Point-by-Point Response to Reviewer 2 (RV2, RC C3024)

Summary

Ice shelf thickness is often derived from surface elevation data by assuming hydrostatic equilibrium for a given depth-averaged ice column density. Then basal melt rates and other quantities can be derived from repeat mappings of ice-shelf elevation and velocity. The accuracy of these methods suffers from the assumption of hydrostatic equilibrium and assumed densities.

In this paper, the authors aim to address the validity of these assumptions by mapping depth-density profiles of from ice-penetrating radar data. The authors develop a method to infer the vertical density profile of ice shelves from wide-angle radar data using an inverse technique that fits reflector travel times assuming that the depth-density profile has a simple functional form.
This new method is based on standard inverse techniques, but has not been applied to wide-angle radar data before in a glaciological setting. The authors develop of robust test of the method using both synthetic models and independent density profiles measured using optical televiewing of profiles on the same ice shelf.

I found this study well-developed and the paper is well written. Most of my comments are minor and can be addressed without significant reanalysis of the data. This paper is both interesting an important. As estimates of basal melt rates from surface elevation data becomes more common due to the proliferation of satellite techniques that can accurately map surface elevation, studies like this are needed to qualify the satellite-based estimates of basal melt. Many groups use radars similar to those of the author, so the techniques they describe could be employed by a variety of groups in a variety of glaciological settings.
Response: Thank you for your positive feedback, we have implemented many of your suggestion. Please find detailed answers to each point below.

Scientific Points

RV2-1: This study assumes a uniform snow density at the surface? How valid is this assumption?
Response: This point was equally raised by RV1. Please see response to RV1-2.

RV2-2: The reasons for spatial variability in firn densification are not that well developed. What factors might lead to denser snow in the channel? Is it just the drift accumulation that would be scoured off ridges and deposited in channels? Or are there strain feedbacks from this loading that also matter?
Response: This point was equally raised by RV1 (cf. Response RV1-2). We now provide a potential mechanisms which may explain increased density in ice-shelf channels in a more global sense (i.e., surface melt water which preferably collected in the channel's surface depression, cf. modified section 5.2). However, as mentioned by RV1, the dataset does actually not allow to unequivocally conclude that firn is denser in ice-shelf channels in general. We, therefore, refrain from speculating about more complicated mechanisms (such as strain feedbacks or re-crystallization) and put more emphasize on the methodology of inferring density from WARR data.

RV2-3: Although most of the profiles the authors present seem simple, channel basal topography is generally complex. What modifications of the method are feasible to allow it to be adapted to profiles conducted over areas of more complex ice-shelf bottom topography?
Response: Raytracing does not require horizontal reflectors and in principle it is possible to include dip angle of reflectors for the inversion. However, here we put an emphasize on inverting simultaneously for reflector depths/densification length and found that including the surface density as an additional parameter was difficult. Adding one dip-angle per reflector aggravates this problem. An iterative approach may be required to find one depth-density function for all reflectors while solving for the reflector-dips individually \citep[layer stripping, cf.][]{Brown2012}.

The changes are implemented in the revised section 5.1.

RV2-3: Data/Code Access

Do the authors plan to release their data (as an example) and/or code to the community? This could be beneficial to multiple groups who use similar radars. Does the Cryosphere have a similar data police to AGU journals?
Response: Yes good idea. A version of the code will be published on GitHub, and the link will be in the Acknowledgements. GitHub may be a good way to include, for example, the reflector dips.

Grammar/Style:

1) Some would object to using inverting as you do. You are inferring a quantity via an inversion, whereas inverting means taking x to 1/x. However, using inverting as you do as common practice, so I'm happy to leave the choice to the authors.
Response: Ok thanks for giving us the choice, and we will be more careful next time. Here, we will stick with the jargon of "inverting" which is often used in a geophysical context.

2)
Subordinate clauses and appositive phrases are often lacking proper punctuation. For example, several times commas are missing preceding subordinate clauses (e.g., "…, which…".
Response: Ok, we found some instances, and will look out for that during proof reading as well.

Specific Comments

5648

5: Densification can have a strong a strain-rate dependence too.
Response: Ok. Densification depends on a number of factors (e.g. also on impurity content), and we chose to mention only some examples in the abstract. Later on we take this point up.

6: Infer depth-averaged density? Or density over some depth interval?
Response: For hydrostatic inversion only the average density (averaged over the entire ice column) is needed. I hope "depth-averaged" is ok to describe that.

9-10: This sentence is awkward. Maybe something along the lines of "We reconstruct depth to internal reflectors, local ice thickness and depth-averaged density using a novel algorithm that includes traveltime inversion and raytracing with a prescribed shape of the depth-density relationship."
Response: Ok, this sounds better. Changed.

