Reviewer 1

Review of "Mapping Snow on Northern Winter Roads: A Dual-Frequency Polarimetric Radar Approach for Snow Characterization over Land, Lake and Sea ice" by Julienne Stroeve et al.

The study is comparing different snow depth mapping methods (also described in Willatt et al., 2023…) with the on-ice KuKa radar to magnaprobe measurements over different terrain used for winter roads in Canada (lake ice, sea ice, muskeg). The results are in line with earlier KuKa results on sea ice that the Ku VH-HH peak provides the best snow depth estimates while the Ku – Ka peak or centroid method does not demonstrate much skill. This finding is obviously concerning when the upcoming CRISTAL snow depth product is based on the Ku – Ka method and it is also interesting to imagine what the studies mentioned in the introduction have derived, using the same method with ALTIKA and CRYOSAT data. There are differences between radar measurements from KuKa and satellite, as also mentioned, but one thing that they have in common is the signal attenuation in the snow layer. This KuKa to satellite discussion could be strengthened. Unfortunately, there are no committed future satellite polarimetric altimeters.

The MS is well written and structured but the analysis could be improved and I have some suggestions below. I think that some parts of the discussion could be strengthened and substantiated by including the measured values in Table 3 and computing the reflectivity and penetration depth and potentially scattering, absorption etc.

We thank the reviewer for their thoughtful and constructive comments, below we outline our responses to the specific recommendations.

In addition, I have a number of specific comments:

The abstract should be detailed with main results.

We added a few of the more quantified results to the abstract, such as adding the mean bias for the landfast ice and tundra results. The abstract now reads as: *"Winter roads are lifelines for remote northern communities. Built over land, lakes, rivers, and sea ice, these travel routes are increasingly vulnerable to warming temperatures and variable precipitation. To ensure safety and adapt to these changes, operators require high-resolution monitoring of snow depth across these diverse surfaces, as natural snow accumulation dictates ice growth rates, route viability and road stability. This study extends our polarimetric radar method, previously demonstrated on pack ice, to landfast sea ice, tundra, and frozen lakes and assesses how well we can retrieve snow depth over these surfaces. Results indicate consistency with earlier sea ice analyses, maintaining a mean snow depth retrieval bias and error within 3 cm over the landfast ice. Promising performance is also found over frozen ground using Ku-band (mean biases less than 6 cm). To address the specific challenge of lake ice, which includes strong returns from the ice/water interface, we present a new interface-detection technique that simultaneously retrieves snow depth and ice thickness. While current validation focuses on undisturbed snow, this approach could provide a path forward for characterizing the cryospheric environment in a way that can directly support the optimization of winter roads."*

There are some differences and similarities between on-ice and satellite altimeter measurements which should be emphasized in the introduction and strengthened in the last part of the discussion.

We felt the flow was better to bring in the difference between satellite and ground-based observations to the discussion section as to not muddy the introduction too much. In response to the comments we have strengthened the discussion to include: *"With respect to the CRISTAL mission, our KuKa data show that since both Ku and Ka co-polarised waveforms mostly show scattering at the air/snow interface, differencing retrieved Ku- and Ka-band peak or centroid ranges does not represent snow depth. For the reasons given above this cannot be assumed to be the case at the satellite scale that CRISTAL will operate on, but could provide insights into where the CRISTAL concept is more likely to provide accurate snow depths"***.**

Sometimes the discussion is really confusing and I give examples below. I would suggest a conceptual model for what happens with snow - radar interaction to illustrate the main principles. What are the snow/ ice parameters affecting the radar backscatter? And how?

The in-situ measurements have uncertainties, the derived snow depths have uncertainties. Please include a discussion and a quantification of the uncertainties.

Yes, all data have uncertainties, and as already mentioned in the text, we limited the snow depth retrievals to depths greater than 2.5 cm to handle range resolution in the radar and biases in the MagnaProbe data. We also list uncertainties in the temperature, density and salinity observations that would in turn give rise to uncertainties in the dielectrics. In terms of the snow depth uncertainties, the largest source of error is the conversion of the radar returns into snow depth. As you note, we use a constant wave velocity through the snow per surface type based on a limited number of snow pit data and a mean fixed density.

If the reviewer feels we need to specifically compute the Root Sum Square (RSS) for the snow depths, we could include this table for example in the Appendix, derived assuming a density error of $\pm$30 kg/m^3 and a representative snow depth of 10 cm. However, this is based on assumptions of these errors, which may be larger or smaller along each transect data point as the density varies. Thus, we are not sure how helpful it is.

Site	Density (kg/m3)	Band	σ_{sys} (cm)	σ_{diel} (cm)*	σ_{manual} (cm)	Total RSS (cm)
Sea Ice 1	300	Ka	1.50	0.36	1.00	1.84
Sea Ice 1	300	Ku	2.50	0.36	1.00	2.72

Sea Ice 2	**324**	**Ka**	**1.50**	**0.35**	**1.00**	**1.84**
Sea Ice 2	**324**	**Ku**	**2.50**	**0.35**	**1.00**	**2.72**
Lake Ice	**302**	**Ka**	**1.50**	**0.36**	**1.00**	**1.84**
Tundra	**264**	**Ka**	**1.50**	**0.38**	**1.00**	**1.84**

L114: please write in the text if Churchill is sea ice or something else. The same for the other sites.

