

## ***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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Received and published: 2 May 2016

- Page 1, line 3: the sentence starting Since. . . does not read well.

Now rephrased.

“Investigating their mass balance, e.g. using the direct glaciological method, is a prerequisite to fill this knowledge gap. Since most recently, terrestrial laser scanning (TLS) techniques operating in the near infrared range have been successfully applied for the creation of repeated high-resolution digital elevation models and consecutive derivation of annual geodetic mass balances of very small glaciers.”

- Page 1, line 4: are->have been. He sentence

Done.

- Page 1, line 9: and->for

We argue it's clearer not to change this (otherwise erroneous).

- Page 1, line 12: remove carefully

Done.

- Page 1, line 13: remove remarkably

Done.

- Page 1, line 15: remove very

Done.

- Page 1, line 22: remove always

Replaced with “so far” instead.

- Page 1, lines 21-22: on hence belong to the size class of very small glaciers (Huss, 2010). Text would flow better by defining small glaciers. Explain what is used in the literature and explain your definition. In this paper we define small glaciers as... (reference). Could refer to that there are different definitions, eg another paper in the cryosphere Bahr and Radic (2012) uses 1 km<sup>2</sup> etc. The mass balance glossary does not define very small glaciers, but define Glacieret as 'A very small glacier, typically less than 0.25 km<sup>2</sup> in extent, with no marked flow pattern visible at the surface' (Cogley et al, 2011)'

Indeed, there are many different definitions of “very small glaciers” used if arbitrary area thresholds are used to classify individual glaciers as “very small glaciers”. For upper thresholds, Bahr and Radic (2012) define 1.0 km<sup>2</sup>, Huss (2010) 0.5 km<sup>2</sup>, DeBeer and Sharp (2009) 0.4 km<sup>2</sup>, Cogley et al., (2011) 0.25 km<sup>2</sup>, Colucci and Guglielmin (2015) 0.1 km<sup>2</sup>. ... Discussing these thresholds is beyond the scope here but will be included

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in ongoing work which is not published yet. Nevertheless, we changed the wording in the abstract, introduction and conclusion in order to be clearer.

“Due to the relative lack of empirical field data, the response of very small glaciers (here defined as being smaller than 0.5 km<sup>2</sup>) to current atmospheric warming is not fully understood yet.”

“Around 80% of the number of glaciers in the European Alps (Fischer et al., 2014; Gardent et al., 2014; Fischer et al., 2015; Smiraglia et al., 2015), and in mid- to low-latitude mountain ranges in general (Pfeffer et al., 2014), are smaller than 0.5 km<sup>2</sup> and hence belong to the size class of very small glaciers according to the definition by Huss (2010).”

“Despite their global predominance in absolute number, empirical field data on very small glaciers, here defined as being smaller than 0.5 km<sup>2</sup>, are currently sparse.”

- Page 2, lines 4-5: since most->in

Done.

- Page 2, line 19: This seems like a conclusion, but next sentence it is said that it is highly promising, rewrite.

Now slightly rephrased.

“Even though the initial costs of the scanner and software license are high, terrestrial laser scanning (TLS) techniques are generally easier and more cost-efficiently applied to individual sites and on the annual to seasonal timescale compared to ALS techniques (Heritage and Large, 2009). As often nearly the entire surface of very small glaciers is visible from on single location (e.g., from a frontal moraine, an accessible mountain crest or summit, or from the opposite valley side), TLS is particularly appropriate to generate high-resolution DEMs, as well as to derive annual geodetic mass balances of very small glaciers. Thus, laborious and time-consuming in-situ measurements could be circumvented, and the spatial inter- and extrapolation of point measure-

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ments over the entire glacier surface avoided, which is known as an important source of uncertainty in direct glaciological mass balances (e.g., Zemp et al., 2015).”

- Page 2, line 25: Add e.g. before Zemp, as several authors have pointed this out, also earlier refs.

Done.

