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Interactive comment on "Two independent methods for mapping the grounding line of an outlet glacier – example from the Astrolabe Glacier, Terre Adélie, Antarctica" *by* E. Le Meur et al.

E. Le Meur et al.

lemeur@lgge.obs.ujf-grenoble.fr

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We here reconsider the main scientific comments of the 2 reviewers (in quotes) and reply to each of them and make reference to the changes done in the new version of the paper when necessary. The new figure 7 (now figure 8) is presented as it reveals the major changes effectuated on the hydrostatic grounding line mainly resulting from a smaller average density for the ice column. Also added is a new figure (fig.15) which explains one important aspect of the paper (the difference between kinematic and hydrostatic GL points)

************* Referee 1 ** *************

This manuscript of Le Meur et al. is about the mapping of the Astrolabe glacier grounding line (GL) using radar profiles and GPS data (static and dynamic methods respectively). Static groundings lines from imagery are available for this glacier but there are known issues associated with these datasets for outlet glaciers. Their study manages to better constrain the Astrolabe glacier grounding line position to 2-20 km downstream of the latest GL from Bindschadler et al. (2011) from discreet points 5-10 km apart. While the study goes in depth into both methodologies, it doesn't really produce any new method for detecting the grounding line except by combining the two different methods. The section on the normalized tidal displacement (d) from GPS profile is very interesting in that it shows how the hydrostatic equilibrium changes across the grounding zone and across a narrow outlet glacier section. Representing and looking at the grounding zone on a cross section is unusual and rather interesting as well.

-> general comment that does not call for any specific response.

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"There is however a major issue regarding the hydrostatic equilibrium assumption throughout the manuscript. Indeed this narrow outlet glacier is shown to be far from fully floating, yet their calculation assumes a fully floating criteria. This contradiction has to be resolved."

-> This is one of the major point of the paper. Ice/ocean interactions can be viewed at two differnt time scales.

On the longer term one (assuming there is no tides), the ice slab can be considered in a static state in equilibrium with the underneath ocean. In these conditions, under constant stress, the viscous part of the visco-elastic deformation takes over and the rigid bending effects are therefore significantly reduced, thereby giving credit to the hydrostatic method. We thus use a first grounding line determination based on on a floatation criterion, but keep in mind and state the associated uncertainties (neglection of the remaining rigid stresses, uncertanties on the inferred ice thicknesses and upper surlace heights) which led us to propose and overall uncertainty of 1 km in the positionning.

On top of this 'reference state' the ice is subject to a much shorter time-scale forcing form the ocean tides, whose amplitude remains relatively small with limited impacts on the hydrostatic grounding line position. At such a time-scale, the ice slabs responds more elastically with increased rigid forces that drive a regional flexing response. One of the main consequence is a deformation pattern that sprays further out the load imprint itself, but with reduced displacements compared to full floatation, even above the ocean. The mentioned partial floatations therefore mainly concern this tidal response which in theory leads to a migration of the contact point forth and back but which remains limited and does not really impact on an average grounding line position in between and for which the hydrostatic assumption remains valid within the associated uncertainty.

These aspects are now cleraly stated in the revised version of the paper including a new figure 3 which more clearly explains this duality on top of an extra figure (Fig. 15) illustrating the ensuing difference between hydrostatic and kinematic GL derived points

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"While the GPS measurements give good constraints for the grounding line position, the inaccuracy of the fully floating assumption is problematic. This doesn't mean that the radar data is not usable for grounding line detection but that a correction has to be applied, maybe with the floating ratio obtained by comparing tidal and GPS amplitude. At the very least, the uncertainty regarding the hydrostatic assumption has to be discussed and taken into account."

