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Discussions

Interactive comment on "Combination of UAV and terrestrial photogrammetry to assess rapid glacier evolution and conditions of glacier hazards" *by* Davide Fugazza et al.

Davide Fugazza et al.

davide.fugazza@unimi.it

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We have prepared a point by point response to the reviewer's comments. In the following text, reviewer's comments are reported as RC, our answers as AC.

RC REVIEW OF THE MANUSCRIPT ENTITLED: Combination of UAV and terrestrial photogrammetry to assess rapid glacier evolution and conditions of glacier hazards By D. Fugazza et al. General comments In this paper, Fugazza et al. present the results of photogrammetric surveys carried out on the lower ablation area of the Forni Glacier in 2014 and 2016. The surveys were performed using photographs taken from the ground and from unmanned aerial vehicles, and their results have been used for inter-

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comparisons aimed at evaluating the accuracy of used techniques, for quantification of glacier changes across 9 years, and for the identification of hazards deriving from the current rapid shrinking of the glacier. The work is interesting and potentially useful as a baseline for future developments of these remote sensing techniques. However, there are several points of the paper that require formal and substantial improvements. In particular: i) there are several claims of uniqueness, originality, lack of previous work and of scientific knowledge, which are untrue and deserve a careful literature review by the authors. Consequently, the results are not unique, and have to be critically assessed in light of previous findings by other authors ii) pros and cons of the tested methods require a thorough discussion, as well as their repeatability (e.g. the peculiar cloud cover conditions) and generalizability, costs, logistics and alternative solutions. A very weak point that requires discussion, in my opinion, is the limited areal extent of the surveyed zone, preventing possible applications aimed, for example, at the estimation of the glacier-wide geodetic mass balance. In addition, such a large glacier normally has several other hazardous areas along mountaineers' tracks, which cannot be comprehensively surveyed using the proposed approach. Which improvements (or alternative methods) would be required? The paper is rather long and contains many descriptive sentences, too generic periods, scholastic explanations. In particular the Results section is difficult to read and wordy. My suggestion is to really focus on the results of the investigations, strongly shortening this part, and moving any (relevant) consideration in the Discussion section. A careful English proof reading is also required to improve the readability and to make the manuscript appealing. The authors should also consider reducing the self-citations, which currently contribute to one third of the reference list. In my opinion, the manuscript requires a major revision before being considered for publication in NHESS. A more complete description of the required formal and substantial improvements is reported in the following section.

AC Dear Reviewer, thank you for your comments. We have rewritten the introduction section reconsidering research gaps and aims of our work in view of the wider literature. We have also rewritten the discussion section entirely, comparing our results with findings from previous studies and discussing advantages and disadvantages of the techniques used in this study, including the small size of the area investigated. We have greatly shortened the manuscript, with particular attention to the results section, by summarizing key points, and moving considerations to the discussion section. We have carefully proofread the manuscript to improve its clarity and appeal and reduced self-citations and the number of citations in general. The answers to your major and minor comments are provided below.

RC Detailed comments

RC Line 30 Page 1: snow cover thickness and/or duration?

AC We have deleted this sentence to shorten the introduction section.

RC Line 39 Page 2: changes of glacier and. . .

AC We have deleted this sentence to shorten the introduction section.

RC Line 40 Page 2: anthropic activities

AC We have deleted this sentence to shorten the introduction section.

RC Lines 39-63 Pages 2-3: some of the mentioned processes are not strictly depending or worsened by climate variations. They are instead typical of the glacial, periglacial and paraglacial environments. I suggest rewriting this part to clarify which processes are typical and which ones are worsened by the current climatic phase. I also suggest mentioning debris flows

AC: We have rewritten the introduction section which now has a sharper focus on glacier hazards, distinguishing between those typical of glacial environments and those that are worsened by climate variations. We also mentioned debris flows following your suggestion. The paragraph now reads: “Glacier and permafrost-related hazards can be a serious threat to humans and infrastructure in high mountain regions (Carey et al., 2014). The most catastrophic cryospheric hazards are generally related to the

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outburst of water, either through breaching of moraine- or ice-dammed lakes or from the englacial or subglacial system, causing floods and debris flows. Ice avalanches from hanging glaciers can also have serious consequences for downstream populations (Vincent et al., 2015), as well as debris flows caused by the mobilization of accumulated loose sediment on steep slopes (Kaab et al., 2005a). Less severe hazards, but still particularly threatening for mountaineers are the detachment of seracs (Riccardi et al., 2010) or the collapse of ice cavities (Gagliardini et al., 2011; Azzoni et al., submitted). While these processes are in part typical of glacial and periglacial environments, there is evidence that climate change is increasing the likelihood of specific hazards (Kaab et al., 2005a). In the European Alps, accelerated formation and growth of proglacial moraine-dammed lakes has been reported in Switzerland, amongst concern of possible overtopping of moraine dams provoked by ice avalanches (Gobiet et al., 2014). Ice avalanches themselves can be more frequent as basal sliding is enhanced by the abundance of meltwater in warmer summers (Clague, 2013). Glacier and permafrost retreat, which have been reported in all sectors of the Alps (Smiraglia et al., 2015; Fischer et al., 2014; Gardent et al, 2014; Harris et al., 2009), are a major cause of slope instabilities which can result in debris flows, by debuttressing rock and debris flanks and promoting the exposure of unconsolidated and ice-cored sediments (Keiler et al., 2010; Chiarle et al., 2007). Glacier downwasting is also increasing the occurrence of structural collapses and while not directly threatening human lives, sustained negative glacier mass balance can also cause shortages of water for industrial, agricultural and domestic use and energy production, negatively affecting even populations living away from glaciers. Finally, glacier retreat and the increase in glacier hazards negatively impacts on the tourism sector and the economic prosperity of high mountain regions (Palomo, 2017)."