- Page 3, line 7: It is, however, . . . . . -> Validation is needed to assess the quality. . . . Note that in order is redundant, can replace throughout the paper or at least in most places

Now implemented accordingly.

“ . . validation of these emerging new methods through comparison to in-situ measurements has so far been pending. It is, however, needed to assess the quality and applicability of close-range high-resolution remote sensing techniques for glacier mass balance monitoring (Tolle et al., 2015).”

- Page 3, line 13: remove very

Done.

- Page 3, line 15: remove or reformulate last sentence

Now removed.

- Page 4, fig. 1: could add box around (d). I prefer a legend instead of having the explanation of crosses and triangles etc. in the figure text. It is room for it in fig a above d. If text is kept, then Red numbers->Numbers 1-5 Red triangles->Triangles.

We now added a box around (d). We'd rather keep the text instead of introducing a legend as we think it's clearer this way.

- Page 5, lines 3-4: Just start with 'To better understand. . .' (remove words before)

Done.

- Page 5, line 5: since a couple of years is vague

Now clarified.

“...the studied glaciers have been subject to detailed scientific research since 2006 (Pizolgletscher), 2012 (Glacier du Sex Rouge, St. Annafirn), and 2013 (Glacier de Pra-pio, Schwarzbachfirn), and a comprehensive set of empirical field data is now available for these sites.”

- Page 5, line 6: delete ‘for these previously unmeasured sites’: later you talk about area and volume studies

Done.

- Page 5, line 21: Retreated back to one third->lost 2/3 of its area

We did not want to always write the same formulations for area changes of the individual study glaciers. The wording reviewer #3 suggests here is already used for other sites. Therefore, we’d rather keep this as it is.

- Page 5, line 24: According to first insights: Rather state when measurements began.

This becomes clear in section 3.2.1 below. – In addition, the first subset (“According to first insights from. . .”) is now removed.

- Page 5, line 27: glaciers. Mean in general or this glacier, clarify by writing ‘of this glacier’ if so.

Now clarified.

“Huss (2010) pointed to the remarkable small scale variability in accumulation and melt processes, to the importance of snow redistribution and the influence of albedo feedback mechanisms on the mass balance of this very small glacier.”

- Page 6, line 21: But you do field work on some of these glaciers, would it not be interesting to compare with dGPS measurements?

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Good comment, could be done in the future, but we unfortunately did not have the data basis needed to do this in our study. dGPS measurements only exist for one of the five studied glaciers (Glacier du Sex Rouge), and comparison to TLS data is unfortunately not possible as only horizontal ice surface velocity but not vertical surface elevation changes were measured with dGPS.

- Page 7, line 1: unclear what is meant by ‘this’ and ‘to an important extent’, be specific

We erroneously wrote “increase” the vertical and horizontal angle increments instead of “decrease”. Now changed accordingly. ‘This’ refers just to the precedent sentence, i.e. to “decrease the vertical and horizontal angle increments, i.e. increase the measurement time, by one order of magnitude”. ‘to an important exten’ refers to the respective values in Supplementary Tab. 1. To clarify, we added a “cf.” there (→“(cf. Supplementary Tab. 1)”).

- Page 7, lines 6-7: add commas after interest and after dust

Done.

- Page 7, line 11: What does manual course registration mean? Could remove course?

It’s “coarse” registration and not “course”, “manual coarse registration” is a standard procedure in TLS data processing (see e.g. Deems et al., 2015, Cold Regions Science and Technology).

- Page 7, line 19: could add reference as for RISCAN PRO, which edition was used?

We argue that no reference is needed here, but we now refer to the edition (10.1) used.

- Page 8, Table 2: What is the source, add manual reference.

“RIEGL Laser Measurement Systems: Preliminary Data Sheet, 07.05.2013; RIEGL VZ-6000 - 3D Ultra long range terrestrial laser scanner with online waveform processing, RIEGL Laser Measurement Systems, Horn, Austria, 2013.” Now added accordingly.

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- Page 8, line 4: Is three and four significant digits in the percentages justified? Would round it.