-> This is exactly what the paper does (at least in its revised version). A first GL guess is proposed (with associated uncertainties) from the hydrostatic assumption. Then kinematic measurements of the ice upper surface are proposed to separate mobile from immobile parts of the glacier. Because of the rigid tilting of the slab under the tidal cycle (not clearly enough stated in the first version) we show (figures 3 and 15) how the outermost line of surface deformation points can expand further out of the line of bedrock contact points. It potentially induces a difference between the hydrostatic GL and a kinematic one based on measuring these uplifted points. This is why we propose to model this rigid tidal behaviour to assess the resulting offset in order to check the consistency of the two approaches for determining the GL position. Ground measurements confirm this view with first detected uplifted points generally upstream of their hydrostatic counterparts, especially given the fact that a minimum displacement of 15 cm is required for the points to be detected, which places the theoretical line even further out. However, the model shows that under the conditions met over the proposed glacier, this ofset remains limited and once applied to our GPS points, it gives a grounding line compatible with the hydrostatic one within the estimated uncertainties.

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"Therefore the delineation of the grounding line should start with the GPS analysis. From the GPS transects and stationary stations, the West flank of the final grounding line should be placed inland of points 1 and 2, and of the second half of section AB (from points 3-4). GPS transect CD should be discarded, as noise seems as important as the actual signal."

-> Given the consistency between the 2 approaches, we don't really see the interest of starting with the kinematic method. We have reconsidered the required density value of the ice column in our hydrostatic grounding line positionning, which now makes points 1 and 2 floating and the new proposed GL passing just downstream of point 3 (see new figure). We thus explain how point 3 is the illustration of these kinematically detected points still in contact with the bedrock or only partly lifted only during high tidal phases.

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************* Referee 2 ** *************

"The manuscript reviews methods for determining the grounding line, and provides field data from the Astrolabe glacier and ice tongue that aim to re-map the grounding line in an adjusted location relative to past determinations. The paper seems to work very hard to shrink the extent of floating ice on Astrolabe, and it is unclear to me why that is. High densities of the ice column are used. Large areas of very nearly floating ice are excluded "

-> An enlargement of possible ice densities (notably towards lower values) led us to propose a larger extent for the floating zone of the glacier (see new figure). As a consequence, areas previously considered as grounded are now included within the grounding line, especially on the west flank of the glacier

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"airborne radar is not shown in profile"

-> A corresponding figure has been added for that.

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"damped tidal signals are considered grounded ice (Figures 11-13)."

-> With the new proposed GL, points 1 and 2 are now effectively floating. Only point 3 and 4 which exhibit respectively very small an no tidal signal remain just upstream of the GL. We believe they belong to the specific outer fringe which can still undergo small displacement but does not lift from the ground (or if so, only partially during the high tidal phases). As a consequence, they therefore lie slightly out of the hydrostatic GL as we define it.

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"Fundamentally, this is a rather thick glacier (500 - 800 m) in a rather narrow fjord (3 to 5 km). Strong effects from the ice flexure, dampening the tidal signal, are to be

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expected. Moreover, a complex thin water layer beneath much of the lower Astrolabe, with isolated and perhaps partial pinning points, would be expected to strongly modify the tidal signal timing and flexural amplitude."

-> The strong effects from the ice flexure are considered, but essentially through the short-term tidal response and no so much from the long-term average interaction of the ice with the underneath ocean (see comments before). The possibility for pining points within the GL has been considered in the new version. The water loading pattern is taken into account... and its impact on the ice response computed. But we rather operate the other way round, from the specificity of the tidal signal (mostly the amplitude) we try to infer the loading pattern, that is in our present case, the respectively grounded and floating parts and the possibility for pinning points or ice plains.

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"A firn correction to density is not considered or discussed (perhaps I missed it?)."

-> Most of the areas concerned by our measurements and computations are only slightly (if not) concerned by the firn. The possible presence of firn was actually mentioned in the first version. We make it clearer in the new one. We especially show that, by being mostly in an ablation zone, firn usually only concerns the uppermost parts of the profiles and is suspected to be responsible for a gradient in the average ice column density along some of the profiles.

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"The airborne WISE profiles are not shown."

-> They are included in the old figure 8 (in map view). Moreover, an airborne radargram is now shown in the new version of the paper.

