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Interactive comment on "Use of an ultra-long-range terrestrial laser scanner to monitor the mass balance of very small glaciers in the Swiss Alps" *by* M. Fischer et al.

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- Title: I wonder if the use of "ultra-long-range" is relatively standard, as it seems to me a bit "excessive". May be that using very long range is enough, or at least the text should inform that is a distance that has been very little used in previous research. As the work deal more in validating the measurements rather than explaining the dynamics of the glacier, may be better to include some reference to the validation itself or the comparison to direct glaciological method (just a suggestion)

We now replaced "ultra-long-range" with "long-range" everywhere in the manuscript, including the title.

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Discussion paper

According to the reviewer's comments, we changed the title of our manuscript to "Application and validation of long-range terrestrial laser scanning to monitor the mass balance of very small glaciers in the Swiss Alps". To keep the title short, we did not directly include that validation is done against dense in-situ measurements/direct glaciological mass balances.

- Introduction. In page 2 line 4 when the importance of studying small glaciers is mentioned, it can be also stated that this is the very likely evolution of many current mid-size glaciers in areas like the Alps, and it is better to properly understand the dynamics of small glaciers when they are indeed very deteriorated

Now implemented accordingly with a new sentence.

"It is likely that currently medium-sized or even large glaciers become very small glaciers due to disintegration and substantial area loss over the next decades in areas like the European Alps (Zemp et al., 2006). A better understanding of their dynamics and sensitivity to climate change is thus important (Huss and Fischer, 2016)."

- Study site: Page 5, line 9. "....were comparatively moderate during" The use of "moderate" is rather ambiguous, I would state that area losses were less than...or similar. In some part of the manuscript, probably here, a brief description of climate characteristics of the analyzed glaciers (and main differences if exits) and mentioning how was the climate during the two analyzed years compared to long-term climate (last decades) in the Swiss Alps would help to better interpret the presented data on mass balance.

We now implemented the first point as suggested

"Observed area losses were smaller than for the other studied glaciers during past decades (Tab. 1)."

Concerning the reviewer's second point, we agree that data about the climate characteristics and variability of the study sites would help to better interpret the presented mass balance data (comparable to, for instance, López-Moreno et al., The Cryosphere

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2016). However, we argue that such analyses go beyond the scope this study, which aims at validating TLS-derived annual geodetic mass balances of very small alpine glaciers with direct glaciological mass balances from dense in-situ measurements. We now refer to a new study by Huss and Fischer (2016, Frontiers in Eartch Science) in the revised version of the manuscript which is about the sensitivity of all very small glaciers in Switzerland to climate change. Further, we now also refer to the 2014 and 2015 annual climate bulletins of MeteoSwiss, which, if desired, will help the reader to better link the resulting measured mass balances as well as their regional and interannual variability to the prevailing atmospheric conditions during the observation periods 2013/14-2014/15.

- Data and methods: Page 6 line 31: -Which is the consequence of range ambiguity? A slightly expanded explanation (or a reference) might be useful.

Now a slightly expanded explanation as well as a corresponding reference are given.

“In order to avoid range ambiguity and associated possible uncertainty due to several laser pulses simultaneously in the air (Rieger and Ullrich, 2012), the pulse repetition frequency was always set to 30 kHz.”

- Page 7. Even if supplementary material inform of the characteristics of the point clouds, I would mention here some numbers about the most usual (or minimum) density of points acquired for this study. - What is an octree filter?

Now implemented accordingly.

“This enhanced the ground resolution of target reflections (point density) to an important extent. For all scans, average point density was 30 m-2 (range 1 to 95 points m-2)(Supplementary Tab. 1).”

An octree filter segments the point cloud into cubes of selected length x, width y, and height z, reducing the data within each cube to a single point. We now complemented this sentence with an exemplary reference.

“An octree filter (e.g., Perroy et al., 2010) was applied to the registered scans to remove noise and generate point clouds with equal numbers of reflections per area”

-Page 9, line 5: Some reference to support the used densities for ice, annual and multi-annual firn?

Done.

“Corresponding densities of 900 kg m-3 for ice ice, 550 kg m-3 for annual firn af , and 700 kg m-3 for multi-annual firn mf (e.g., Cuffey and Paterson, 2010) applied to calculate a glacier-wide volume-to-mass change conversion factor. . .”

- Page9, line 20, again, although this is presented as supplementary material some numbers on the density of snow depth measurements may be better than just saying "...with a sufficient spatial coverage..."

