We want to thank the referees for their comments and suggestions and for the time they spend reviewing our manuscript. Below please find our responses to the reviewer's comments and the revised manuscript, wherein the changes we made are marked:

Answers to Anonymous Referee #1

1. The authors present a summary of their methodological developments in terrestrial photogrammetry for glacier monitoring. Unfortunately, most of the material in the manuscript has already been presented in a previous paper by the authors (Rosenau et al. 2013). Since the authors provide the reference to their previous study only on page 23 I was left with the impression to read through original material and spend the better part of a day on this review!

   The contribution that we submitted is meant to be an overview paper on recent photogrammetric methods and applications in glaciology, written by photogrammetrists and addressed to a broader readership. The contents published in the Rosenau-2013 paper play only a minor role therein, and there is no identical text or identical figures. Rosenau-2013 was actually never meant to be a methodological paper; the focus was clearly on the interpretation of the velocity fields and not on the algorithms to determine them. Of course there is a chapter covering the photogrammetric method as well, but it is only one page.

   From the following comments we got the impression that there is one main misunderstanding: Our main goal is to present the concept of our method in detail. In addition, some case studies are shown to show the potential of the methods; some of these case studies have been published before, but in a completely different context.

   We started time-lapse measurements and methodical developments in 2004 (Jakobshavn Isbrae, Greenland) and conducted further field campaigns in 2007 (Jakobshavn Isbrae, Greenland), 2009 (San Rafael Glacier, Chile), 2010 (Jakobshavn Isbrae, Equip Sermia, Store Qarajac, Greenland; Colonia Glacier, Chile), 2013 (Colonia Glacier, Chile), 2014 (Colonia Glacier, Grey-Glacier, Chile), 2015 (Kaskawulsh Glacier, Kanada). This was done in cooperation with various partners and with different investigation goals. The experiences gained through all of these campaigns were used to further develop our method. As we are photogrammetrists, our research focus is on methodical development and accuracy assessment/optimization. Rosenau-2013 thus is just one of several studies from which we gained experiences.

   We rephrased parts of the introduction to make the objective of our contribution become more clearly and to early address this previous paper.

   <u>Detailed comments:</u>

2. The introduction provides a historical perspective on the use of terrestrial photogrammetry for glacier studies but I feel it leaves out some significant recent advances in the field of environmental monitoring with photogrammetric methods including the monitoring of glacier (e.g. Messerli and Grinsted 2015), landslides (e.g. Travelletti et al. 2013) or discharge monitoring (e.g. Stumpf et al. 2016). Some of those tools are readily available in the public domain and can be used for the proposed applications. It would therefore be helpful to explain briefly possible shortcomings of available methods and how the proposed method addresses those issues.

   Addtitional references:

   - Messerli, A. and Grinsted, A.: Image GeoRectification And Feature Tracking toolbox: ImGRAFT, Geosci. Instrum. Method. Data Syst., 4, 23-34, 2015, doi:10.5194/gi-4-23-2015
   - Travelletti, Julien, et al. "Correlation of multi-temporal ground-based optical images for landslide monitoring: Application, potential and limitations." ISPRS Journal of Photogrammetry and Remote Sensing 70 (2012): 39-55.
   - Stumpf, André, et al. "Photogrammetric discharge monitoring of small tropical mountain rivers: A case study at Rivière des Pluies, Réunion Island." Water Resources Research 52.6 (2016): 4550-4570.

   We integrated the proposed references in the introduction.

3. **Comment:** p.3, l.12: 'translation into object space' Maybe 'transformation' or 'mapping' would be more adequate than 'translation' here

   We changed this.

4. p.5; l.9: "This can be achieved by establishing a local photogrammetric network (consisting of several convergent images taken from different positions as shown in Figure 2)" As I understand this, this authors suggest a single 3D reconstruction of the glacier surface for a single time steps as opposed to the time-lapse camera which will acquire time-series for the motion measurements? This implicitly comprises the hyphothesis that the glacier surface topography will not undergo large changes during the monitoring period. In particular for the observation of calving event this appears as a rather strong assumption which should be explained in greater detail.

   Correct, this is the limitation of a single camera system (monoscopic approach): a DEM is not available in the same temporal resolution as the time-lapse measurement series. This can only be provided by a synchronized multi camera setup. Section 2.1 discusses advantages and disadvantages of both approaches.

   In this contribution we are presenting the monoscopic approach and how we are going to deliver distance values for scaling. In contrast to other approaches (e.g. Box and Ahn, Messerli and Grinsted) we do not use an external DEM that needs to be registered with the time-lapse image (and will most likely be even less representative). We prefer an integrated solution to derive the DEM and its registration with the time-lapse image in one step. This offers high inner accuracy, good accordance with the cameras field of view and avoids registration errors. That's the statement of the section of which you picked the cited sentence from. Please note that the DTM is mainly used to determine scale factors to translate trajectory lengths from pixels to meters. Therefore, the requirements to the accuracy and resolution of the DTMs are not high. Our assessment has shown, that a DTM obtained from multiple images taken at the beginning and/or end of an image sequence is suitable to determine scales at an error <1%.