Now rounded to two and three significant digits.

- Page 8, lines 8-9: neither nor, ->assumes constancy of the density profile

We argue that our initial formulation is clearer here.

- Page 9, line 1: could add that in the past other values have also been used, typically 900 kg/m<sup>3</sup>

This is already implemented with what we write just before “Three basic approaches exist to convert geodetic volume to mass changes (e.g., Huss, 2013): (1) Application of a density of volume change of 900 kg m<sup>-3</sup> based on Sorge’s law (Bader, 1954); (2)..”

- Page 9, line 2: Based on the numerous... here->Based on information collected in field (supplementary Tab. 2), approach (3) was applied here.

Implemented accordingly.

“Based on information collected during field surveys (Supplementary Tab. 2), approach (3) was applied here.”

- Page 9, line 12: Please add some more details on how zones were mapped prior to the 2013 surveys. Does this yield all 5 sites as one of them not measured and some began in 2012 and 2013 according to section 3.2.1?

Done and yes.

“Due to field observations and repeated oblique and aerial orthoimagery, the spatio-temporal evolution of the firn thicknesses and extents during and prior to the measured years 2013–2015 could be assessed, and firn compaction assumed to be negligible as a result.”

- Page 9, line 14: Be specific on the displacement, e.g. <xx m/a

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Now implemented accordingly.

“Ice dynamics were likely negligible for the study glaciers as measured surface displacement rates were smaller than the resolution of the LiDAR DEMs (orders of magnitude 10-1 m yr<sup>-1</sup> vs. 100 m) and...”

- Page 9, line 27: The information on the startup of the programmes could have been added in section 2.

Now we refer to section 3.2.1 in section 2 (see response above).

- Page 9, line 28: Mostly->Usually

Done.

- Page 10, line 14: Could add short details on the stations with reference to the data (e.g. MeteoSwiss?) Use ‘and’ or ‘or’ not ‘and/or’. Do you mean that you use their results or their methodology, a bit unclear.

In our opinion, there is no need to give more details on the weather stations which refer to our meteo data used (beyond the scope here). All weather stations are indeed included in the MeteoSwiss network. We therefore now refer to MeteoSwiss in the text. ‘and/or’ is now replaced by ‘or’ only.

“... as well as daily air temperature and precipitation data from nearby MeteoSwiss weather stations. A detailed description of the methodology is given in Huss et al. (2009) or Sold et al. (2016).”

- These results would be interesting to compare with the spatial pattern found from the annual/biannual geodetic surveys, has this been compared?

Yes. Please refer to section 5.2 and Fig. 4 vs. Supplementary Fig. 1.

- Page 11, Table 3: Text. Divide sentence, is very long and hard to read.

Table caption is now shortened.

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“Limits of detection for the TLS-derived surface elevation changes ( $\sigma_{\text{MSA}}$ ) and number of points used for the Multi-Station Adjustment fine registration of consecutive point clouds ( $n$ ) for both observation periods and the surveyed Glacier de Prapio (PRA), Glacier du Sex Rouge (SER), St. Annafirn (STA), Schwarzbachfirn (SWZ) and Pizol-gletscher (PZL). In addition, the mean ( $\mu$ ), median ( $\sim x$ ), standard deviation ( $\sigma$ ) and interquartile range (iqr) of elevation differences from the comparison of TLS-derived annual surface elevation changes over stable terrain (all in m) are given.”

- Page 12, are not snow patches masked out?

Snow patches adjacent to the glaciers were, of course, not used for registration of two consecutive LiDAR point clouds. Nevertheless, they appear afterwards on the DEMs of Difference (as for instance on Fig. 3a which we refer to here).

- Page 15, line 22: can remove ‘very small’

Done.

- Page 15, line 24: Give results first, before interpreting them for better flow

Implemented accordingly.

