

Reviewer 1

Accepted as is.

Reviewer 2

The authors have addressed my previous comments carefully, and I appreciate their substantial efforts. In my view, most of my main concerns have been resolved. The manuscript is now comprehensive, well organized, and scientifically valuable. Its main novelty lies in monitoring approximately the same ice floes through the season, which provides empirical evidence for temporarily overestimated Ku-band radar freeboards under specific snow and atmospheric conditions.

I agree with the authors' indirect justification that the observed short-term increases in retracked radar freeboard are unlikely to represent real thermodynamic growth. The required ice growth would be unrealistically fast, especially during warm and snowy conditions, and the increases also disappear too quickly to be interpreted as physical thickening. I therefore accept the basic interpretation that these are likely overestimations in the radar-freeboard retrievals.

My remaining comments are minor and mainly concern terminology, framing, and interpretation. I think the manuscript is close to publication, but a few statements should be refined to avoid overinterpreting retracker-dependent quantities as direct physical quantities.

1. Refining definitions of frequently used terminology

Several terms are used repeatedly throughout the manuscript, including "dominant return", "full penetration", "principal radar backscattering response", and "principal radar backscattering height". These terms are commonly used in the sea-ice radar-altimetry literature, but they are not always defined consistently. I suggest that the authors define them more explicitly in this manuscript.

In particular, I find the current definition of radar freeboard somewhat ambiguous. The manuscript defines radar freeboard as the height of the "principal backscatter response" from the snow/ice interface relative to local sea level. I suggest defining radar freeboard more simply as the radar-waveform-derived estimate of ice freeboard, where ice freeboard itself is the well-defined height of the snow/ice interface above the local instantaneous sea surface.

We have reviewed the definition of radar freeboard and now define it as:
"Radar altimeters provide estimates of the radar freeboard, which we define here as the

waveform-derived estimate of ice freeboard without correction for the delayed radar wave propagation in the snow. In this definition, the radar freeboard is directly linked to a geophysical height (the ice freeboard) through the snow correction factor. The radar freeboard can therefore be biased if it does not correspond to the ice freeboard after applying this correction.”

This distinction is useful because different retrackers estimate radar freeboard under different assumptions. Conventional retracking approaches often assume full snow penetration and a dominant return from the snow/ice interface, while snow propagation effects are handled later through a snow-delay correction. If a retracker explicitly accounted for the full snow processes affecting the waveform, including propagation delay, refraction, attenuation, and scattering from the snow surface or snow volume, then the radar-freeboard estimate would ideally already agree with the true ice freeboard without requiring a separate correction. This point helps clarify why radar freeboard should be treated as a retracker-dependent estimate, not simply as a directly observed scattering height.

I also suggest separating three assumptions that are sometimes mixed together:

"Full penetration" means that the Ku-band signal reaches the snow/ice interface and that some return from this interface contributes to the waveform.

"Dominant return from the snow/ice interface" is a stronger assumption, implying that the snow/ice-interface contribution dominates the waveform or determines the retracking point.

A further assumption is that snow processes do not significantly affect the waveform shape used for retracking, except through the snow-delay correction applied "after" retracking.

It is a useful suggestion that we clarify what each of these terms means and ensure we use them appropriately throughout the paper. We have re-written the entire section where we introduce the word ‘radar freeboard’:

“Correctly interpreting radar altimetry waveform returns over sea ice requires understanding how the radar waves interact with the snow layer and underlying ice. State-of-the-art algorithms used in the production of pan-Arctic SIT estimates assume that the dominant Ku-band radar return originates from the snow/ice interface \citep{Laxon2003HighRegion, Laxon2013CryoSat-2Volume}. This assumption implies that i) some portion of the incident Ku-band waves fully penetrate the snow cover and reach the snow/ice interface (further referred to as "full penetration"), ii) the return from surface scattering at the snow/ice interface makes a dominant contribution to the detected

waveform compared to returns from other interfaces or from snow volume scattering, and
iii) snow processes do not significantly affect the shape of the waveform, apart from the effect of delayed wave propagation, which is corrected in a later step of the algorithm.

A waveform must be retracked to obtain a precise range measurement. Through the retracking process, conventional retracker algorithms provide estimates of the radar freeboard, which we define here as the waveform-derived estimate of ice freeboard without correction for the delayed radar wave propagation in the snow. In this definition, the radar freeboard is directly linked to a geophysical height (the ice freeboard) through the snow correction factor. The radar freeboard can thus be biased if it does not correspond to the ice freeboard after applying this correction. Such a bias can either originate from deviations between the assumed scattering at the Ku-band wavelength and the actual scattering processes in the snow and ice system, from limitations or biases introduced in the waveform retracking process, or biases from the interpolation of sea-surface height at local leads to local floes.”

Additionally, we have rephrased the sentences related to this definition to ensure consistency throughout the manuscript.

Line 788: Please be careful with the phrase "rise of the principal radar backscattering height". This height is a conceptual or model-dependent quantity rather than a directly observed physical surface. It may be more precise to describe the mechanism as increased relative contributions from snow-surface and/or snow-volume scattering, or a reduced relative contribution from the snow/ice-interface return, leading LARM to retrieve a higher tracking point.

