions alleviate the reviewer's concerns on the winter roads relevance.

L59: Neither here nor later I found information about the length of the transects along the measurements were carried out. The entire scale of the experiment remains vague at this point.

All the transects were of different length. Figure 1 does provide an overview of the areas covered with the transects, but we acknowledge it is not possible to tell the length from this. To address the reviewer's concerns we have added detailed figures in the appendix with the transects and the location of the snow pits along with their distance (see example of the figure above).

L89-93: I well understand that it is not an issue to overprobe the snow depth in case the surface underneath the snow cover is solid - like pebbles or ice. But for the site in Churchill you wrote about the average height of the vegetation underneath as 20 cm to 80 cm and about the type of it, being - among others - shrubs. Hence I would assume that the surface underneath the snow is not necessarily overly solid at this site. Please reflect on this and, if needed, change the text accordingly.

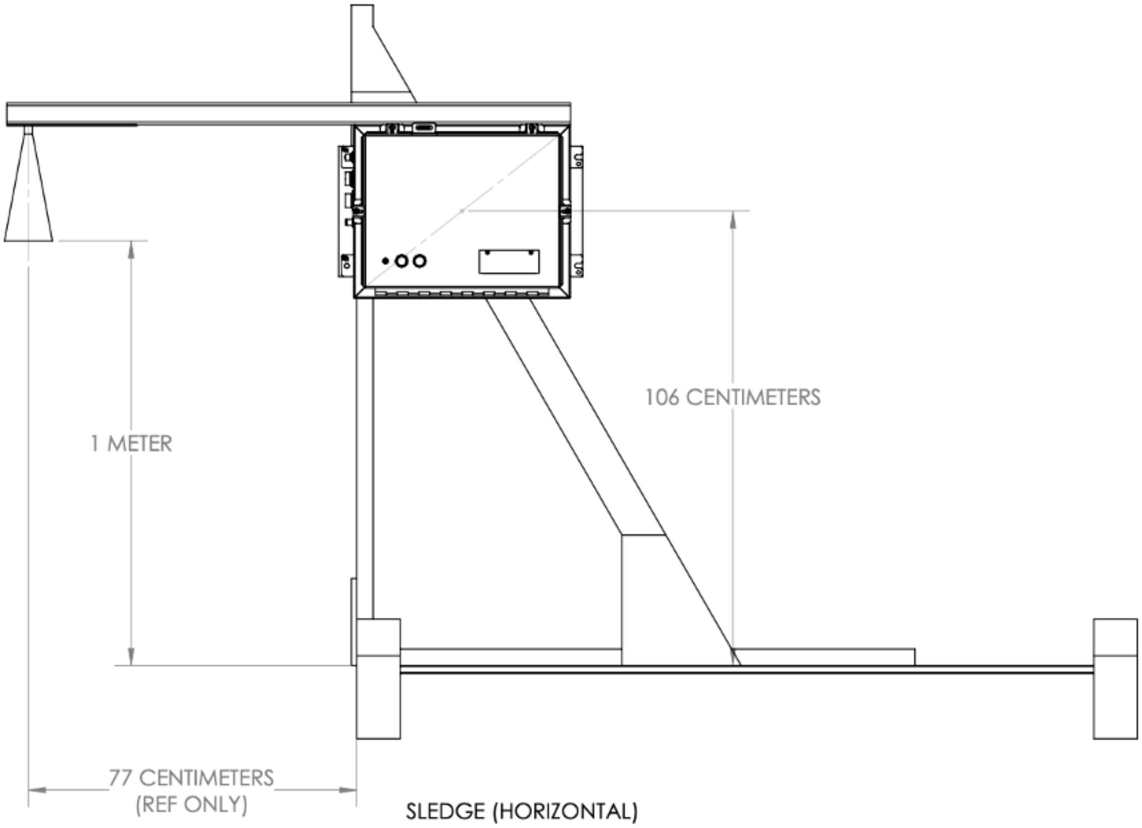
The impact strongly depends on the type and density of vegetation, which were not actually measured. However, shrub stems were sparse and did not influence the snow retrievals at the specific site, while the description in lines 68–69 refers to the general regional conditions, not to the specific conditions along the measurement profile. From experience, snow depth over grassy meadows may be overestimated by about 5–10 cm, while on mountain slopes with dense shrub vegetation the bias can reach 20–30 cm (which was not the case here).