Here, we do not refer to winter snow accumulation measurements, but to snow probings performed if there was a significant amount of fresh snow at the time of the annual LiDAR survey in autumn (as mentioned in the text). – Autumnal fresh snow covers are, from our experience, usually spatially much more homogeneous than end-of-winter snow accumulation patterns, so a smaller density compared to the winter surveys was enough. We now refer to the recorded mean density (as a number of measurements per square kilometer) of autumnal snow probings on the respective glaciers.

“Snow probings on the glaciers with a complete spatial coverage and a mean density of about 400 measurements km-2 were performed on the same days as the LiDAR surveys, and recorded snow depth values inter- and extrapolated to the entire glacier surfaces.”

- Uncertainty assessment: Page 10 lines 22-24. Even if ground is stable, small instabilities may occur between the tips of the tripod and the bare rock, of if the ensemble of the tripod, or the tripod with the TLS is not properly ensured.

We fully agree. – That’s why we wrote “Provided that the RieglVZ-6000 used here

operated reliably and ground motion was prohibited while scanning, . . .". So our formulation already implies that for instance small instabilities between the tips of the tripod and the bare rock may occur!

- Where comes from that uncertainties of volume change for ice is set to +/- 20 kg m-3?

This is just a conservative estimate for a range in ice density for small mountain glaciers (see e.g., Cuffey and Paterson, 2010). Now clarified.

". . .(estimated by +/- 20 kg m-3 here). . ."

- Page 15, line 9. I do not fully understand the procedure (rerunning the mass...) used here. - I think that authors made their best to produce robust numbers on the uncertainty of the used methodology. They provide a very useful approach that may be replicated in future research. However, my feeling is the computation of each component of the uncertainty is based in equations and assumptions that are uncertain themselves. In this way, I think that in discussion (SECTION 6) .it should be remarked the difficulties to give exact numbers of uncertainty, that may vary spatially and also along the time, and at the end (at least in my opinion) an overall qualitative estimation that accumulated errors in the different methodological steps are much lower than observed changes in the elevation surface of the ice, is the most important, and it can be demonstrated when TLS estimations are directly compared with the changes in each ablation stake (Figure 5), or observing the annual changes in elevation surface over stable terrain (Figure 3).

Now clarified.

"It is assessed by rerunning the mass balance model by Huss et al. (2009) used for calculating glacier-wide mass balance (cf. section 3.2.2) by closely constraining it with the seasonal field data for each site and observation period but sets of melt parameters that differ from the calibrated ones by predefined ranges similar to those chosen by Kronenberg et al. (2016)."

We now remind the reader of this important issue in the discussion (section 6).

“Even though we consider our approach to quantify both σ_B_TLS and σ_B_direct as robust and promote its application to similar studies in the future, we want to remind the reader that it’s generally difficult to give exact numbers of such uncertainties, and that each component of σ_B_TLS and σ_B_direct is based on assumptions that are, to some extent, uncertain themselves. By its nature, the stochastic uncertainty in the glacier-wide TLS-derived geodetic mass balance σ_B_TLS is much lower than the potential error in the observed surface elevation changes for single pixels, as estimated for instance from the comparison of DoDs over stable terrain (Fig. 3).”

References: It is cited a paper of our team that at the time of writing this paper was in TC discussion, and now is definitively published on TC., perhaps is better to change the citation: López-Moreno, J. I., Revuelto, J., Rico, I., Chueca-Cía, J., Julián, A., Serreta, A., Serrano, E., Vicente-Serrano, S. M., Azorin-Molina, C., Alonso-González, E., and García-Ruiz, J. M.: Thinning of the Monte Perdido Glacier in the Spanish Pyrenees since 1981, The Cryosphere, 10, 681-694, doi:10.5194/tc-10-681-2016, 2016.

We now refer to the revised TC (2016) version of the corresponding study by López-Moreno et al. Thanks.

Tables and figures: Table 1: I think it would be interesting to add the mean and maximum scanning distances for each glacier.

We think that this would be a bit misplaced in Table 1. Nevertheless, the reader already has this information, as mean and maximum scanning distances related to the study glaciers’ extents are already nicely visible on Figure 1.

Figure 1: Is it possible to provide pictures of the glaciers (1-5) just from the scanning positions? (It could ello saving Figure 2).

Actually, all pictures (1-5) in Figure 1 were taken just from the respective scanning positions. This is also mentioned in the figure caption (“Red numbers correspond to

individual photographs of the study glaciers which were taken from the respective scan positions"). We'd rather keep Figure 2 to show the scan setting and installation of the tripod/scanner on stable ground, as this is also referred to in the methods part of our manuscript.

Table 3. Probably there is space to write in the header what is each column, instead of using the symbols that needs a very long caption

No, there actually isn't, sorry. We are aware of the rather long table caption but argue that it remains clearer and better understandable for the reader to keep Table 3's caption and heading as in the TCD version of our manuscript.

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