We say Churchill and Resolute because we are showing all the surface types in Figure 4. To avoid confusion, we changed the sentence to read: "*Figure 4 summarizes the snowpack properties over the different surface types in Churchill (upper panel), with results from Resolute Bay shown in the lower panel***."**

Figure 4: all these parameters could contribute to the uncertainty, I suggest to use them in the analysis for comparing the different sites and for computing reflectivity and penetration depth.

We are unclear what the reviewer means by uncertainty here. We did already evaluate how these variables influence the sea ice dominant scattering surfaces which is in terms of the dielectric properties listed in Table 3, and we included a discussion for some of the snow pits to evaluate how changes in complex permittivity impact the dominant scattering surface, which we feel is more relevant than talking about penetration depth or reflection. For the tundra it is more difficult to repeat this type of analysis because of the potential large errors in the densities which would influence the interpretation as to how density variations influence the dominant scattering surfaces. If the reviewer could be more specific in their request we can address it.

L158: the snow density in Eq. 1 is in [g/cm3]. Please specify that. Otherwise you are using [kg/m3].

Done

L161: The sentence is unclear, please clarify. The "liquid water" which is, I think, brine, is affecting the loss (penetration depth?), but according to Eq. 1 the "wave speed" (speed of light?) is only a function of snow density. Please use the terms consistently (e.g. "liquid water" ->

"brine") and substantiate your statements with references or by computing the "loss", "Wave speed/ speed of light" with models.

The presence of brine does indeed suggest the presence of liquid water (specifically a saline solution) within the snowpack. Further, we use equation 1 as a first-order approximation as there is no way to have the density/dielectrics for the entire transect. Thus, for the histograms and the scatter plots, we rely on equation 1.

Given the reviewer's concerns, we have revised the sentence and added more context: **"***While Equation 1 provides a wave speed correction based on snow density for dry snow, the presence of salinity at the base of the snowpack introduces brine that increases the complex permittivity. Specifically, the real part (ε') further reduces the wave speed, while the high ionic conductivity of the brine increases the imaginary part (ε''), leading to significant dielectric loss. Based on analysis of our snow pit dielectrics (see Discussion section), the difference in using this assumption is on the order of 0.09 ns or less. Given that we do not have the dielectrics along the entire KuKa transects, we have chosen to apply the dry snow scaling as a first-order correction consistently across all snow pits. 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).***"**

L165: "…we assume c' values range from 0.77…": The c' value is computed using Eq. 1, write that instead of "assume". The speed of light in snow is not 0.77, it is 0.77 times the speed of light in a vacuum (as written in line 158). Please clarify.

Thanks for pointing this out, we didn't say that quite right. We re-wrote: "*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)***."**

Figures 7 and 8 it is not totally clear what "Range" means. Is it the two-way travel time times the speed of light in a vacuum? Please clarify. Also could you reference these plots to the snow and ice surface? It is very difficult to see if it is a track-point misalignment or an actual variation in the snow and ice surface height. Please also write the average snow and ice thickness in the figure caption.

Range is the distance from the antenna to the scattering targets. Since the reviewer may not be familiar with these types of measurements we have added to the Figure 7 figure caption: "*The vertical axis represents the radar range, defined as the distance from the antenna phase centre to the scattering target***." Otherwise no changes are made to the figure as it is not appropriate to write the average snow and ice thickness since it varies over the track and we did not measure ice thickness along the same track, only the MagnaProbe data at ~1 m spacing.**

Figure 7: Judging from the "range" you do not get returns from deep within sea ice. Please clarify. Is it because of sidelobes or other off-nadir returns?

Perhaps the reviewer meant to say " you do get returns from deep within sea ice"? For first-year sea ice, the basal snow at the snow–ice interface is often saline because of brine

wicking from the underlying ice, and this brine-rich layer can cause strong attenuation of radar waves, thereby limiting penetration to deeper interfaces or shifting the apparent scattering horizon upward (Barber and Nghiem, 1999). Apparent returns from within the ice should therefore be interpreted cautiously, as they are more likely to arise from system artifacts or off-nadir returns than from true penetration to those depths, consistent with the discussion in Newman et al. (2024) of sidelobes, radar multiples, and off-nadir footprint effects in KuKa FMCW radar data. To address the reviewer's concern we have added a paragraph about the returns seen below the ice surface: "*Finally, we note that some returns within the sea ice are visible in these echograms. Apparent returns from within the ice are more likely to arise from system artifacts or off-nadir returns than from true penetration to those depths, consistent with the discussion in Newman et al. (2024) of sidelobes, radar multiples, and off-nadir footprint effects in KuKa FMCW radar data.*"

L265: I would suggest to replace "volume scattering" with "rough surface scattering".

Volume scattering and rough surface scattering are not the same. We feel that in the context of the sentence that volume scattering is applicable.