The special case calving event: The "rather strong assumption which should be explained in greater detail" is explained in the following sections (compare especially section 2.4.3). From the DEM we obtain a distance value for the starting point of a trajectory. We want to apply the monoscopic approach; therefore we need to make assumptions about the glacier motion. The basic assumption we make is, that glacier point is moving within a vertical plane which is oriented along the flow direction of the glacier. This allows us to distinguish between vertical and horizontal components of the motion vector as far as the glacier motion follows our model assumption. Let's assume the glacier is rising and falling close to the glacier front during a calving event while moving forward, these motions can be separated and measured. Problems would arise from motions across flow direction. The more the real motion deviates from the assumed motion model, the less accurately it can be split into its horizontal and vertical component. From the calving events that we observed we did not get the impression that there are significant across-flow motions that disturbed the velocity measurements.

5. General comment on 2.2 Measurement Setup: While the section clearly describes several options for the measuring setup and states requirements (e.g. "should be replaced by differential GNSS measurements." "an elevated camera position is required", "it is necessary to have static points", "it is recommendable to use redundant information in the process of geo-referencing"). While I agree with those considerations it is still not clear for me which (similar or different setups and strategies were used in the study. I would encourage the authors to provide more explicit information on the actually realized setups.

   It's the general methodology that we want to present in detail with this contribution, not a certain study. All strategies we suggest were realized and tested in various field campaigns (see answer to comment 1). Each measurement area is unique and may put individual restrictions to measurement setup and data processing. We wanted to provide a method that can handle most of these situations, and we thus integrated accordant options in our software. So for each individual measurement case/ application, the user must decide, which of the provided strategies is the most appropriate. Say in this section the one who developed the method tries to give recommendations on which option best fits which situation.

6. p. 8: "Thus, the first strategy might be applied when tracking signalised points" Similar to my previous comment, please avoid hedging, and state what has been actually done.

   Ok agree, this sentence sounds too vague. Changed "might" into "has to be".

7. p. 12, l.7: 'higher than the single standard deviation' The standard deviation of the gray values within the search patch? This automatically assign several pixels as shadow pixels even if not shadows are present at all. It seems to me that on a glacier this might mask many areas with important texture and could leave you only with the areas that are difficult to match? Please comment.

   That's why it is an iterative process. After the first iteration step the state is as you describe it above: Some shadow motion pixels are removed but also some non-shadow motion pixels. The removal of the shadow motion pixel now is what makes the following iteration converge to a better solution. This means more shadow motion pixel but less non shadow motion pixel (less "important texture") are removed during the subsequent iteration step. In order to find the best compromise to exclude as much shadow motion pixel but at the same time keep enough of the glacier texture to allow for a successful next matching we look at the difference image of the master patch defined in image 1 and its corresponding patch detected in image 2. High differences indicate shadow shifts on the one hand but also important glacier texture. Now we have to find an appropriate threshold that removes disturbing shadow influenced pixel in order to guarantee a better solution in the next matching step but keep enough good glacier texture for the matching as well. When looking at the histogram of the difference image the difference values are approximately normally distributed in most cases. The shadow influenced pixels show the highest grey value differences and accumulate at the upper and lower margin of the histogram. Thus, using the single standard deviation of the difference values as a threshold ensures that no more than ca. 30% of the pixels of a patch are excluded and enough texture remains in the patch. Our procedure also consists of a solution for non-normally distributed cases but that would probably lead to far for the paper.

   We rephrased our explanations in order to make the algorithm become better understandable.

8. p.13, l.2: "error influence on the motion vectors" This sounds a bit awkward. I suggest something like 'error source that might impact'...

   Agree, we changed this as you suggested.

9. p.14, l.9: "two image shift parameters and the rotation parameter" If you are only considering those two parameters you will estimate a rigid transformation and won't need to invoke an affine transformation. Please clarify.

   You are right; as it is described in the paper we should have called it a rigid transformation.
   However, in our procedure it is implemented as an affine transform with the option to also estimate scale parameters. We used them to test whether refraction affects the measurement of the fix targets or as an indicator for changes of the interior orientation of the time lapse camera. Since these issues are not part of this paper we changed the term into "rigid transformation".

10. p.16, l.10: "Going a step further and calculating the sparse cloud while providing the measured camera positions to PhotoScan, the thus determined 3D coordinates of object points can also be exported and used as approximate values for the bundle block adjustment." I do not understand the purpose of this step. Errors in the internal and external calibration parameters plus matching errors will propagate into the sparse point cloud. Running another bundle adjustment with the resulting 3D points will hence certainly suffer from those errors? Please clarify.