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"The MOA-based grounding line for Astrolabe Glacier has been significantly revised since the publication of 2007, using a second MOA mosaic assembled in 2010. This is available from NSIDC. See attached. The new line is similar to the Bindschadler et al 2011 ASAID line."

-> That is right, we were so far using an old version which was going far too far inland. We retrieved the new one which we added in the new version, and indeed, it is much more compatible with that of Bindschadler. However, our final grounding line (though extended), still remains more seaward of these 2 space-borne ones, especially over the bottom of the fjord and over the west flank of the glacier.

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"While it looks like perhaps the western margin of the Astrolabe embayment should be adjusted slightly inward relative to past determinations, there is a lot of complication and subjective selection of interpretation paths in the publication as it stands. While it is a good exercise in several different means of using field data and modeling ice flexure and response, the final result lacks confidence."

-> The new proposed GL now adopts a simpler form and particularly lacks the previous curving part that was initially making GPS points 1 and 2 grouned. The new text makes it clearer the consistency between the hydrostatic and kinematic GL and therefore makes us believe that we end up with a more reliable GL

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"It seems clear to me that the kinematic GPS points 1,2,3,and 4 show evidence of floatation."

-> As said before, points 1 and 2 are actually floating. Point 3 is in between but excluded from our hydrostatuically derived floating area. No tidal signal is decently detectable at point 4

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Caption of the new version of fig. 7 (now fig. 8) : Hydrostatically determined transitions

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between grounded (blue) and floating (red) ice along all radar profiles performed over the coastal part of the Astrolabe Glacier as a function of the chosen value for ice density. Assuming the central value of 880 kg.m$-$3 for the ice density and giving more credit to the ground radar profiles when conflicting with airborne ones (see text), a grounding line position is proposed under the form of the yellow line. The green ar- row points towards the radar profile intersection where a large discrepancy in ice thickness is observable. Y1 and Y2 denote both ends of the radar profile of Fig. 7. Question marks indi- cate places of possible partial grounding (pinning points). The white and brown lines are the grounding lines as proposed by Bindschadler et al. (2011) and Scambos et al. (2007). ————————————————-

Caption of the new figure 15 :

Hydrostatically-balanced ice slab in the low-tide position onto which is then applied a water push (featured as the red arrows) leading to the high tide configuration (dashed lines). GL and GH respectively denote the low and high-tide grounding lines with G the average position here placed in the middle and corresponding to our hydrostatic position. F is the landward limit of tidal upper displacements and X a seaward point where the uplift becomes significant enough to overcome the noise threshold of the chosen kinematic method. Top red arrows represent the FG and FX distances. Of importance is to notice that the part of the slab situated between points F and G can possibly undergo surface movements whereas still in contact with the bedrock as the result of the tidal bending moment of the ice slab.

Interactive comment on The Cryosphere Discuss., 7, 3969, 2013.