L333: This explanation is confusing. According to Eq. 1 there is no permittivity contrast between Ku- and Ka-band and if there is difference in the air/snow surface scattering then it is the wavelength dependent roughness. Both frequencies scatter at the snow surface but there may be differences in snow penetration at Ku- and Ka-band and how much reaches the snow ice interface (and back). Please clarify.

Line 333 talks about vertical migration of the dominant scattering surface which is relevant for both frequencies since at times it is the snow/ice interface, at times it is within the snowpack and at times it is the snow/ice interface (though not often at Ka-band). Because this surface varies with snowpack properties it does challenge current assumptions.

It is correct that based on equation 1, Ku- and Ka-band permittivities are equal, but this is because snow wetness is not taken into account (this was not measured in this study), e.g. in Hallikainen et al. (1986) the Debye-like equations include frequency.https://www.researchgate.net/publication/3016464_Dielectric-Properties_of_Snow_in_the_3_to_37_Ghz_Range.

After reviewing the paragraph of concern we realized it could have been better stated and we now write: "*The interaction of radar waves with snow and ice is governed by the material's complex dielectric permittivity which influences signal penetration, attenuation, and backscatter. In satellite radar altimetry, waveform retrackers are employed to identify a specific point on the return echo, such as the leading-edge midpoint or the peak, to define the effective scattering surface. However, the range to this retracked point is a complex function of snow density, microstructure, and frequency-dependent penetration. Consequently, the vertical migration of this effective scattering center within the snowpack, driven by changing snow properties, challenges the fundamental assumptions of altimetric retrievals and complicates the accurate estimation of both snow depth and sea ice freeboard".*

Table 3 is nice and I would even suggest to include penetration depth and Fresnel reflection coefficient as columns. However, the permittivity is not consistent with Eq. 1. I think that you could even achieve better results if you use the Table 3 permittivity for computing the speed of light in snow (Eq. 1). In any case there should be consistency between Eq. 1 and the permittivity in Table 3.

While we agree in principle that equation 1 is an approximation of how the radar waves slow down in dry snow, often in remote sensing we do not have the dielectrics to compute c' more precisely than using an assumed density of the snowpack. Further, we do not know the actual dielectrics for every radar point on the transect. Thus, we used an average density based on the snow pits for computing c' for the different surfaces along the KuKa transects.

However, we also have data from a handful of snow pits we can evaluate in more detail. To evaluate how the results in Table 3 would have altered c' from what we used, we computed c' using the data in Table 3 for each layer and then summed through n layers of the snow layers. For each layer the EM wave speed is $c' = \frac{c}{\sqrt{\epsilon'_{eff}}}$. For each layer of thickness h_i, the one way travel time is $\frac{h_i\sqrt{\epsilon'_{eff,i}}}{c}$ and we sum over all layers.

The results are summarized below for 2-way travel time and reveal that in all cases the difference is 0.0977 ns or less, which for a 10 cm snow depth would cause a depth error of 0.3 cm.

- **Timing differences from Halliken assumption at first landfast sea ice location in Resolute. Results listed for Ku-band (in ns) and values are slower than the assumption for dry snow: Pit 1: 0.0481, Pit 2: 0.0602, Pit 3: 0.0977, Pit 4: 0.0626, Pit 5: 0.0438, Pit 6: 0.0955**

We realize that standard radar metrics are penetration depth and Fresnel reflection. However, in the context of saline snow, the effective permittivity provides the most direct insight into the dielectric changes that govern both absorption loss and volume scattering. Since Table 3 is quite dense, we opted to instead evaluate these variables in the context of our case studies. To satisfy the reviewer, we computed the penetration depth $\delta_p \approx \frac{\lambda_o\sqrt{\epsilon'}}{2\pi\epsilon''}$ and Fresnel Reflection at normal incidence $R = \left|\frac{\sqrt{\epsilon_{eff}}-1}{\sqrt{\epsilon_{eff}}+1}\right|^2$, and we added in the text a representative calculation for Pit 6 and 4 to illustrate the highly lossy barrier in our discussion. Specifically we now state:

"**...***While this is a small fraction, brine is highly conductive and its presence leads to an increase in the absorption characteristics of the snow (e.g. Ku-band ε'' = 0.34) and hence reduces penetration to the snow/ice interface. Calculated penetration depths (e.g. the depth at which the power of the radar signal has been attenuated to 1/e (about 37%) of its original value at the surface) for this brine layer are significantly restricted, reaching ~1.5 cm at Ku-band and ~1.0 cm at Ka-band, effectively masking the underlying surface. Overall for Pit 6, the radar signal* *reaches the critical loss threshold within the first 3.5 cm. Evaluation of the waveforms shows a dominant peak at both Ku- and Ka-band HH waveforms at the air/snow interface, and a weaker secondary peak just above the ice surface at Ku-band that appears to align with the high salinity layer (Figure 6). Analysis of snow pit 4 reveals a distinct layer of elevated brine volume (1.53%) between 2 and 5 cm above the ice surface. This increase in brine volume drove a simultaneous increase in the complex permittivity, raising the real part (ε') from 1.62 to 1.99, enhancing refractive contrast, while the imaginary part (ε'') jumped from 0.09 to 0.25, creating a highly lossy barrier with a penetration depth of only 2.0 cm at Ku-band. Plotting the corresponding waveforms, we find a downward shift of the Ku-band co-polarized peak aligning with the top of this saline layer...*"

Table 3: how is the salinity computed/ measured? Density cutter-> bagged sample-> melted->salinity measured->multiplied by the density ratio?