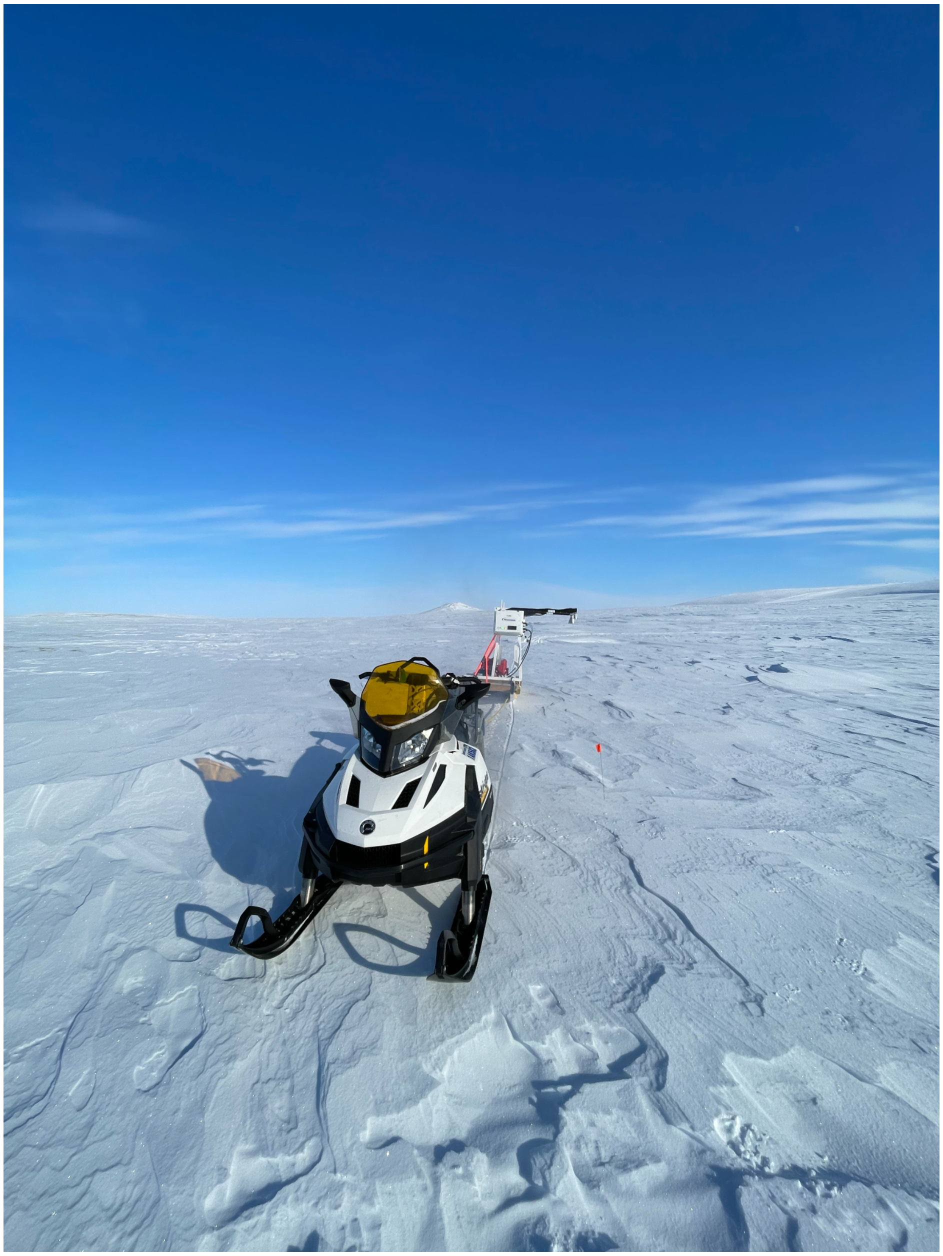
L107/108: Here you write that you used the density cutter at 3 cm vertical intervals; I assume this applies to both sites, Churchill and Resolute. The profiles shown in Figure 4, top, do exhibit, however, a vertical spacing of values every 2 cm. How did you realize that? I note that in Fig. 4, bottom, the vertical spacing seems indeed to be 3 cm. Table 3 reveals that the distance between successive points was also sometimes 4 cm or even more.

Thank you for this comment, upon further investigation it appears a 2cm cutter was used in Churchill and we have revised the text accordingly. Note that when the spacing is greater than the density cutter, this happens because the total snowpack depth cannot always be partitioned into discrete intervals.

L149/150: Even though more details of the system are given in the paper cited in L148 a reader would appreciate to know that the antennas are side looking, right. Also, there needs to be a beam protruding far enough from the sledge to the side to allow the mentioned "nadir viewing" configuration.