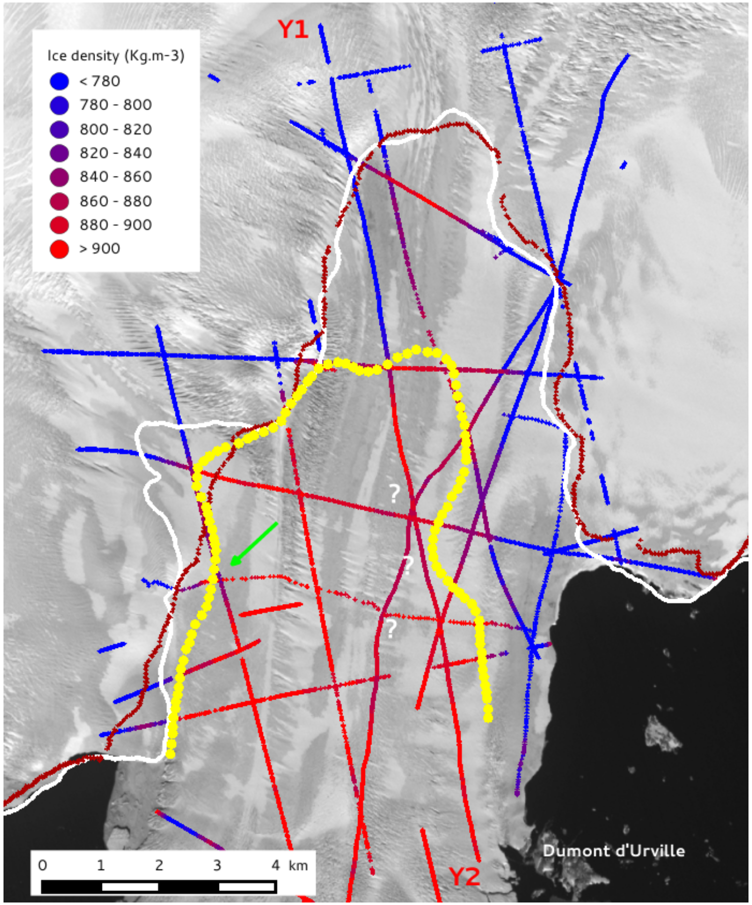
Ice density (Kg.m-3)
< 780
780 - 800
800 - 820
820 - 840
840 - 860
860 - 880
880 - 900
> 900
Y1
Y2
Dumont d'Urville
0 1 2 3 4 km

Fig. 1.

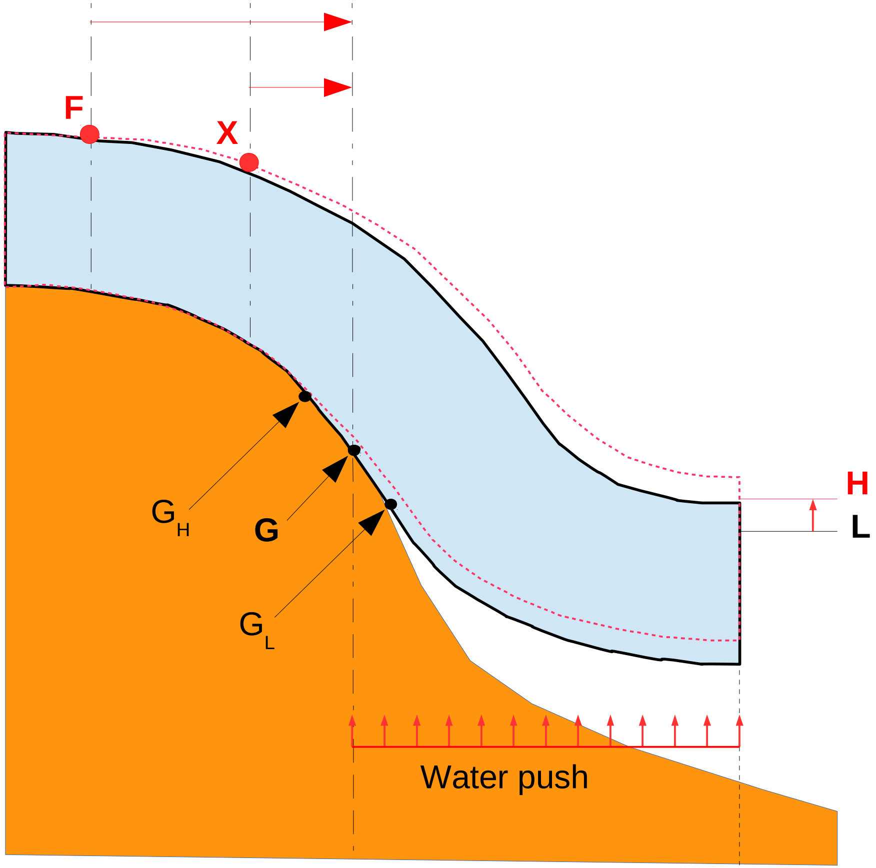

Fig. 2.

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