Dear colleague,

Thank you very much for your effort and valuable comments. We have tried to consider every single one of your suggestions – hopefully to your satisfaction.

Best regards

The Authors

Response to reviewer #2

Comment 1: I would expand a little this part, maybe you could also refer directly with the term "intensity".

The reviewer's suggestion has been considered. Please see comment 12. By reviewer #1

Comment 2: Expand, furnish more information on the methodology.

The reviewer's suggestion has been considered.

"As a first step planar segments have to be extracted from the original point clouds. Then, identical planes are computed instead of matching single points such as in radiometric approaches. By using planes instead of points, the precision of the resulting transformation parameters notably increases. However, the approach relies on the existence planar areas within a region of interest and is hence mostly applied in urban environments. The most popular registration method uses redundantly captured regions of two point clouds and is called the iterative closest point algorithm (ICP) as proposed by Besl & McKay (1992). A substantial advantage of the last strategy over the aforementioned ones is the actual use of the information present in the point cloud. A drawback of the algorithm is its dependence to a sufficient pre-alignment of two datasets."

Comment 3: I'm not sure that this subsection title is fitted to the matter. Maybe simply "pre-alignment methodology" or something similar is more effective.

The reviewer's suggestion has been considered by restructuring the manuscript. The mentioned paragraph can now be found under section 2 existing methods.

Comment 4: But this could be in contradiction with the need to avoid "any form of user-interaction", stated above. At least this could be the first impression the reader could have; however if you say explicitly that ransac method automatically filters out sensitive areas (I mean the ones with high deformation leading to problems of alignment) the possible contradiction is avoided.

The reviewer's suggestion has been considered.

"Kromer et al. (2017) approach this issue by applying Fischler and Bolles' (1981) Random sample consensus (RANSAC) in order to **automatically** reject correspondences between two epochs which either arise as a consequence of deformation or false matches."

In addition, the following sentence has been modified:

"In order to avoid falsification of the deformation measurement process and consequently the analysis of deformation, it is unavoidable to **automatically** identify deformed areas within point clouds and to reject them from the computation of transformation parameters"

Comment 5: Which is the meaning of "object space"???

The reviewer's suggestion has been considered. The term object space has been replaced by "area of interest".

Comment 6: sentence not clear

The reviewer's suggestion has been considered by rephrasing the sentence. " The ICProx is based on a spatial segmentation of the original datasets and identifies deformation respectively stable areas by comparison of locally computed transformation parameters for individual segments (Wujanz et al. 2016b). "

I will fuse this section with 2.1

The reviewer's suggestion has been considered by restructuring the according sections.

Comment 7: Say some words to give information on the approach. Sentence not much clear, explain better. Consider rephrasing, the link with the preceding sentence is not clear.

The reviewer's suggestion has been considered.

"Phase 1 in turn contains **three steps** while the first one automatically carries out the pre-alignment of data. Therefore the 4PCS-algorithm as proposed by Aiger et al. (2008) is used in the **first step**. In the **second step**, the coarsely aligned data is segmented in cubes of equal size that are also referred to as octree cells (Samet 2006 p. 211 ff). Subsequently the ICP-algorithm is locally applied within each octree cell that represents the **last step** of Phase 1.

Comment 8: How the size is defined?

In the current implementation this step is based on empirical settings. We have mentioned the following in the outlook: "Hence, an extension has to be implemented that is capable to determine an optimal octree size under consideration of the local topography."

Comment 9: Are the candidates stable areas in the selected subdomains???

No, at the very beginning it is not clear which regions in the point clouds are stable. It is the task of the ICProx-algorithm to clarify this issue. Candidates are samples that reduce the data volume of the original dataset. This step is carried out in every implementation.

Comment 10: Not clear, is the portion of deformation the size of cubes (octree cells)?

No, but the size of the cubes influences the local amount of deformation. The smaller the cubes the higher the local influence of deformed / stable areas. If the octree size is too small, the ICP will simply fail since it will converge into local minima.

Comment 11: sentence not clear

The sentence has been rephrased. See also comment 22 of reviewer #1.

"The general concept of this feature considers the fact that every scan of a stable object yields in a different point sampling (Wujanz et al. 2016b)."

Comment 12: I'm wondering if the stables areas should have some requirements (e.g., relative amount of stable areas over unstable, geographical distribution, etc.) in order to have a final good alignment. From your figure 1 stable areas is almost all located on the left side...

The reviewer's suggestion has been considered.

“From a geodetic perspective the most desirable arrangement would be a more or less connected region that is subject to deformation which is surrounded by stable areas. In addition, the ratio between stable and deformed regions should be rather large in order to being able to compute transformation parameters with the highest possible redundancy. However, the distribution of stable areas as well as their relative amount are usually unpredictable in practice since every region of interest has got its own individual characteristics. Countermeasures in order to receive favourable arrangements can be achieved by carrying out the surveys more frequently and/or to perform panorama scans which increases the chance of capturing additional stable areas. It is obvious that the result depicted on the right of **Error! Reference source not found.** may yield in imprecise transformation parameters due to the fact that a large amount of octree cells are subject to deformation while the arrangement of stable cells is unfavourable.”

Comment 13: I would use letters to identify figures.

After discussing your suggestion we have decided to stick to our original scheme.

Comment 14: Did you tried the suggested approach on synthetic data so as to have a kind of benchmark?

We did not use synthetic data yet we have used two different scenarios in order to verify the approach (see Wujanz et al. 2016). In the first one a scanner’s viewpoint remained constant over the course of several captured epochs. By this, reference transformation parameters were known: they had to be all 0! In the second one the deformation was locally restricted and well defined (we have used data from a crash test). A third alternative strategy was used in the submitted manuscript.