The density cutter sample was bagged, and melted. We did not multiply by the density ratio since the salinity measure is meant to represent the salinity of the snow volume sample.

L361: I think that this sentence is misleading. Depolarization is also happening in dry snow, so I am skeptical if it depends on brine pocket scattering. Loss is the sum of absorption (brine) and scattering (snow grains). Please define the “Mie-regime”. What is “rapid depolarization”? Please reformulate these two sentences and substantiate the statements.

Mie regime is when the scatterer is on the order of the size of the wavelength. Rapid depolarization implies shortened depolarization length, in other words the distance the wave travels before the ratio of cross-polarization to co-polarization (VH/HH) increases significantly due to multiple orders of scattering. We agree with the reviewer that depolarization is also happening in dry snow. However, our intention was to highlight why the VH peak shifts more significantly in saline conditions. While dry snow grains (typically < 2mm) act as Rayleigh scatterers at Ka-band, the introduction of brine increases the dielectric contrast and creates large effective scattering structures. We have rewritten the sentences as:

"*Finally, the VH returns at Ka-band suggests a slight upward shift away from the snow/ice interface in Pit 4. At the Ka-band wavelength (λ~ 8.6mm), the combination of large basal ice grains and brine-wetted inclusions (r ~ 1-3 mm) results in a transition toward the Mie scattering regime. In this regime, the scattering cross-section increases significantly as the scatterer size becomes comparable to the wavelength, and the scattering phase function becomes more complex than the Rayleigh approximation. While depolarization is inherent to volume scattering in dry snow, the high dielectric contrast and elevated loss factor (ε'' ~ 0.13) in the saline basal layer of Pit 4 enhance the probability of multiple scattering events. This leads to depolarization over a shorter travel distance (i.e. higher volumetric depolarization), which, combined with increased signal absorption, shifts the effective VH scattering center upwards from the physical snow/ice interface.*"

L367: Compute the Fresnel reflection coefficient in Table 3 to make a substantiated assessment of the “initial reflection”. According to Eq. 1, the permittivity is only a function of snow density.

As discussed above, we use equation 1 as a first order calculation to compute snow depth across the entire transect length since we do not have density/dielectrics except for a handful of snow pits.

To substantiate the assessment of a 'strong' initial reflection for Pit 2 (April 6), we computed the power reflectance (R) using the measured effective permittivity ($\epsilon_{eff,Ku}'$=2.10). At normal incidence angle, the Fresnel reflection coefficient (Γ) is ≈−0.183, resulting in a power reflectance of 3.36%. In contrast, the lower-density snow layer from Pit 4, with ρ=309.4 kg/m^3 yields an ϵ_{eff}' of 1.81 and a reflectance of 2.17%. The 425.1 kg/m^3 density in Pit 2 thus represents a 55% increase in reflected power. As the reviewer notes, since salinity in this layer is negligible (0.58 ppt), Eq. 1 (where ϵ is a function of ρ) confirms that this enhanced 'initial reflection' is driven by the densification of the upper snowpack, providing a distinct dielectric horizon even in the absence of brine-driven loss.

We know that it is incredibly complex to calculate how much radiation is scattered and in which direction, and these simplistic calculations are not going to be representative. E.g. Willatt et al. (2010) shows the complexity - even if the density and wetness are known exactly where radar data are collected there is a huge variety of waveforms. Densification at the surface due to wind would cause a larger dielectric contrast but other changes - temperature, movement of brine, surface roughness, exact KuKa incidence angle and many more would also affect the waveforms. We therefore think it could cause confusion to calculate these based on a limited set of geophysical information. Modules in models such as SMRT are designed to simulate these processes and waveforms but are still under development, indicating the complexity of the task.

L374: why would compacted snow be “high extinction”? Please clarify and define the term extinction here.

In this context, extinction refers to the total attenuation of the radar signal as it propagates through the snowpack, represented by the sum of absorption and scattering coefficients ($\kappa_e = \kappa_a + \kappa_s$). By 'high extinction,' we refer specifically to the increased scattering coefficient (κ_s) resulting from a higher number density of ice grains per unit volume in the compacted snowpack. While the total number of grains in the column remains constant, their closer proximity and the mechanical development of grain-to-bond clusters (sintering) effectively shorten the mean free path of the radar pulse. This increases volume scattering, which may attenuate the return from the snow-ice interface more rapidly than in undisturbed, lower-density snow. In response to the second reviewer’s comment also on this, we have slightly edited this paragraph to now state: “*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*

L417: I agree that KuKa is not sensitive to large scale surface roughness in the same way as satellite altimeters. However, KuKa is still sensitive to surface roughness. Please clarify and describe what KuKa is sensitive to.