RC Line 68 Page 3: please add some references concerning glacier change detection using DEMs

AC: We have added “Fischer et al. (2015); Berthier et al. (2016)” accordingly.

RC Line 72 Page 3: remove indeed

AC: We have deleted this sentence to shorten the introduction section.

RC Line 92 Page 4: please replace battery support with e.g. battery life or charge duration

AC: We have deleted this sentence to shorten the introduction section.

RC: Line 110 Page 5: must be completely observable from. . ..

AC: We have deleted this sentence to shorten the introduction section.

RC: Lines 114-118 Page 5: previous work reporting comparison between photogrammetry and LiDAR or more traditional survey techniques on glaciers actually exists. Please, see for example Kaufmann and Ladstädter (2008), Piermattei et al., (2015 and 2016), Kaufmann and Seier (2016), Westoby et al., (2016), Seier et al., (2017), and contributions in the book from Pellikka and Gareth Rees (2010). Kaufmann, V. and Seier, G., 2016. LONG-TERM MONITORING OF GLACIER CHANGE AT GÖSSNITZKEES (AUSTRIA) USING TERRESTRIAL PHOTOGRAMMETRY. International Archives of the Photogrammetry, Remote Sensing & Spatial Information Sciences, 41. Kaufmann, V. and Ladstädter, R., 2008. Application of terrestrial photogrammetry for glacier monitoring in Alpine environments. Ele, 2700(2800), p.2900. Petri Pellikka, W. Gareth Rees. Remote Sensing of Glaciers, Taylor & Francis Group, London, UK (2010) Seier, G., Kellerer-Pirklbauer, A., Wecht, M., Hirschmann, S., Kaufmann, V., Lieb, G.K. and Sulzer, W., 2017. UAS-Based Change Detection of the Glacial and Proglacial Transition Zone at Pasterze Glacier, Austria. Remote Sensing, 9(6), p.549. Westoby, M.J., Dunning, S.A., Hein, A.S., Marrero, S.M. and Sugden, D.E., 2016. Interannual surface evolution of an Antarctic blue-ice moraine using multi-temporal DEMs. Earth Surface Dynamics, 4(2), p.515.

AC: Thank you for the interesting list of articles which we had overlooked. We have rewritten this paragraph, mentioning studies conducted with terrestrial and UAV photogrammetry in high mountain glacial environments. The paragraph now reads: “Recent years have seen a resurgence of terrestrial photogrammetric surveys for the generation of DEMs (Piermattei et al., 2015; Kaufmann and Seier, 2016) due to important technological advancements including the development of Structure-from-Motion (SfM) Photogrammetry and its implementation in fully automatic processing software, as well as the improvements in the quality of camera sensors (Westoby et al., 2012). In parallel, unmanned aerial vehicles (UAVs – Colomina & Molina, 2014, O’Connor et al., 2017) have started to emerge as a viable alternative to TLS for multi-temporal monitoring of small areas. UAVs promise to bridge the gap between field observations, notoriously difficult on glaciers, and coarser resolution satellite data (Bhardwaj et al., 2016a). Although the number of studies employing them in high mountain environments is slowly increasing (see e.g. Fugazza et al., 2015; Gindraux et al., 2016; Seier et al, 2017), their full potential for monitoring of glaciers and particularly glacier hazards has still to be explored. In particular, the advantages of UAV and terrestrial SfM-Photogrammetry, and the possibility of data fusion to support hazard management strategies in glacial environments needs to be investigated and assessed.”.

RC Line 119 Page 5: protected in which sense?

AC: Forni Glacier lies in Stelvio National Park, which is a protected area under the Italian law. We have added “(Stelvio National Park)” to clarify this point.

RC Line 121 Page 5: two distinct aircrafts

AC: The words within parentheses have been deleted as suggested by the other reviewer.

RC: Line 124 Page 5: please provide a length for short and long time scales

AC: We have rewritten this sentence as “investigating ice thickness changes between 2014-2016 and 2007-2016 by comparing the two UAV DEMs and a third DEM obtained from stereo-processing of aerial photos captured in 2007.” to clarify the length of scales involved.

RC: Lines 125-126 Page 5: please try to improve this sentence, which is too long

AC: We have rewritten this sentence as: “identifying glacier-related hazards and their evolution between 2014-2016 using the merged point cloud from UAV and terrestrial photogrammetry and UAV orthophotos”. The description of glacier hazards mapped in this study was moved at the start of the paragraph.

RC Line 129 Page 6: confluencing ice tongues?

AC: This part has been deleted as suggested by reviewer 2.

RC Line 134 Page 6: retreating rate? Shrinking rate?

AC: The papers describe an acceleration in the shrinking rate. We have changed the sentence accordingly.