Wujanz, D., Krueger, D. and Neitzel, F.: *Identification of Stable Areas in Unreferenced Laser Scans for Deformation Measurement*. The Photogrammetric Record, 31(155), pp. 261-280, 2016.

Comment 15: Are you sure that this manually classified map correspond to the true? How you identified stable and unstable areas????

Every manually generated ground truth contains subjective influences. In order to overcome this, we generated the reference in an iterative fashion.

1. Register point clouds based on ICP
2. Generate change map
3. Remove areas with systematic shift / deformation
4. Repeat steps 1 to 3 until only random noise remains

Please also have a look at our remarks to comment 20

Comment 16: “….were sampled with 0.75 m on average.”

Every implementation of the ICP contains a downsampling step that reduces the input data in order to i) reduce the required effort for correspondence determination and ii) to restrict the size of the normal equation matrix during parameter estimation. A disadvantage of randomly sampling these “candidates” is that the majority of samples will be located closer to the scanner since the local point density is also closer opposed to regions of the point cloud that are further away. The defined measure means that one candidate should be located every ~0.75 m. This ensures a (approximately) systematic sampling over the original point cloud.

Comment 17: Explain better how the georeferenced reference has been derived as well as its accuracy.

The location of all applied tie points are highlighted in Figure 3 to 5. From a geodetic point of view it is not meaningful to report their accuracy as the distribution is quite unfavourable. One could have placed all tie point 1 m away from the scanner which would yield in very small residuals yet, these values are only valid for this very limited range. We have critically commented this issue throughout the contribution.

Section 4.1 “It can notably be seen that the distribution is rather unfavourable from a geodetic point of view as the active zone of the glacier, that is highlighted by a white dashed line, is not surrounded by registration points. This may lead to extrapolative respectively leverage effects.”

Section 4.2 “As a consequence the computed transformation parameters based on the reference points can only be seen as an approximate solution as they are very likely to be subject of extrapolative effects and hence have to be refined by e.g. surface based registration.”

Comment 18: Insert legend for colour coded map.

We decided to leave the written description of the colour map at the very beginning of chapter 5. The information was to lengthy for the figure.

Comment 19: Quite high standard deviation, even if I don't think that with 3 values you can compute confidently a standard deviation....I would say that the accuracy of prediction of unstable areas is quite variable (worst case table2).

We have removed the listed standard deviations. The accuracy of the algorithm of course depends on the geometric characteristics of the area of interest, the chosen octree size as well as the point density of the acquired datasets. We have mentioned this aspect several times throughout the contribution, e.g.

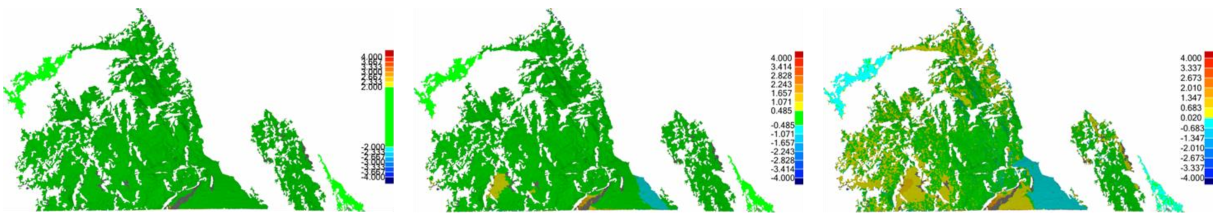
“Hence, an extension has to be implemented that is capable to determine an optimal octree size under consideration of the local topography. This information could also be used to dismiss certain octree cells due to insufficient geometric properties **that would otherwise occur in the algorithm’s numerical and visual assessment**.”

The worst example in this contribution is listed in table 3 (13% of undetected deformation) and not in table 2 (2% of undetected deformation). We have also listed reasons for this effect:

“The numerical assessment of the generated results is depicted in **Error! Reference source not found.** and shows that a comparably large part of deformed areas was not correctly assigned as indicated by the numbers in the red coloured cell. The reason for this is twofold and can be found both in the ratio among the low magnitude of deformation and the corresponding local spatial uncertainties as well as the heterogeneous occurrence of geometric changes.”

Comment 20: To feel more confident I would try the method on sintethic data set where you know truly which are stable and unstable areas. As a second option you should use a case study in which you have a more efficient network of control points so as to have a more accurate and precise reference dataset for comparision.

The precision of the reference data is of course dependent to the registration. We have shown three strategies of how to deal with this problem; please see remarks to comments #14 and 15. Yet, what should also be considered is the influence of the deformation pattern: the chosen settings of these colour coded representations have a large impact onto the outcome and hence, the confusion maps that we produce based on it. If you ask three people to generate change maps you’ll most likely end up with three very different results as shown below.



Hence, we have implemented an algorithm that visualises only statistically significant deformations in dependence to the:

- Local sampling density (as we've done in the submitted manuscript)
- Stochastic properties of the applied scanner (Wujanz et al. 2017)
- Inhomogeneous influence of the registration, in contrast to Lague et al. (2013)

Lague, D., Brodu, N. and Leroux, J.: *Accurate 3D comparison of complex topography with terrestrial laser scanner: application to the Rangitikei canyon (NZ)*. ISPRS Journal of Photogrammetry and Remote Sensing, 82, pp. 10-26, 2013.

Wujanz, D., Burger, M., Mettenleiter, M. and Neitzel, F: *An intensity-based stochastic model for terrestrial laser scanners*. ISPRS Journal of Photogrammetry and Remote Sensing, vol. 125, pp. 146-155, 2017.