No, the antennas were nadir looking for this experiment as stated in the methods. And yes they are attached to an arm that extends out from the sled (see schematic below). We have photos of the original configuration in Stroeve et al. (2020) and thus, we did not feel it necessary to add another image here. But if the reviewer would like this in the appendix we can add it.





L153: It is not clear what you mean by "combined cross-track and along-track tilt". How did you combine the two tilt estimates?

This was incorrectly stated. We now state: "*To mitigate errors caused by sensor orientation, KuKa measurements with cross-track and along-track tilt angles exceeding 10^o were further excluded from analysis***."**

L204: "each grid cell" --> This seems to be out of context here because so far the paper talks about in-situ observations along tracks and about KuKa observations also along a certain track ... so far ... no mentioning of a grid took place. From your description so far it is not obvious that the KuKa provided a spatial distribution of snow depths.

Yes but we are binning everything to a common grid so that we can intercompare the two snow depths. Following Willatt et al. (2023) which describes the binning process, we aggregated the data into 2D bins of different sizes in order to more accurately intercompare the two measurements. Since we reference the paper and already state: "*Following Willatt et al. (2023), we use two-dimensional spatial binning to aggregate the KuKa-derived snow depths for comparison with the Magnaprobe snow depths, where the bin size ranges from 1 m (for highest spatial resolution analysis) up to 145 m (for large-scale mean comparison). Within each grid cell, the mean of all coincident KuKa dual-polarimetric peak and centroid snow depths, as well as the mean of all coincident Magnaprobe snow depths were calculated. This process yields spatially averaged snow depth maps for both instruments, providing a robust basis for statistical comparison between the radar-derived and ground-based snow depth observations*." we feel that no additional changes are needed.**

L279-285: This paragraph is quite qualitative ... I was wondering whether you could give quantitative values for the degree of agreement.

Yes this is a qualitative description of the histograms with the scatter plots providing the more quantitative intercomparison. To address the reviewer's comment we have added a bit more quantitative discussion before moving onto the scatter plot analysis.

"*While visual inspection of the histograms suggests a general agreement for the landfast ice and tundra surfaces, quantitative distribution metrics reveal some key differences. This fit was assessed by computing the overlap coefficient (Inman and Bradley, 1989) and the non-parametric Kolmogorov-Smirnov test (Massey, 1951). Specifically, values of overlap coefficient between 0.80 and 0.85 are seen in most Ku-band sites except for the lake ice, along with low KS values, indicating that the Ku-band retrieved snow depths well match the MagnaProbe distribution. Lower overalp values at Ka-band Centroid, and lake sites signify mismatches, while high KS statistics for Ka-band also reveal that there is a shift in the distribution towards the left.*"

L353: But this secondary peak is indeed very weak for HH-polarization; it is much more pronounced at VH polarization. Is that secondary peak significant in relation to the measurement accuracy / the noise?

Yes this peak is small compared to the dominant peak found at the air/snow interface. However, metal plate response of KuKa is a good representation of system impulse response. Range sidelobes near the peak are about 20 to 30 dB lower than the peak. Since our secondary peak is above this level, we do believe it is a true response of the brine layer in the waveform.