We agree with the reviewer and have rephrased this section as suggested, to avoid saying "rise of the principal radar backscattering height".

2. Separating what LARM perceives from what physically happens

I also suggest clearer separation between what LARM retrieves and what physically occurs in the snow-ice system.

The waveform parameters and backscatter coefficients indicate that the waveform/scattering regime changes during some events, such as warming and snowfall periods. Physically, this could be caused by increased non-snow/ice-interface returns, reduced snow/ice-interface scattering, increased attenuation, actual roughness changes, or a combination of these processes, as already described in the manuscript.

However, LARM fits a simulated waveform to the observed waveform by optimizing a limited set of model parameters. If significant returns arise from sources not represented in the

assumed model, those effects may be absorbed into the available free parameters, including tracking point, RMS height, small-scale roughness, and amplitude. In this sense, an increase in optimized RMS height should be interpreted as evidence that the waveform has broadened or otherwise deviated from the assumed model, not necessarily as an independent measurement of physical surface roughness.

This is an important subtlety. The optimized RMS height is useful, but it is part of the LARM internal fitting process. It should not be used too directly to explain the physical mechanism causing the bias. What LARM "perceives" as increased RMS height may correspond physically to several different processes that broaden or reshape the waveform. I therefore suggest referring to this quantity as "optimized RMS height", "retrieved RMS height", or "effective RMS height", and explicitly stating that it may reflect actual surface roughness and/or missing snow-scattering processes in the waveform model.

We agree that we should be more explicit in stating that the RMS height indicates that a waveform is broadened/narrowed, and that these changes might reflect actual changes in the surface roughness but may also reflect changes in snow scattering mechanisms that are not captured in the LARM waveform model.

We have rephrased the following paragraph accordingly:

"A radar altimetry waveform must be retracked to obtain a precise range measurement. Since the retracking point is directly linked to the shape of the waveform, it can be challenging to assess whether a temporary positive bias corresponds to a deviation in the scattering processes in the snow and ice from the assumed behavior at Ku-band, or if it is an artifact introduced purely by the retracker. By careful inter-comparison of the time series of radar freeboards, radar waveform parameters, and C-band SAR backscatter, we find pieces of evidence pointing towards the fact that the temporarily biased radar freeboards seem to originate (at least partly) from changes in the scattering processes of the snow and ice, rather than being introduced purely by the retracker. One of the parameters optimized by LARM is the surface topography root-mean-square (RMS) height, or more explicitly the RMS of the radar scattering distribution if it is not just a single surface contributing to the detected waveform. Changes in the effective RMS height thus indicate changes in the shape of the waveform (broadening/narrowing), which may result from changes in the surface roughness, but may also result from changes in snow scattering mechanisms that are not captured in the LARM waveform model. Figure \ref{fig:RMS height time series} in the Supplementary Material shows the seasonal evolution of the effective RMS height for FYI and MYI. For MYI we see that the effective surface roughness closely follows the patterns of atmospheric conditions during the winter: periods with warmer temperatures and heavy snowfall have a higher effective roughness, i.e. broader waveforms. These are also the

periods when we observe heightened radar freeboards over MYI. Remarkably, no concurrent changes in other waveform parameters or Ku-band backscatter are observed for MYI, though there is a temporary decrease in C-band SAR backscatter in the HV-polarization during the mid-March warming event and in the period leading up to melt onset. A drop in SAR HV-polarized backscatter indicates a decrease in volume scattering, and increased effective surface roughness indicates the waveform has broadened; both implying actual changes in the scattering processes on the surface. The fact that two independent sensors observe a change is a strong indicator that the temporary increases in radar freeboard over MYI are caused by changes in the scattering processes on the surface. For FYI we also see an increase in effective surface roughness in periods of higher temperatures and snowfall, but the increase is less pronounced and not of temporary nature (Fig. \ref{fig:RMS height time series}). The time series for FYI suggests very level and smooth ice. We see a first slight increase in effective roughness during the warming event in mid-March, when the newly-formed ice first gets snow-covered. In contrast to the radar freeboards that decrease again after the warming event, the increase in effective roughness remains, i.e. waveforms stay broadened. We observe a large, concurrent shift across all waveform parameters for FYI, and a decrease in nadir Ku-band and C-band SAR backscatter. Again, the fact that we see a simultaneous change in the C-band SAR backscatter indicates that the rise in FYI radar freeboards likely originates from a change in the scattering processes in the snow and ice.”

3. Study objectives

Around line 120, the word "test" still feels slightly strong. The manuscript provides valuable empirical support for previously proposed mechanisms under a relatively controlled fast-ice setting, and it helps build a more comprehensive hypothesis. However, because the mechanisms are not separated through controlled experiments, "test" may imply a stronger causal demonstration than the data provide. I suggest using a slightly softer term such as "evaluate", "examine", or "investigate".

We have adjusted the wording in this sentence.

4. Missing citation

Line 96 still contains "(?)", which appears to be an unresolved note or missing citation.

The citation has been fixed.