“Measured mass losses were remarkably stronger for the second time period ( $-1.65$  m w.e. in 2014/15 averaged for the four glaciers measured with both methods compared to  $-0.59$  m w.e. in 2013/14), which agrees well with the different prevailing atmospheric conditions (especially in summer) recorded during the observed years (MeteoSwiss, 2015, 2016).”

- Page 15, line 25: why not give estimate for geodetic for all five?

Because we could not validate the TLS-derived geodetic mass balance for Glacier de Prapio and explicitly refer to the glaciers “measured with both methods” here.

- Page 20, line 7: This can be explained by the higher point density and more complete coverage than for most other glaciers (...)

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Implemented accordingly.

“This can be explained by the higher density and more complete coverage of winter and summer point measurements for our study glaciers than for most other glaciers (Supplementary Tab. 2; WGMS, 2013).”

- Page 20, line 10: Remove With comparatively low uncertainty

Done.

“Their very small surface area and the absence or minor fractions of very steep and/or heavily crevassed zones are, of course, optimal preconditions to accurately measure direct glaciological mass balances.”

- Page 20, lines 11-12: May remove this inserted clause, which we use. . . , for better flow

Done.

“Hence, the quality of both the geodetic mass balances derived by repeated terrestrial LiDAR surveys and the direct glaciological mass balances extrapolated from dense in-situ measurements is very good.”

- Page 20, line 14: Be specific on what you recommend here, specify your methodological approach

We now rephrased the sentence into a more general statement.

“ . . .we recommend the application of terrestrial laser scanning for future mass balance monitoring of very small Alpine glaciers.”

- Page 20, line 20: Simplify by starting: Significant amounts of fresh snow or remaining firn on the glacier results is more error-prone. . . .

Done.

“Significant amounts of fresh snow or firn on the glacier results in more error-prone

conversions of TLS-derived volume to mass changes, even more if no additional in-situ measurements of their area fraction and density are performed..”

- Page 20, line 24: over the last years, which years?

Changed accordingly.

“On the other hand, from field evidence we know that along with the recorded atmospheric conditions (especially in summer) and the continuously negative mass balance context in the Swiss Alps over the last decade (Supplementary Tab. 3; Huss et al., 2015), the studied very small glaciers hardly exhibit significant ratios of annual to perennial snow and firn anymore.”

- Page 20, line 25: Delete applying our approach

Done.

- Page 20, line 28: Instead of ‘Following’... Start sentence ‘A disadvantage of using the TLS is the...’ And refer to reference in parentheses.

Now implemented accordingly.

“Disadvantages of using the long-range TLS system and our approach to derive annual surface elevation and geodetic mass changes of very small Alpine glaciers are the high costs for the purchase of the device itself and licenses for the data analysis software provided by the manufacturer, as well as the complex and time-consuming post-processing of the LiDAR data. The required level of expertise and experience with TLS data acquisition and processing is likely higher than for direct glaciological mass balance monitoring (see e.g., Raveland et al., 2014).”

- Page 21, line 2: ...very small glaciers, here defined as (<0.5 km<sup>2</sup>)...

Implemented accordingly.

“Despite their global predominance in absolute number, empirical field data on very

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small glaciers, here defined as being smaller than 0.5 km<sup>2</sup>, are currently sparse.”

- Page 21, lines 13,23: very dense -> dense

Done.

- Page 21, lines 28-32: Unclear sentences and ending, be specific

Implemented accordingly.

“Our results show that, under some restrictions, the TLS-based monitoring approach presented in this paper yields accurate results and is therefore suitable for repeated mass balance measurements of very small Alpine glaciers. The most important shortcomings of our approach are related to the abundance of snow and firn at the time of the TLS surveys. They are insignificant in a highly negative mass balance context, as observed for instance for most of our field sites over precedent years. Under these circumstances, laborious, time-consuming, and potentially dangerous field measurements may be circumvented and the uncertain spatial inter- and extrapolation of point measurements over the whole glacier surface avoided.”

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Interactive comment on The Cryosphere Discuss., doi:10.5194/tc-2016-46, 2016.

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