Because KuKa is a surface-based instrument, it samples only a very small local area relative to a satellite footprint, so the main issue is how representative that local patch is of the broader surface seen from space. KuKa is therefore more sensitive to local-scale properties, including roughness at the air–snow and snow–ice interfaces, as well as snowpack salinity through its effects on dielectric contrast and attenuation. We slightly modified this section to now state: "*The KuKa radar has a much smaller footprint. As a result, KuKa is sensitive to local-scale properties, including roughness at the air–snow and snow–ice interfaces, as well as snowpack salinity through its effects on dielectric contrast and attenuation. Combined with the ability to collect coincident geophysical data, KuKa allows for detailed investigation of the effects of snow and ice characteristics on waveforms.* "

Figure 17. Are there any measurements of ice thickness and can this be used to derive the effective permittivity of the ice… or snow?

Unfortunately, we only have one ice thickness measurement on Lake Resolute since the thick, cold ice "ate" one of our augers, and on Malcolm Ramsay lake, no thickness data was collected.

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

Reviewer 2

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.

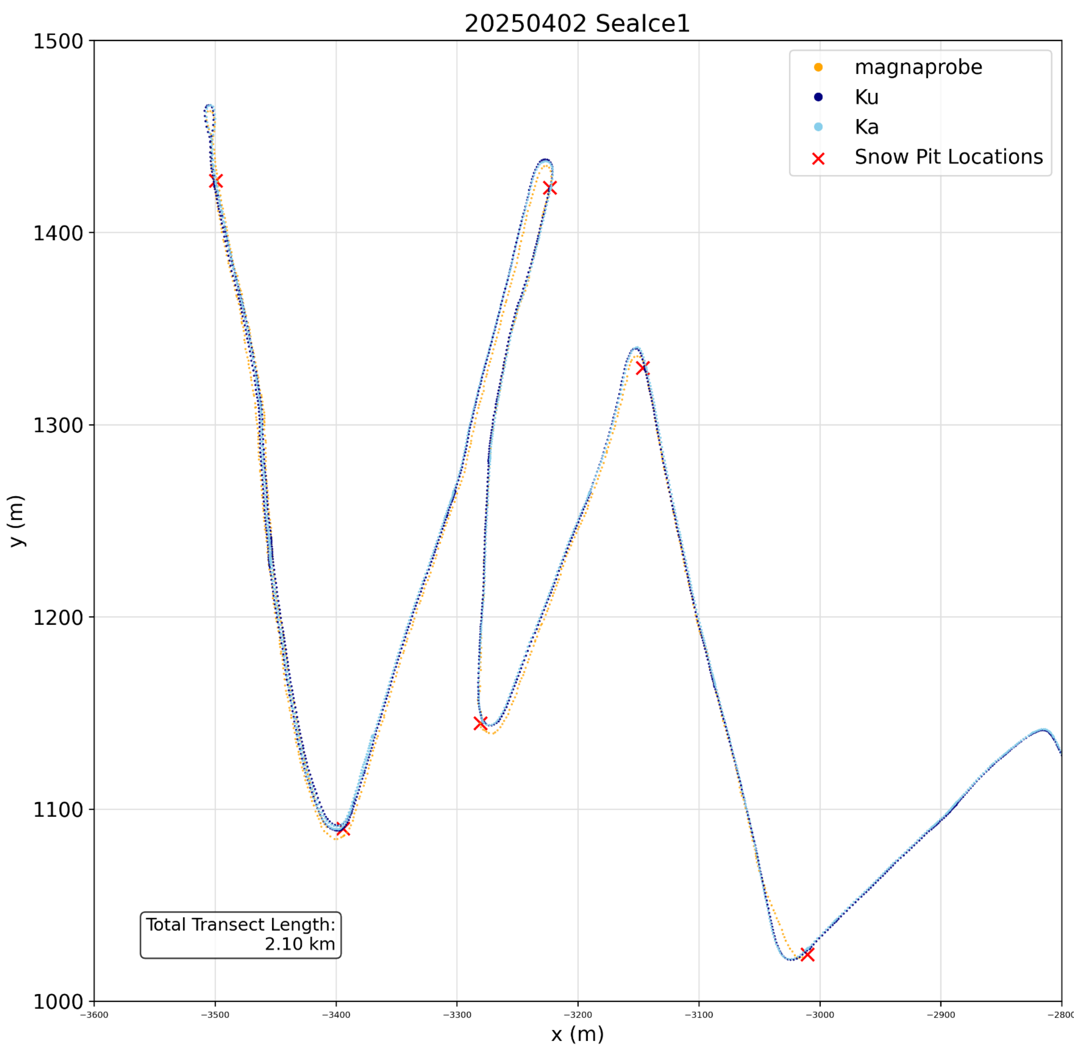
While we did not specifically address the role of permafrost thaw, an evaluation of snow cover impacts on permafrost stability near a highway embankment in the Northwest Territories demonstrated enhanced permafrost thaw with snow accumulation, and recommended mechanical snow removal and/or snow compaction 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.