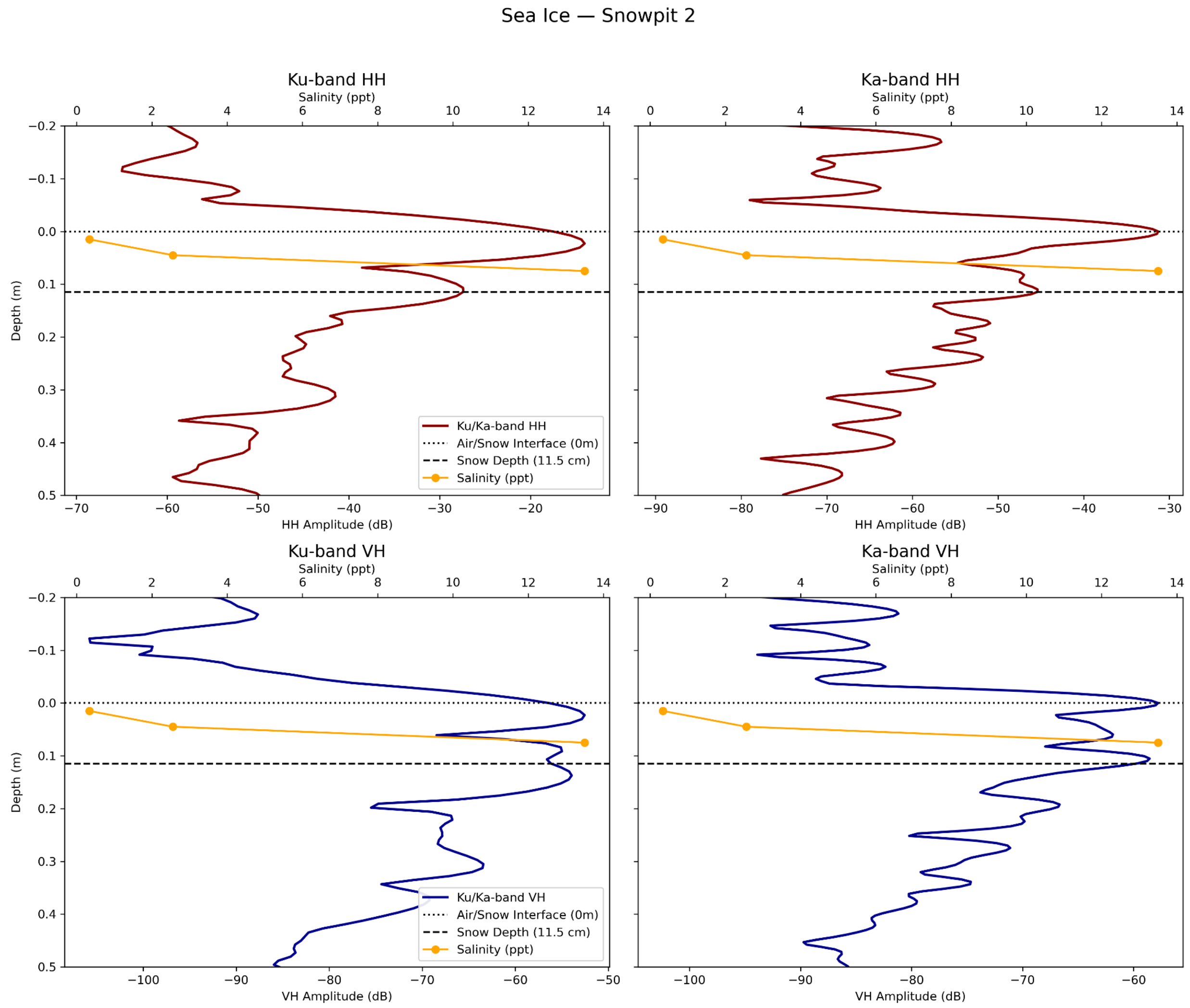
L357/358: This comment connects a bit to the previous one. You see this as a downward shift of the Ku HH peak ... I would say that the air/snow interface still has a very strong peak; the saline snow layer provides another peak, that is even higher, true, but only by 3-4 dB. I am wondering, whether given the range resolution that can be achieved, you are not at the edge of what you can credibly resolve and the differences in the (three) peaks we see over these two interfaces plus the saline layer at Ku HH are perhaps not significant?

The range resolutions are 1.5 cm (Ka) and 2.5 cm (Ku) and thus the reviewer is correct that we cannot get the precise location. But we can evaluate how the variations in the snowpack dielectrics could impact the location of the scattering surfaces. We did this analysis in order to better understand why at times the polarization approach works well and why at times it doesn't. It is not a perfect correspondence as we are also averaging 5 KuKa tracks around each snowpit location given the lat/lon uncertainties to get a direct match.

Table 3: I would be very interested how figures like Figure 15 and 16 would look like for the thicker snow layers on sea ice, i.e. snow pit 3 on April 2 and, particularly, snow pit 2 on April 6. Is the main reflrection horizon for the two bands still the snow/air interface? How much of the signal reaches below the highly saline basal snow layer? I would find a focus on these two snow pits also more interesting in terms of their representativity for future conditions in the Arctic (and current conditions in the Antarctic) with respect to snow depth on sea ice.

We attach the two figures here. You can see for the second snow pit that at Ka-band the first peak remains at the snow/air interface at HH and VH but at Ku-band it is slightly shifted downwards. For the third snow pit, there is a slight shift away from the air/snow interface at both frequencies and polarizations and the VH signal appears aligned with the high salinity at the base. If the reviewer feels these are worth including, we could add them

to the Appendix.