RC Lines 135-136 Page 6: AWS1 Forni was not the first. There is at least one precedent, i.e. the AWS that has been operated on the Careser Glacier (10 km from Forni) from 1989 to 1998 (Rossi and Stojkovich, 1992; Novo and Rossi, 1998). Rossi G. C. and Stojkovic, P. (1992) Scientific programmes for meteo-climatic and environmental observations in Alpine glacial areas. Presented at First Ev-K2-CNR Scientific Conf. on Scientific and Technological Research at High Altitude and Cold Regions. Milano, 10–11 April 1992. Novo, A. and Rossi, G.C., 1998. A four-year record (1990–94) of snow chemistry at two glacier fields in the Italian Alps (Careser, 3090m; Colle Vincent, 4086m). Atmospheric Environment, 32(23), pp.4061-4073.

AC: The sentences concerning the AWS have been deleted as not strictly relevant to this study.

RC: Lines 142-155 Page 6: I suggest shortening these points and possibly moving some of the concepts and references in the discussion section (if relevant). In section 1.2 all references are self-references. I wonder how much they are functional to this work.

AC: We have deleted the sentences about recent glacier changes, the AWS (see previous comment) and previous research on the site (and related references), deleted bullet points and merged their content with the previous sentence, as suggested by reviewer 2. The paragraph now reads: “The Forni Glacier (see Fig. 1) has an area of 11.34 km2 based on the 2007 data from the Italian Glacier Inventory (Smiraglia et al., 2015), an altitudinal range between 2501 and 3673 m a.s.l. and a North-North-Westerly aspect. The glacier retreated markedly since the little ice age (LIA), when its area was 17.80 km2 (Diolaiuti & Smiraglia, 2010), with an acceleration of the shrinking rate in the last three decades, typical of valley glaciers in the Alps (Diolaiuti et al, 2012, D’Agata et al; 2014). It has also undergone profound changes in dynamics in recent years, including the loss of ice flow from the eastern accumulation basin towards its tongue and the evidence of collapsing areas on the eastern tongue (Azzoni et al., submitted). One such area, hosting a large ring fault (see Fig. 2d) prompted an investigation carried out with Ground Penetrating Radar (GPR) in October 2015, but little evidence of a meltwater pocket was found under the ice surface (Fioletti et al., 2016). Since then, a new ring fault appeared on the central tongue, and the terminus underwent substantial collapse (see Fig. 2a,b,c,e). Continuous monitoring of these hazards is important as the site is highly touristic (Garavaglia et al., 2012), owing to its location in Stelvio Park, one of Italy’s major protected areas, and its inclusion in the list of geosites of Lombardy region (see Diolaiuti and Smiraglia, 2010). The glacier is in fact frequently visited during both summer and winter months. During the summer, hikers heading to Mount San Matteo take the trail along the central tongue, accessing the glacier through the left flank of the collapsing glacier terminus. During wintertime, ski-mountaineers instead access the glacier from the eastern side, crossing the medial moraine and potentially collapsed areas there (see Fig. 1). ”

RC Line 159 Page 7: the meaning of reconstructing is not fully clear, I suggest writing explicitly that it is a topographic survey (also in the following)

AC: We have revised in the paper the use of the term “reconstruction,” changing or integrating this word to make it clear we mean the generation of a faithful digital 3D model of the object. The term “topographic survey” is generally used when geodetic methods are applied, so we preferred to use of “3D surface reconstruction”, “3D modelling” or “point cloud acquisition.”

RC Lines 169-171 Page 7: it is not clear why morning hours should be preferable to the central hours of the day. Please state it clearly.

AC: The explanation is provided in the description of the 2014 survey, which has now been moved to the top of the data section as suggested by you and the other reviewer.

RC Lines 171-173 Page 7: it is not clear how low cloud cover inhibits direct solar radiation, it should be the contrary. Moreover, what to the authors mean with low cloud cover? Which fraction of the sky covered? By which type of clouds? And why should the direct solar radiation be avoided? How often can these ideal meteorological conditions be met in the alpine environment during summer? Which is the impact of ice ablation during the three-day survey period? Is there any measurement? In my opinion this information is of relevance for future applications and repeatability of the proposed survey techniques.

