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Interactive comment on "Recent accumulation rates of an alpine glacier derived from firn cores and repeated helicopter-borne GPR" *by* L. Sold et al.

Anonymous Referee #2

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The manuscript by Sold et al. submitted to the Cryosphere presents an approach to inversely relate radar signal reflections in an accumulation area of a glacier in the Swiss Alps to accumulation rates. To convert measured TWT values to SWE, they use a snow/ firn densification model together with a rather simple approach to account for meltwater redistribution. For validation and layer relation to summer surfaces, they use results from 2 firn cores drilled during the first radar campaign in 2012. While data on annual winter accumulation rates (point measurements) is available for this glacier, it is not presented in the manuscript. A comparison of these point measurements (and spatial extrapolation thereof) with results for the most recent accumulation derived from GPR data could support the main conclusion from this manuscript that

radar accumulation estimates have a much better spatial representation to assess the actual accumulation rates on glaciers. However, only a very small part of the recorded radar transects is discussed and presented in this manuscript

In terms of language, the manuscript is well written, however, a couple paragraphs should be thoroughly revised (see below). Shorter and less nested sentences facilitate following your statements.

The major point I come up with is that the presence of liquid water is disregarded in the manuscript even though it has a very strong impact on radar wave velocity even for very small volume fractions. I can see that this is beyond the scope of this paper but certainly needs to be discussed as you deal several times with it. I will explain my concerns more in detail:

To convert TWT in depth, you use Frolov and Macheret (1999) to determine layer respective bulk propagation velocities. Here, you use only a 2 phase mixing formula empirically determined for dry snow/ firn conditions. The firn temperature however is set to be constant at 0C. Additionally, you define that a cold content transmitted from the surface into deeper parts is compensated by meltwater refreezing. Actually, to refreeze liquid water you need to have temps below 0C to compensate for the release of latent heat. For your assumption of isothermal conditions within the firn pack, you must assume liquid water being present. At the same time, you use equations for the conversion of EM wave velocity to density which are only valid for dry conditions. These 2 assumptions are contradictory and it means that you expect the firn always being at a certain state where all liquid water is already refrozen and the cold content of the overlying snowpack/ firn layers hasn't yet reached the layer you are observing. In my opinion these assumptions have to be discussed more in detail. This point is very crucial for your assumptions since even small portions of remaining liquid water alter the wave speed significantly (e.g. Schmid et al., 2014).

In section 3.3 you state that no melting occurs in the accumulation area during the winter season. This statement is somehow useless unless you define winter season. And for several accumulation areas at Alpine glaciers you will find massive melt freeze crusts within the snowpack in late April early May. On page 4444 L.13-18 you describe weather conditions which usually produce melt-freeze layers at the snow surface. The 3rd point dealing with liquid water I am concerned with is that you do not account for lateral flow, mass loss through melt and percolation of liquid water from surface layers into previous accumulation layers. You just present a 9% density increase to "affected" layers. The whole Section 3.4 needs to be revised and clarified, which layers are affected by when and at which date! Additionally, I would expect that mass loss is discussed. This manuscript presents a similar approach than the one from van Pelt et al., 2014 here for an Alpine glacier instead of polar/ subpolar glaciers. Please discuss differences.

Some other major points that must be addressed:

A) the structure of the presented manuscript is not appropriate. There is no Result-Section. Eg Section 4.1 involves a large discussion part of the results of the chemical analysis of the firn core. I recommend changing the whole Section 4 to Results and Discussion and name 4.3 Data interpretation and error analysis instead of Discussion.

B) Neither you do present a number on the ice velocities of this glacier nor any reference dealing with this ("slow" is not appropriate here). However, you compare exactly ("intersections of radar transects") the same locations at the surface of 2 consecutive years. This is only possible when the ice velocity is 0m p.a. You need to discuss this, since your work is based on an Alpine glacier with a significant topography (Fig. 1).

C) Concerning the topography, for steep reliefs, your radar data processing scheme is not adequate. See http://www.sandmeier-geo.de/Reflex/refl2da.htm for parts where you do make significant errors for airborne radar data analysis if you lack a proper topography migration/ correction. It is impossible for the reader to identify in Fig. 1 with 100m contour lines whether such a correction is necessary or not. A minor point

concerning the processing routine but nevertheless essential for the presentation of good radar data is a proper surface correction. In Fig 2 bouncing surface signals are recognizable while zooming in. This can easily be corrected in ReflexW! Applying such a static correction enables further processing to remove noise and enhance continuous reflectors (running average filters etc.)

Minor points that should be addressed:

- the title indicates that this paper addresses mostly accumulation rates. Please modify to present the major part of this work which is the methodology. - please use SI units and indicate for whenever values have to be converted to fit models

- P4432 L3 this is not completely "new" - see van Pelt et al., 2014 - L10 IRH correspond to density max and/or liquid water occurrences. Changes in liquid water in snow can dominate any density gradients - see Schmid et al., 2014 - P4433 L24-26 this sentence is hardly understandable please rephrase! - P4434 L8 comment while taking melt into account for temperate glaciers. I don't think you can fully neglect residual liquid water in the firn pack. See major point above. - L20-27 I am missing the point here - P4435 L22 indicate in Fig 1 where the AWS are located or give distances in the manuscript. - P4437 L11-18 again, the glacier has to be stationary for this kind of analysis, you need to comment on this! - L23 (e.g. Kovacs...) - P4439 L5 you do have sufficient data to prove this is an appropriate assumption, right now it is just a number - L5ff this is kind of too fast here. Please present equations and detailed steps how you convert TWT to accumulation in w.e. - L14 what is "considerably lower" quantify! - P4440 L3 this is confusing I think you want to rephrase this sentence - L28ff next page; again the reader would benefit from a more detailed description and presentation of equations which you use e.g. what is the characteristic length scale, time scale etc? - P4441 L10 any citation that can support your assumption that $T_{ss}=T_A-4.9$ is always valid. I doubt this especially for melt conditions. - L13ff please rephrase to enhance readability - P4449 L16ff well you could present a plausibility check to prove that it is impossible that this layer does represent a former summer horizon. If you feed your model with this

IRH what is the accumulation output. Is it a reasonable value and corresponds more or less with manual measurements? This could be performed almost everywhere, where an AWS can be used to relate radar derived accumulation with precip measurements. I think presenting such a plausibility check may allow you to present the statement in the following lines. Otherwise, you do need firn cores and complex data analysis to relate IRH to summer surfaces. And this is not an efficient data acquisition!

Bibliography Schmid, L., Heilig, A., Mitterer, C., Schweizer, J., Maurer, H., Okorn, R., Eisen, O. (2014). Continuous snowpack monitoring using upward-looking ground-penetrating radar technology, Journal of Glaciology, Vol. 60, No. 221.

Interactive comment on The Cryosphere Discuss., 8, 4431, 2014.