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 ±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 $\boldsymbol{c' = \frac{c}{\sqrt{\epsilon'_{eff}}}}$**. For each layer of thickness h$_i$, the one way travel time is** $\boldsymbol{\frac{hi\sqrt{\epsilon'_{eff,i}}}{c}}$ **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 $\rho=309.4$ 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.