AC: The reason why direct solar radiation should be avoided is that it can lead to image saturation on highly reflective surfaces such as ice or snow, as explained in the paragraph describing the 2014 survey. On both surveys in 2016, the weather was too unstable in the morning (i.e. chance of rain). When we actually undertook the surveys, the sky was overcast, i.e. 8/8 of the sky were covered by stratocumulus clouds. We thus found that these peculiar cloud cover conditions are suitable for UAV flights, while also common in Alpine environments during the summer. We have rephrased this sentence as “both around midday with 8/8 of the sky covered by stratocumulus clouds” and further discuss meteorological conditions in the discussion section where we have added a paragraph that reads:”We conducted UAV surveys under different meteorological scenarios, and obtained adequate results with early-morning operations with 0/8 cloud cover and midday flights with 8/8 cloud cover. Both scenarios can provide diffuse light conditions allowing to collect pictures suitable for photogrammetric processing, but camera settings need to be carefully adjusted beforehand (O'Connor et al., 2017). If early morning flights are not feasible in the study area for logistical reasons or when surveying east-exposed glaciers, the latter scenario should be considered.". As concerns the impact of ice ablation, measurements from ablation stakes collected in summers 2009-2010 (Senese et al., 2012) and 2015 (unpublished data) indicate values of 3-5 cm day-1. Additionally, Ice flow ranges between 1 and 4 cm day-1 (Urbini et al., 2017). This mostly affected the photogrammetric reconstruction of the UAV dataset from 2016 as surveys were performed two days apart and the last one 3 days since GCP placement, and the comparison between the UAV point cloud and other techniques. Measurements of the vertical displacement of stakes taken with GNSS in 2006 also show similar values ranging between 2.8 and 4.6 cm day-1 (unpublished data). We can thus hypothesize a combined effect on the uncertainty of UAV photogrammetric reconstruction between 10 and 20 cm, and lower on GCPs as they were placed on boulders where ablation is reduced. have added a paragraph in the discussion section that reads: "In this study, the uncertainty of the 2016 UAV dataset (40.5 cm RMSE on GCPs and 21.1-37.7 cm RMSE when compared against TLS) was slightly higher than previously reported in high mountain glacial environments (Immerzeel et al., 2014; Gindraux et al, 2017; Seier et al., 2017). Contributing factors might include the sub-optimal distribution and density of GCPs (Gindraux et al., 2017), the delay between the UAV surveys as well as between UAV and other surveys and the lack of coincidence between GCP placement and the UAV flights. This means the UAV photogrammetric reconstruction was affected by ice ablation and glacier flow, which on Forni Glacier range between 3-5 cm day-1 (Senese et al., 2012) and 1-4 cm day-1, respectively (Urbini et al., 2017). We thus expect a combined 3-day uncertainty on the 2016 UAV dataset between 10 and 20 cm, and lower on GCPs considering reduced ablation owing to their placement on boulders. A further contribution to the error budget of GCPs might stem from the intrinsic precision of GNSS/theodolite measurements and image resolution. The comparison between close-range photogrammetry, and TLS, being only one day apart, was less affected by glacier change and the RMSE of 6-10.6 cm is in line with previous findings by Kaufmann and Landstaedter (2008). To improve the accuracy of UAV photogrammetric blocks, a better distribution of GCPs or switching to an RTK system should be considered, while close-range photogrammetry could benefit from measuring a part of the photo-stations as proposed in Forlani et al. (2014), instead of placing GCPs on the glacier surface.".

RC Line 177 Page 8: potentially causing motion blur to the acquired imagery

AC: This sentence was shortened as suggested by Reviewer 2.

RC Line 179 Page 8: at a relatively low altitude of 50 m

AC: By "Relative" in this sentence we meant "relative to ground". We have rephrased the sentence to clarify this point, from "with flights at low relative altitude of 50 m" to "with a flying altitude of 50 m above ground"

RC Line 216 Page 9: please consider replacing coordinate frame with coordinate system (also in the following)

AC: We have replaced the word frame with system accordingly throughout the manuscript.

RC: Line 218 Page 10: same days of the UAV survey?

AC: We have specified the exact dates when the surveys took place. We discuss potential issues due to ice ablation between surveys in the discussion section, as described in the answer to your comment at lines 171-173.

RC Line 225 Page 10: consider replacing pipeline with workflow

AC: We have replaced this word accordingly.

RC Line 245 Page 11: evolves rapidly, or is rapidly evolving

AC: This sentence was deleted as it was connected to the following one, see next comment.

RC Line 246 Page 11: it is unclear why a complex shape and a rapid evolution make the glacier terminus not suitable for quantitative evaluation of the ice bulk? What do the authors mean with this sentence?

AC: We have removed this sentence as it lacked clarity and was unnecessary for the reader.

RC Line 249 Page 11: including GCP surveying

AC: We have modified the manuscript accordingly. The sentence was moved to the Discussion section as suggested by Reviewer 2.

RC: Line 251 Page 11: same days of the UAV survey?

AC: The TLS survey was conducted on the same day as the first UAV survey. We have added "On the same days as the first UAV survey of 2016," at the start of the paragraph to clarify this point.

RC Line 268 Page 11: remove the purpose of

AC: We have modified the manuscript accordingly

RC Line 274 Page 12: how much stable has to be considered a GCP placed at the glacier surface, close to the terminus and for more than one day during the ablation season? Please discuss this issue

AC: All GCPs at the terminus were actually located on large boulders, whereas only one GCP at the highest site on the central part of the tongue was placed directly on the glacier surface. Large boulders are known to shield the underlying ice from ablation, often leading to the formation of glacier tables. Thus, the effect of ice ablation on

GCPs is reduced. We have added a paragraph concerning this issue in the discussion section, see the answer to your comment at lines 171-173.

RC: Lines 284-285 Page 12: with which consequences? Fewer than planned surveyed GCPs? Why not using post-processing correction?

AC: Two of the points had to be collected and post-processed in fast-static mode due to the loss of radio connection. This effect could have not been planned in advance. We have added: “Non-RTK points were processed in fast-static mode, requiring a longer measurement time of approx. 12 minutes. ”

RC Line 287 Page 13: in my opinion it should be better arranging the methods in chronological order

AC: The paragraph about the 2014 survey was moved to the top of the data section, in accordance with your comment and the other reviewer’s. We have followed the other reviewer’s suggestion as to the order of the data section, leaving the 2007 aerial photogrammetric data at the bottom as it is the only dataset we did not collect ourselves and we believe it should be separated from the others.