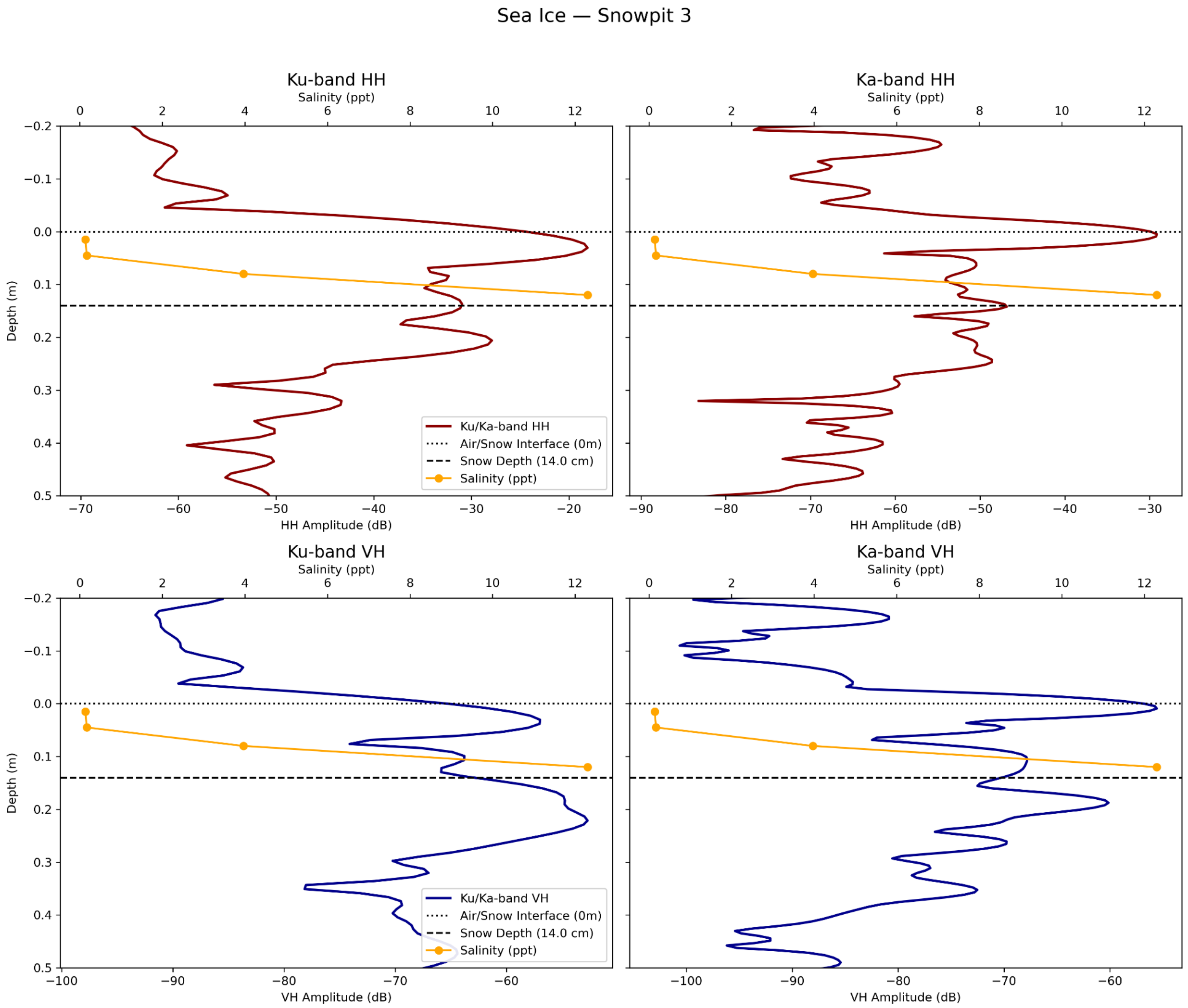


Figure 16: Why is the peak Ku VH return located so deep in the ice layer? Why is the return from both the snow/air interface and the saline snow layer so much weaker for this snow pit than for snow pit 6?

This is a great question, for the 4th snow pit the Ku-band HH peak is broader than the 6th snow pit. This suggests perhaps more surface roughness or a more metamorphosed or slushy basal layer. Also for the 4th snow pit, the VH signal doesn’t show a single sharp peak but instead has a long tail or secondary humps. The presence of brine pockets or large depth hoar near the base of the snowpack can cause the signal to “bounce” internally. This increased path length creates a “late” return, so that the signal is coming from deeper. Further since the 6th snowpit had higher salinity, the larger dielectric loss means a sharper waveform.