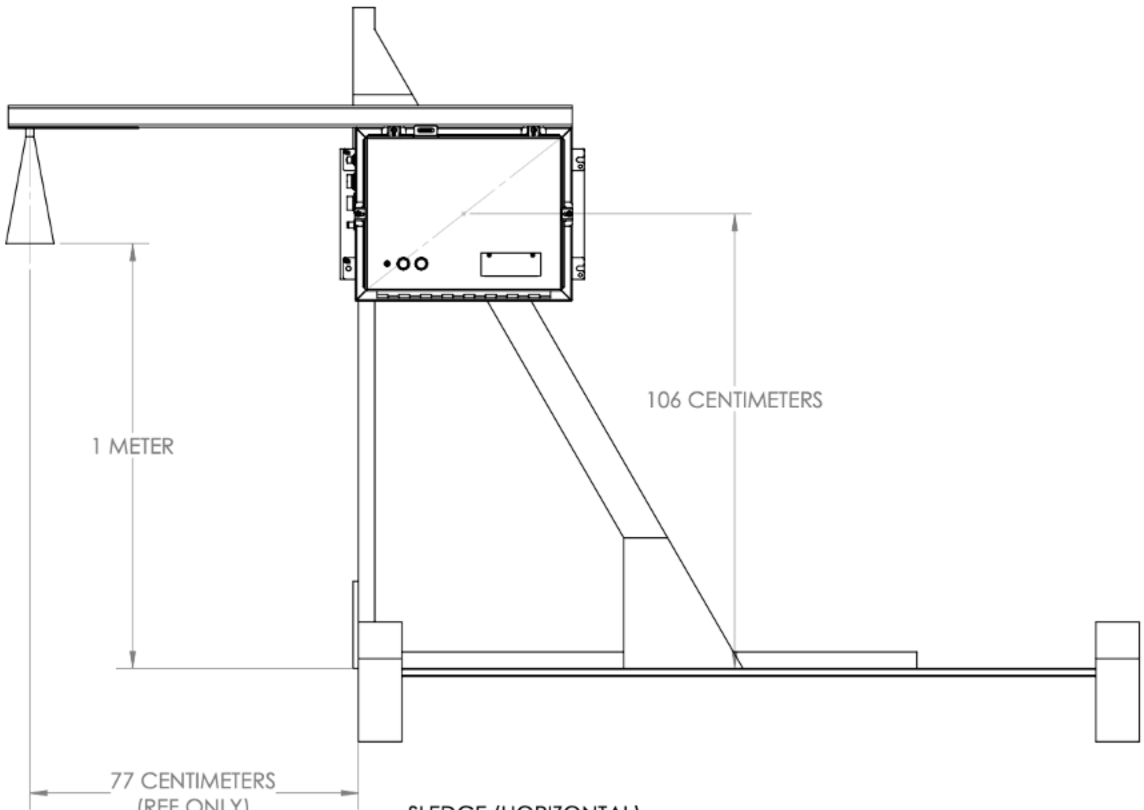
The impact strongly depends on the type and density of vegetation, which were not actually measured. However, shrub stems were sparse and did not influence the snow retrievals at the specific site, while the description in lines 68–69 refers to the general regional conditions, not to the specific conditions 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.

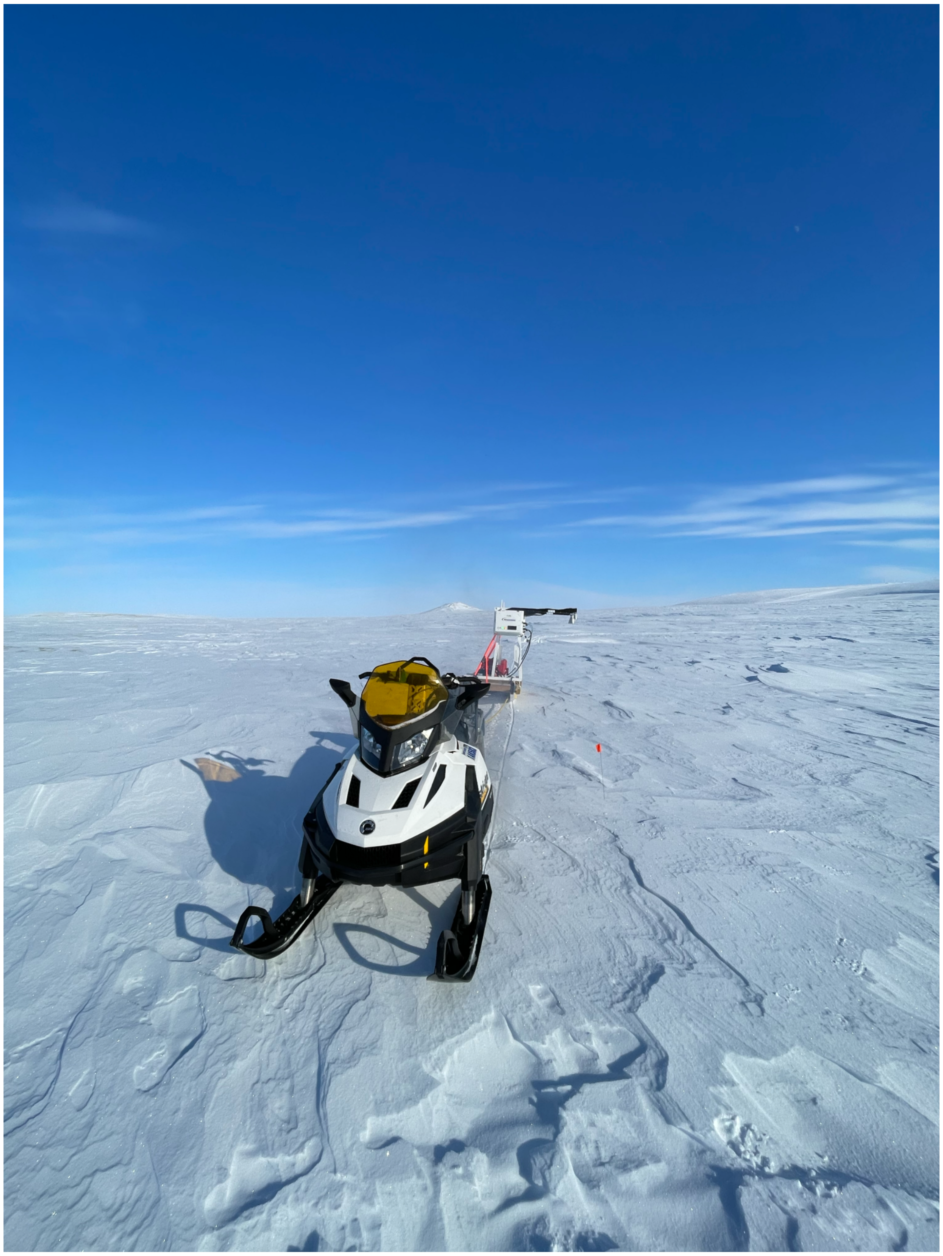
Thank you for this comment, upon further investigation it appears a 2cm cutter was used in Churchill and we have revised the text accordingly. Note that when the spacing is greater than the density cutter, this happens because the total snowpack depth cannot always be partitioned into discrete intervals.