RC Lines 294-301 Page 13: here is the explanation why early morning is preferable. Another reason for moving this part above the 2016 survey, according to me. What about cast shadows? Are they a further reason to avoid direct solar radiation and/or surveys carried out later in the day, with the possible occurrence of shadows from scattered cumulus clouds? What is the repeatability of this method if applied to east-exposed glaciers?

AC: We did not experience cast shadows from cumulus clouds during the 2016 survey. Based on our experience with UAVs, it is generally possible to adjust camera settings (ISO, aperture and shutter speed) before each flight to account for different light conditions, and produce pictures that are suitable for photogrammetric processing (see also O’Connor et al., 2017), although cast shadows will decrease the image dynamic range

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and might complicate the matching process owing to the lack of contrast. As a rule of thumb, early morning flights with 0/8 cloud cover might generate the best images for photogrammetric processing, but are not always possible due to logistical constraints and meteorological conditions. As you also mention, it might not be possible to obtain these conditions when monitoring east-exposed glaciers. However, we also demonstrate how UAV flights with overcast conditions under stratocumulus clouds produce suitable images. We have added a paragraph where we discuss issues related to meteorological conditions in the discussion section, as described in the answer to your comment at lines 171-173.

RC Lines 332-340 Page 15: this part has some repetitions from previous paragraphs. Please rephrase

AC: This part was deleted to avoid repetitions.

RC Line 358 Page 16: what about spatial trends in elevation differences? Are they inexistent, negligible or not taken into account?

AC: We did not take into account spatial trends in elevation differences but when calculating the uncertainty of volume changes, we assumed the uncertainty of elevation differences as totally correlated in space. This is unlike other approaches where errors in elevation differences are assumed as random and the final uncertainty of volume change is smaller (Fischer et al., 2015). Thus, our estimates of volume change uncertainty represent a worst-case scenario.

Fischer, M.; Huss, M. and Hoelzle, M (2015). Surface elevation and mass changes of all Swiss glaciers 1980–2010, The Cryosphere, 9, 525-540

RC Lines 361-390 Page 16: this part is too long and does not present results

AC: This part has been condensed as follows: “The analysis of point clouds generated during the 2016 campaign had the aim of assessing their geometric quality before their application for the analysis of hazards. These evaluations were also expected to provide some guidelines for the organization of future investigations in the field at the Forni Glacier and in other Alpine sites. ” and moved to subsection 4.1 in the methods section.

RC Lines 391-409 Page 17: why not using the entire overlapping area? The area surveyed by terrestrial photogrammetry is already small, therefore I do not understand why the authors decided to perform a (subjective) sub-sampling taking very small areas, which on the other hand are very similar to each other. I suggest comparing the entire area in common among the different surveys, and then analyse separately glacier areas with peculiar characteristics

AC: We have considered this suggestion. However, there are some independent registration errors in the data sets from UAV photogr., terrestrial photogr. and TLS. While these errors do not have any influence when analysing the point density and completeness, they do when computing the distances between point clouds. Therefore, we preferred to perform this analysis in individual sample locations, so that the errors due to registration could be compensated by a local refinement of the co-registration between point clouds. We have therefore rewritten the paragraph about the comparison between point clouds as: “Finally, we compared the point clouds in a pairwise manner within the same sample locations. Since no available benchmarking data set (e.g. accurate static GNSS data) was concurrently collected during the 2016 campaign, the TLS point cloud was used as a reference, as it less influenced by controlling factors (network geometry, object texture, lighting conditions). When comparing both photogrammetric data sets, the one obtained from UAV was used as reference because of the even distribution of point density within the sample locations. The presence of residual, non-homogenous geo-referencing errors in the data sets required a specific fine registration of each individual sample location, which was conducted in CloudCompare using the ICP algorithm (Pomerleau et al., 2016). Then, point clouds in corresponding sample areas were compared using the M3C2 algorithm implemented in CloudCompare (Lague et al., 2013). This solution allowed us to get rid of registration

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errors from the analysis, which could then be focused on the capability of the adopted techniques to reconstruct the local geometric surface of the glacier in an accurate way." and moved it to the methods section.

RC Lines 410-411 Page 18: please avoid describing in the text what figures and table present (their caption already does it)

AC: This sentence has been removed accordingly.

RC Lines 414-415 Page 18: a more dense point cloud? The term consistent has a too general meaning (and here is misleading)

AC: We have modified the manuscript accordingly.

RC Lines 415-417 Page 18: the flexibility of terrestrial photogrammetry, compared to UAV photogrammetry, is questionable

AC: We have modified the sentence as follows: "Considering point density, terrestrial photogrammetry resulted in a denser data set than the other techniques. This is mostly motivated by the possibility to acquire data from several stations with this methodology, only depending on the terrain accessibility, reducing the effect of occlusions with a consequently more complete 3D modelling. ". The sentence was also moved to the discussion section.

RC Lines 419-432 Pages 18-19: please summarize this part and avoid too scholastic sentence such as the first. I suggest simply stating which metrics are used and which results they provided.