L371-374: Since you use "winter roads" and their monitoring as one of the main motivations of your paper (it is even in your title) I find this paragraph a bit weak and very hypothetic. Aren't there studies published, e.g. in the journal Cold Regions Research and Technology about the effect of artificial / mechanical compaction of snow on physical snow properties?

We thank the reviewer for their comment, which led to us researching this more and we discovered earlier work by CRREL. We have changed the paragraph to read: "*Finally, while our validation focused on undisturbed snow, the mechanical compaction inherent to winter roads would alter the snowpack's dielectric properties. Mechanical compaction increases snow density to 500–600 kg/m*^{3} *(Abele, 1990). Higher density and sintering lead to increased volume scattering at Ku-band frequencies, which may obscure the snow-ice interface. However, our preliminary results suggest the VH-proxy remains stable in moderately compacted Arctic snow.*"

Figure 17: Did you explain these pairs of snow depth values that are kind of aligned vertically (left of 200 m and of 400 m) in the Lake Resolute snow depth somewhere?

We thank the reviewer for pointing this out. The reason for this is that the GPS with KuKa is taking a measurement about half as frequency as each waveform is collected, which results in two points having identical lat/lons. We have now forced every other point to appear half way between each GPS location to make the visualisation clearer.

Typos / Editoral Remarks:

L80, L84 & Figure 2 caption for wind speed: "km/hr" should be replaced by "km/h".

Corrected

Figure 1 caption: What is meant by "- newer"?

That was a typo.

Figure 5, caption. Please note in the caption that the vertical axis is reversed to the one in Figure 4.

Hi yes this is true, and we now note it in the Figure 5 caption. Unfortunately, we could not align the SMP the same way given that it did not always penetrate all the way through the snow. We added to the figure caption: "*Note the vertical axis is reversed compared to Figure 4 as the total snow height measured by the SMP was sometimes not achieved due to incomplete penetration of the SMP***."**

L165: 0.77 and 0.85 cannot be correct ... the speed of light in vacuum is 3 x 10^8 m/s ... so, maybe a 10^8 is missing and a unit is missing as well.

Thank you the other reviewer also pointed this out so we have corrected it to say: "*Based on the bulk densities measured, reduced wave speed scaling factors ranged from 0.77 (368 g/cm*^{3}*) to 0.85 (209 g/cm*^{3}*)***."**

Table 2: Why is the Ku-Band VH Ice/water interface power threshold (dB) higher than the one for HH? (VH: -20dB, HH: -30dB). This seems to be rather unusual.

Agreed, that this is unusual. The thresholds are used to find the first location where the waveform first exceeds these values, though the actual value of the interface could be anything above these thresholds. We went back through the code and set them both at -30 dB with no difference in results.

L206 "maps" --> It is not sufficiently clear how the kind of measurements that were carried out can results in maps.

We changed the wording to grids

Figure 7, caption, "Light yellow lines indicate MagnaProbe snow depths" --> I am not sure I fully understand how you overplotted the MagnaProbe Snow depth onto these echograms ... you need to have a reference height (range) from which you subtract the snow depth? So, if for Ku VH the light yellow line dips down to a range of 2.0 m .... what is the reference height (range)? 1.6 m? Some clarification might increase the readability.

We scale the magnaprobe snow depths by c' (as mentioned in the text) and we add that to the height of the sled above the surface, estimated to be 1.56. As such it is not a perfect overlay as this distance can vary with the surface undulations. However, this is a better way than referencing the magnaprobe data to the peak HH return, which at times do not represent the air/snow interface. We have added this clarification to the figure caption.

Figure 14: The font size within the panels should be increased to the same size as used in Fig. 13.

Yes, we apologize, it was a setting in overleaf that made the figure smaller than the others, this is now corrected.

Figure 15, caption: I think it needs to read "6th" snow pit - at least according to the title of the figure and the match with "SI6" in Figure 4.

Yes, typo is now fixed!

L366-368: But you don't show figures like 15/16 here so maybe add "(not shown)"?

Good point, we have now said "not shown".

Figure 17: The font sizes are really small. You could consider increasing it.

Thanks, we have now fixed it.

L429: Given the complexity of the returned signal from whatever is underneath the snow in case of a tundra that you mentioned above a few times, I suggest to not include snow depth over trundra in this sentence.

Actually, the approach worked well for Tundra based on our analysis and thus, we do think this technique would help to map snow depth over land surfaces.

We made other minor changes for clarity and flow as shown in the tracked changes