15: Is this consistent with theoretical calculations of firn densification?
Response: We don't know the principal mechanism which dominates the densification (cf. modified section 5.2), so it is difficult to compare to theoretical calculations.

17: Awkward wording. Maybe "…which reveals that the firn inside the channel is 10% denser than the surrounding firn outside the channel"?
Response: Ok, this sounds better. Changed.

18-19: Awkward wording. Maybe "Hydrostatic ice thickness calculations used for determining basal-melt rates should account for the denser firn in ice-shelf channels."?
Response: Ok, this sounds better. Changed.

19-21: One critical weakness I see is practical. Many radar systems do not permit wide-angle acquisition.
Response: Ok, some radars do not allow to separate receiver and transmitter, but actually a fair amount do, particularly systems with lower frequencies than 250 MHz.

5649

11-12: This is a more complex process than compaction as dynamic recrystallization may also occur affecting the density profile and that process depends on more than just overburden pressure (temperature and longitudinal and lateral strain are also important as are many other factors).
Response: I think you refer to line 4-6 rather than 11-12. We have mentioned temperature, surface mass balance, impurities as additional mechanisms for densification other than the overburden pressure. We added the recrystallization and strain dependence in that list.

5650

1-10: Spatial scale of measurements might be important to mention here. This isn't a point measurement but it is still spatially limited and there are issues of matching the raypath samples with that of the surface illuminated. So there must be an assumption of uniform density and flat reflectors over some area. Hopefully some of this is mentioned in the methods section to follow.
Response: Yes these assumptions are mentioned further down (p. 5654 l.8f). However, note that raytracing in principle can cope with non-uniform density and dipping reflectors.

18-19: Discuss that some studies say they are destabilizing and others say stabilizing? Evidence for the effect on ice-shelf stability is conflicting.
Response: Yes, this is why we did not pick a side and just said "influence". We included your point.

25: Not sure imprint is the right word here, maybe "impact"?
Response: Ok.

5652

2: Change "monotonous to monotonic"? Not sure what mathematical connotation is attached to monotonous.
Response: Ok.

2: Some would object to using inverting as you do. You are inferring a quantity via an inversion, whereas inverting means taking x to 1/x. However, using inverting as you do as common practice, so I'm happy to leave the choice to the authors.
Response: Ok, see above.

18-20: Might be worthwhile to note that triggering via this method would become unreliable due to missed air-wave arrivals at larger distance than you used (~ 1 km separation or more), which is an important consideration for surveys over thicker ice. Alternate triggering methods via fiber-optic cable or radio link should be considered.
Response: Ok, noted.

25: Why was it necessary to handpick internal reflectors? They look quite bright in your data and easily pickable. What power criteria was used to pick reflectors, if first break or change in concavity in the Ricker-like wavelet common for these types of radars, an autopicker seems likely to be more dependable than handpicks.
Response: Ok. Handpicking is not required, it was just convenient in the software environment that we used. Autopicking will work as well.

25-26: What was your rationale for choosing reflectors? How many and why?
Response: Some of the Sites showed more reflectors than others, but we wanted to use the same amount of reflectors in each dataset (to easily compare the different measurements). The sensitivity analysis makes it clear that you need to use more than two. Not all datasets allowed picking more than four reflectors.

26: Could the reflection at Site 6 be associated with a basal terrace?
Response: Maybe, but from my understanding there are usually multiple basal terraces. In that case I would expect a more diffuse response. An off-angle basal crevasse seems more likely.

5656

15-20: How do you select v(z) configurations?
Response: The shape of the v(z) configuration follows immediately from the prescribed density profile. If the initial guess for surface density and densification length are too much off-target, then the raytracing model cannot find a raypath for each shot.

5657

2: Change objection function to “objective” or “cost” function?
Response: Ok. “cost function” it is.

Eq 11: Shouldn’t the C matrices be inverses? #
Response: Yes, thanks.

5658

18: “inverstion” to “inversion”
Response: Ok, thanks.

5659

20: Any idea of how much A actually varies?
Response: Not really. See modified Section 5.2 and answers above.

5666

11-14: There is a discussion between local and shelf-wide hydrostatic assumptions. Locally, the hydrostatic assumption does not hold, but over a large scale the entire shelf is in hydrostatic equilibrium. This method would allow estimation of the appropriate spatial scales for the hydrostatic assumption, which would be a useful application worth mentioning.
Response: Ok, good idea. However, because the focus here is on density and not bridging stresses we have not included it here.

Figures

Figure 1: Perhaps just use gray color scale instead of red-green color scale. Or some other color scale, just to avoid colorblindness issues.
Response: Indeed, my color-blind co-author did not complain because he did not see colors at all! Changed.

Figure 2: Make dot on Antarctic inset a bit larger.
Response: ok.