AC: This part has been shortened as follows: "Specifically, we analysed point density (points/m2) and completeness, i.e. % of area in the ray view angle. Point density partly depends upon the adopted surveying technique, since it is controlled by the distance between sensor and surface and the obtainable spatial resolution. In SfM-Photogrammetry, the latter property is affected by dense matching, while in TLS it can be set up as data acquisition input parameter. In this study, the number of neighbours

N (inside a sphere of radius R=1 meter) divided by the neighbourhood surface was used to evaluate the local point density D in CloudCompare (www.cloudcompare.org). To understand the effect of point density dispersion (Teunissen, 2009), the inferior 12.5 percentile of the standard deviation of point density was also calculated. The use of these local metrics allowed to distinguish between point density in different areas, since this may largely change from one portion of surface to another. A further metric in this sense was point cloud completeness, referring to the presence of enough points to completely describe a portion of surface. In this study, the visual inspection of selected sample locations was used to identify occlusions and areas with lower point density."

RC Lines 437-443 Page 19: here the authors skip to the concept of point cloud completeness, introducing a heuristic evaluation method that is not fully described. Afterwards, they resume with point density. My suggestion is to rearrange paragraphs in a more logical order

AC: This paragraph has been reorganized by introducing first point density and then point completeness. Visual inspection of the sample locations was used to identify areas of occlusions or with lower point density. We now specify this in the text as: "A further metric in this sense was point cloud completeness, referring to the presence of enough points to completely describe a portion of surface. In this study, the visual inspection of selected sample locations was used to identify occlusions and areas with lower point density."

RC Line 445 Page 20: please remove the sentence: The following general considerations can be made (and other analogous sentences in the manuscript).

AC: We have removed this and similar sentences throughout the manuscript.

RC Line 448 Page 20: comparable or three times smaller?

AC: We have modified these sentence as follows since Table 5 already displays the results: "Terrestrial photogrammetry featured the highest point density, while UAV photogrammetry had the lowest.”.

RC Lines 454-455 Page 20: this is expected and confirmation of findings from previous works. Please add references

AC: We have reorganized this part of the text, which has been moved in the Discussion Section. This sentence has been modified as follows: “Since any techniques may perform better when the surface to survey is approximately orthogonal to the sensor looking direction, terrestrial photogrammetry is more efficient for reconstructing vertical and subvertical cliffs (Sample areas 1 and 2) and high-sloped surfaces (Sample areas 3 and 4). On the contrary, airborne UAV photogrammetry provided the best results in location 5 which is less inclined and consequently could be well depicted in vertical photos. In general, point clouds from terrestrial photogrammetry provide a better description of the vertical and subvertical parts (see e.g. Winkler et al., 2012), while point clouds obtained from UAV photogrammetry are more suitable to describe the horizontal or sub-horizontal surfaces on the glacier tongue and periglacial area (Seier et al., 2017), unless the camera is tilted to an off-nadir viewpoint (Dewez et al., 2016; Aicardi et al., 2016). ”

RC Lines 455-458 Page 20: which are the practical consequences? Which method for which application? Please discuss in the appropriate section

AC: These sentences have been moved in the Discussion Section, where the optimal type of terrain per each method is described. The main practical consequence is that to have an exhaustive 3D model of the whole surface topography, both point clouds from terrestrial and UAV photogrammetry should to be merged. We have thus added a sentence in the Discussion section, which describes our practical suggestions and reads: “While our integrated approach using a multicopter and terrestrial photogrammetry should be preferred to investigate small individual ice bodies, fixed-wing UAVs, ideally equipped with an RTK system and ability to tilt the camera off-nadir, might be the platform of choice to cover large distances (see e.g. Ryan et al., 2017), potentially reducing the number of flights and solving issues with GCP placement. ”

RC Line 469 Page 21: this is another highly-expected result. However this is a very small area, compared to the entire tongue (or the entire glacier). Further considerations are required, e.g. in the discussion.

AC: This part was condensed as suggested by Reviewer 2, as: “The analysis of point density shows significant differences between the three techniques for point cloud generation (see Table 2). Values range from 103 to 2297 points/m2 depending on the surveying method, but the density was generally sufficient for the reconstruction of the different surfaces shown in Fig. 5, except for location 5. Terrestrial photogrammetry featured the high point density, while UAV photogrammetry had the lowest. ”. We have added further considerations in the Discussion section as follows: “In our pilot study, we covered part of the Forni glacier tongue, and only investigated hazards related to the glacier collapse. Our maps can help identify safer paths where mountaineers and skiers can visit the glacier and reach the most important summits. However, the increase in collapse structures owing to climate change requires multi-temporal monitoring. A comprehensive risk assessment should also cover the entire glacier, to investigate the probability of serac detachment and provide an estimate of the glacier mass balance with the geodetic method. ”

RC Line 477 Page 21: similar point densities were found

AC: We have modified the manuscript accordingly.

RC Line 484 Page 21: the former are more suitable. . ..

AC: We have rephrased this sentence as described in the answer to your comment at lines 454-455

RC Line 486 Page 21: please see comment L445. These sentences make the paper boring and difficult to read

AC: We have modified the manuscript as follows: “ In relation to TLS, a mean value of point density ranging from 141-391 points/m2 was found, with the only exception of location 5, where no sufficient data were recorded due to the position of this region with respect to the instrumental standpoint."