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.



SLEDGE (HORIZONTAL)



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 10º 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.

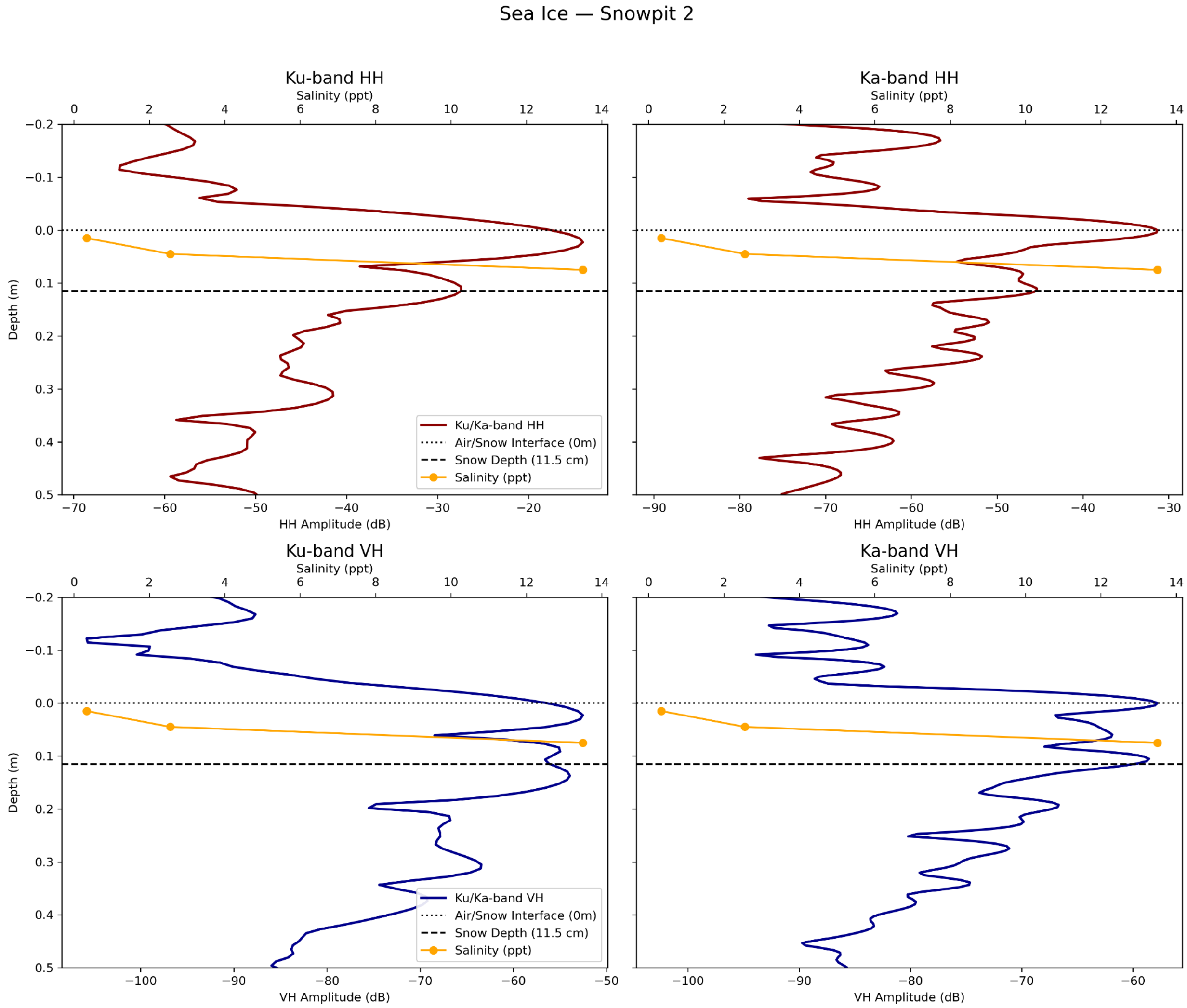
L357/358: This comment connects a bit to the previous one. You see this as a downward shift of the Ku HH peak ... I would say that the air/snow interface still has a very strong peak; the saline snow layer provides another peak, that is even higher, true, but only by 3-4 dB. I am wondering, whether given 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.