RC Lines 491-492 Page 22: the suitability of a survey technique depends largely on the final aims of the survey. LiDAR DEMs obtained with point densities as low as 2 pt/m2 are enough for glacier-wide and/or regional scale glacier change assessments, for example. Please comment on that in the discussion

AC: These lines belong to a part that has been cancelled to shorten the manuscript. We discuss the suitability of the techniques employed in our study in the discussion section. While it is outside the scope of this manuscript to present a comprehensive comparison of aerial LiDAR vs UAV for natural hazard management and glaciological purposes, UAVs have already been used to cover distances up to 280 km2, e.g. by Ryan et al. (2017). We thus believe they could eventually replace this technique for the purposes mentioned in the study. We have added a paragraph in the Discussion section that reads: "In our pilot study, we covered part of the Forni glacier tongue, and only investigated hazards related to the glacier collapse. Our maps can help identify safer paths where mountaineers and skiers can visit the glacier and reach the most important summits. However, the increase in collapse structures owing to climate change requires multi-temporal monitoring. A comprehensive risk assessment should also cover the entire glacier, to investigate the probability of serac detachment and provide an estimate of the glacier mass balance with the geodetic method. While our integrated approach using a multicopter and terrestrial photogrammetry should be preferred to investigate small individual ice bodies, fixed-wing UAVs, ideally equipped with an RTK system and ability to tilt the camera off-nadir, might be the platform of choice to cover large distances (see e.g. Ryan et al., 2017), potentially reducing the number of flights and solving issues with GCP placement. Such platforms could help collect sufficient data for hazard management strategies up to the basin scale in Stelvio National Park and other sectors of the Italian Alps, eventually replacing aerial LiDAR surveys. Cost analyses (Matese et al., 2015) should also be performed to evaluate the benefits of improved spatial resolution and DEM accuracy of UAVs compared to aerial and satellite surveys and choose the best approach for individual cases."

RC Line 493 Page 22: please see comment L410

AC: We have modified the manuscript as follows: "The analysis of the completeness of surface reconstruction also revealed some issues related to the adopted techniques (see Fig. 6). Specifically, TLS suffered from severe occlusions which prevented acquisition of data in the central part of the sample area, while UAV photogrammetry was able to reconstruct the upper portion of the sample area but not the vertical cliff. Only terrestrial photogrammetry acquired a large number of points in all areas."

RC Line 496 Page 22: please replace here and elsewhere "exposed upward" with horizontal, or sub-horizontal, or moderately sloping (maybe adding slope thresholds for improved understanding).

AC: The term has been modified accordingly throughout the manuscript.

RC Line 516 Page 23: the sections 3.1 and 3.1.1 are very long and can be highly summarized, presenting just the results and moving further considerations in the discussion section.

AC: We have shortened these sections. Relevant considerations have been moved to the Discussion Section following your comments.

RC Lines 518-523 Page 23: I suggest removing or strongly summarizing this part

AC: These lines were deleted to shorten the manuscript.

RC Line 523 Page 23: do the authors have ablation measurements (or estimates) during the survey period? What is the impact of glacier ablation in calculations?

AC: We have added a paragraph concerning this issue in the Discussion section, as described in your comment to lines 171-173.

RC Line 540 Page 24: retained or based on some metrics/methodological constraints?

AC: The accuracy of TLS is less influenced by controlling factors (network geometry, object texture, lighting conditions) than the accuracy of photogrammetry. For this reason we have decided to adopt TLS point clouds as benchmarks. We have thus added:"Since no available benchmarking data set (e.g. accurate static GNSS data) was concurrently collected during the 2016 campaign, the TLS point cloud was used as a reference, as it less influenced by controlling factors (network geometry, object texture, lighting conditions). "

RC Line 576 Page 25: ΔDEM could be replaced by the more commonly-used dem of difference (DOD)

AC: We have replaced the term accordingly throughout the manuscript

RC Lines 575-579 Page 25: this part is poorly written and hardly readable/understandable. Please reformulate

AC: We have deleted this part as suggested by Reviewer 2.

RC Lines 579-581 Page 25: this part is obvious and redundant

AC: We have removed this sentence accordingly.

RC Line 593 Page 26: please complete numbers with minus sign and measurement units

AC: We have modified the manuscript accordingly. We use minus signs when we use the term "changes" but no sign when we use the term "thinning" and related since thinning already implies a loss. We have added measurement units wherever needed.

RC Line 594 Page 26: the eastern part of the ablation tongue

AC: We have rephrased as "the eastern section of the glacier tongue"

RC Lines 603-610 Pages 26-27: I am not fully convinced that the paper deserves section 3.3. My suggestion is to remove it and move concepts above, when the authors write about the complementarity of the two survey techniques.

AC: Merging of the two datasets required a fine coregistration which was important to mention. We have therefore moved Subsection 3.3 to the methods section and provided more information on the merging procedure, as suggested by Reviewer 2.