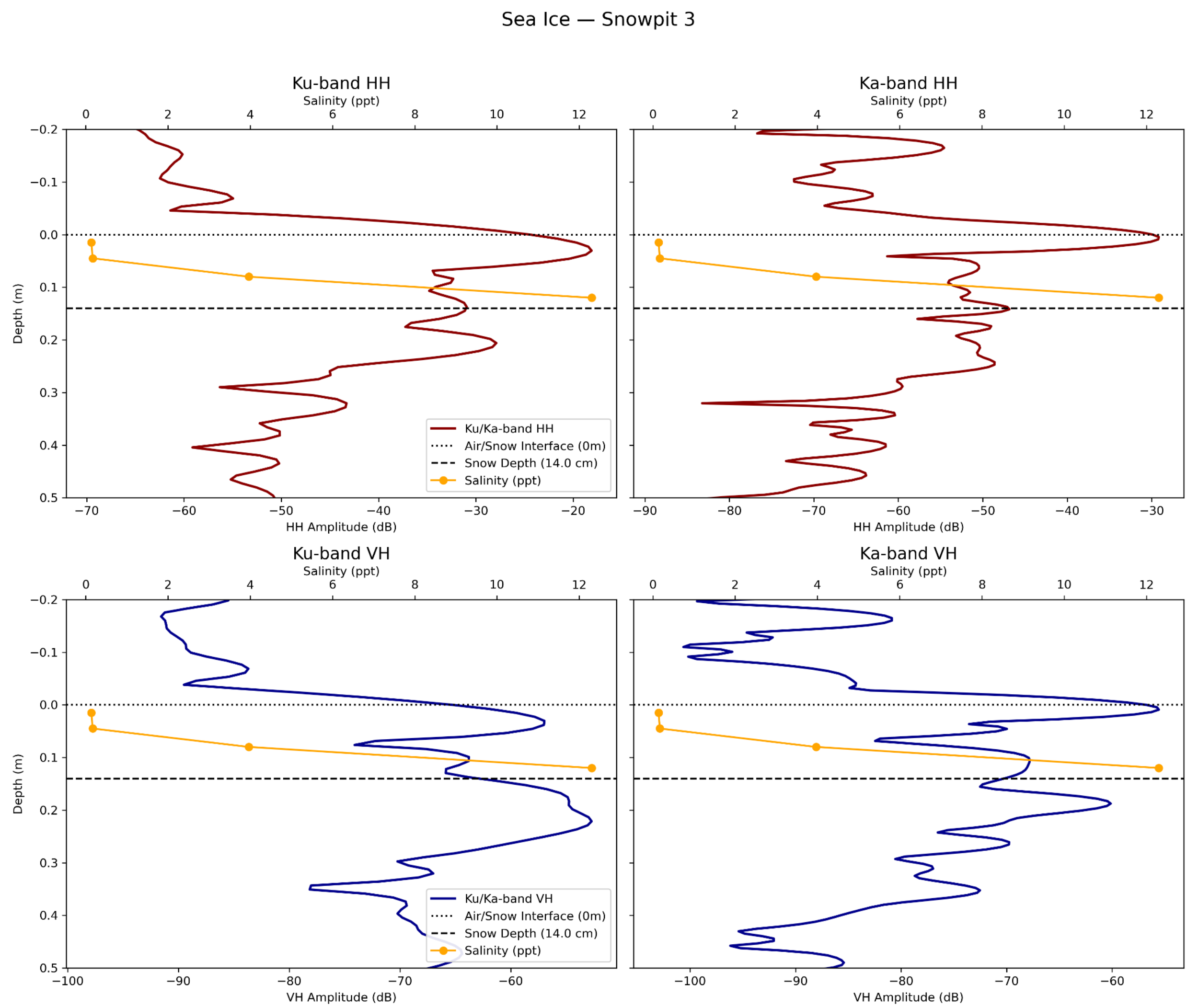


Figure 16: Why is the peak Ku VH return located so deep in the ice layer? Why is the return from both the snow/air interface and the saline snow layer so much weaker for this snow pit than for snow pit 6?

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