RC Lines 613-622 Page 27: the authors try to validate their geodetic mass balance estimates in the lower glacier tongue, using specific mass balance estimations at the surface, for one point (whose location is not reported). Their approach is not correct, because they are comparing single-point vs. mean areal estimates, which can be highly different in the study area given the high lateral gradients in mass balance and elevation changes (Fig. 11), likely attributable to debris cover and differential ablation. Moreover, local geodetic and glaciological mass balance estimates seldom match on glaciers, because the surface elevation change is the result of a complex combination of surface, internal and basal mass exchanges, and of ice dynamics. In particular, vertical displacements (emergence velocity) have to be quantified for local comparisons of the two methods (see for example Fischer, 2011; Sold et al., 2013).

Fischer, A., 2011. Comparison of direct and geodetic mass balances on a multi-annual time scale. The Cryosphere, 5(1), p.107. Sold, L., Huss, M., Hoelzle, M., Andereggen, H., Joerg, P.C. and Zemp, M., 2013. Methodological approaches to infer end-of-winter snow distribution on alpine glaciers. Journal of Glaciology, 59(218), pp.1047-1059.

AC: We have deleted this paragraph accordingly.

RC Lines 612-645 Pages 27-28: in my opinion this is not discussion, but mostly a presentation of results. Here the authors should discuss the accuracy of their results, the problematics in data collection and processing, the generalizability and the added values of the employed techniques. In particular, they should provide a discussion of the pros and cons of the proposed approaches, a comparison of their results with the existing literature, and critical evaluation of local-scale high-resolution surveys vs.

glacier-wide surveys, which are required for geodetic mass balance estimates and comprehensive glacier hazard mapping. Which of the used methods has the highest potential for monitoring rapid glacier evolution and deriving hazards? Is there a method that has the potential to become a standard in glacier monitoring strategies, according to the authors? With which improvements/adjustments?

AC: We have moved the description of glacier hazards to the results section and deleted the paragraph on geomorphological evolution of the glacier tongue as not relevant to this study. In addition, the new Discussion section has been rewritten by rearranging content from the results section and providing more information to discuss the issues mentioned in your comment.

RC Line 687 Page 30: I wonder if there is a more quantitative approach to be used here (such as DOD) to better exploit the new technologies. All the surface features described in this section are so large to be clearly visible by quick field observations and the tourist path can be easily changed accordingly. In my opinion the advantage of AUV and/or terrestrial photogrammetry lies in the possibility of automatically mapping and measuring these features from the DOD. Therefore, I suggest to add this quantitative assessments, starting from elevation changes as displayed in Fig. 11, where the collapse structures are evident.

AC: We agree that tourist paths can be changed but to do so, one requires a comprehensive mapping of hazard features and an insight into their evolution which can not be obtained by simple field observation. While the areas that underwent substantial collapse can be easily mapped with an automatic approach from the DoD, in other areas manual interpretation is required to map newly opened fractures whose vertical displacement is too low to be effectively recognized and to distinguish them from crevasses. Recent fractures are particularly important to map to predict the future evolution of the glacier. Therefore, we preferred manually mapping the hazard features. We now clarify the methodological basis for this mapping in the methods, section 4.2 and added further information concerning the vertical displacement of features in the results section. Section 4.2 now reads: “The investigation of glacier hazards was conducted by considering datasets from 2014 and 2016. In 2014, only the point cloud and UAV orthophoto were available, while in 2016 the point cloud obtained by merging UAV and close-range photogrammetric data sets was used in combination with the UAV orthophoto. In this study, we focused on ring faults and normal faults, which were manually delineated by using geometric properties from the point clouds while color information from orthophotos was used as a cross-check. On point clouds, mapping is based on visual inspection of vertical displacements following faulting or subsidence. On orthophotos, both types of structures also generally appear as linear features in contrast with their surroundings. As these structures may look similar to crevasses, further information concerning their orientation and location needs to be assessed for discrimination. The orientation of fault structures is not compatible with glacier flow, with ring faults also appearing in circular patterns. Their location is limited to the glacier margins, medial moraines and terminus (Azzoni et al., submitted). After delineation, we also analysed the height of vertical facies using information from the point clouds. ”

RC Line 695 Page 30: increased rate of surface lowering (not necessarily equal to surface ablation).

AC: We now use the term “thinning” or “thinning rate” throughout the manuscript.

RC References Page 32: the reference list is rather long and, notably, one third of the references are self-citations. Please check if all these references are pertinent and functional to the paper

AC: The list of references has been shortened from 72 to 61 references, of which 10 are self-citations.

RC Table 2 Page 40: please provide explanation for GSD

AC: The table was removed to shorten the manuscript.

RC Table 3 Page 41: I guess that the last column shows elevation differences “with” co-registration shifts

AC: We have modified the column header accordingly.

RC Table 8 Page 46: I suggest showing in a figure the extent and location of the common reference area

AC: The extent and location of the reference area is now provided in Figure 1

RC Figure 5 Page 51: I think that a) and b) are inverted

AC: We have modified the panel order accordingly.

RC Figure 7, 12 and 14 Page 53: these figures can be merged in a single image AC: We have deleted Figure 12 and Figure 14. The location of trails is now shown in Fig. 1 and Fig. 7 where the hazards are shown as well.

Interactive comment on Nat. Hazards Earth Syst. Sci. Discuss., https://doi.org/10.5194/nhess-2017-198, 2017.