   During a bundle block adjustment a non linear equation system needs to be solved. The process of linearising the equations requires approximate values for each unknown parameter. Running our own bundle in order to calculate 3D glacier point's means we need an appropriate start value for each coordinate that will converge to an optimal final value during the iterative adjustment procedure. We just take advantage of the sparse point cloud of PhotoScan as a source of approximate start values for our own bundle (which – unlike PhotoScan – does not have a strategy for automatic approximate value generation). Therefore possible errors of the sparse cloud don't matter because these values are all estimated anew, as well as the external orientation parameters of the camera.

Internal calibration parameters of the used cameras were always externally estimated with high accuracy beforehand. For this purpose we used an adequate calibration field and photogrammetric calibration software. In the following process they don't need to be estimated anew and are thus set as fix values (in PhotoScan as well as in our own bundle).

11. Similar too my previous comments p.16 comprises a lot of ambiguity. Some example: "we predominantly used structure from motion (SFM) tools (such as Agisoft PhotoScan)" Which other SFM tools where used and for what?

This contribution (which is meant to be a conceptual methodological paper) is based on experiences gained during a variety of different studies between 2004 and 2015:

With "Bundler", the first structure from motion library was first released in 2008. PhotoScan started in 2010. After that the development in this field rapidly increased. This means for the processing of all measurement campaigns before 2011 we solely had to rely on our own bundle. Then, we started to use "Bundler" for the measurements of corresponding image points and finally started to integrate the functionalities of PhotoScan into our work flow. Thus we "predominantly used structure from motion (SFM) tools (such as Agisoft PhotoScan) in combination with our own photogrammetric bundle".

There is still the option to solely use our own photogrammetric bundle, which is completely flexible and adaptable to different geo-referencing concepts (e.g. using height control points, introducing scale conditions, calculating the individual error for each estimated parameter,…), but requires a deeper photogrammetric understanding from the user. PhotoScan as a commercial software on the other hand is easy to handle, fast and optimized. To use the advantages of both, we had to define an appropriate interface between them. It depends on the individual geo-referencing setup of a measurement scene, up to which state of the workflow we can use PhotoScan or need to switch to our own software.

12. "It can be adapted to different types of control points as well as different sets of camera calibration parameters, scale conditions can be defined, and it provides the possibility to define each variable as fix or parameter to be estimated". Which type of cameras and camera calibration models where used? How did you adapt the tool and the free parameters and based on which criteria?

We simply wanted to state that an open photogrammetric bundle has advantages in comparison with the PhotoScan bundle. The latter cannot be used as flexible as an open bundle, especially regarding the issues mentioned in the cited sentence. An open photogrammetric bundle just offers more options. Thus, we also have more options when deciding for a certain measurement setup in the field.

To answer your special questions:

- type of cameras: We used central perspective cameras during our campaigns, mainly mirror reflex cameras. However our in-house bundle contains of different fisheye-camera models, a panorama camera model and a laser scanner model as well. So if we e.g. would insist to use a GoPro as time-lapse camera we could easily switch to a fitting fisheye model.

- calibration models: We mostly used the calibration model as described in Luhman (2006), because this is widely used in photogrammetry and also implemented in the external calibration software we used (AICON 3D Studio). (*Luhmann, T; Robson, S; Kyle, S; Harley, I.: Close Range Photogrammetry: Principles, Methods and Applications. [Book]. (1st ed. ed.). Whittles: UK, 2006*). Computer vision calibration software might use other sets of calibration functions. PhotoScan also uses an individual calibration model that even varies between different program versions. If we pre-calibrate cameras and thus have to process our data with different software we need to overcome such inconsistencies. In this respect, the advantage of an open bundle is that each type of calibration model can be integrated as far as it is openly documented.

- free parameters: If we use height control points we have to fix the Z-coordinate of a control point but let X and Y free to be estimated.

However, we think it would be a bit out of scope to explain all of these special aspects in detail. The paper already consists of 30 manuscript pages, and we should probably not extend it to a textbook.

13. "Since many SFM tools are rather optimized for fast processing and 3D-visualization than for accurate measurement purposes, some limitations may have to be taken into account, when applying them for measurement tasks."Which tools are you talking about? Can you back this with numbers or previous studies?

Most SFM-tools like Bundler, PhotoScan, VisualSFM,… originate from computer vision. In computer vision the focus usually is on optimizing algorithms for fast processing and 3D-visualization whereas the focus of photogrammetric approaches is on optimizing algorithms for high accuracy. Bundler e.g. does not provide an integrated geo-referencing, PhotoScan turns more and more into a photogrammetric software, but it still doesn't provide information about the individual error of each estimated parameter and doesn't provide flexible parameterizations such as the use of height control points.

We added some references which back up this statement:

Eltner, A., Schneider, D.: Analysis of Different Methods for 3D Reconstruction of Natural Surfaces from Parallel-Axes UAV Images. In: The Photogrammetric Record, 30(151), pp. 279–299, 2015

James, M.R., Robson, S., d'Oleire-Oltmanns, S., Niethammer, U.: Optimising UAV topographic surveys processed with structure-from-motion: ground control quality, quantity and bundle adjustment, In: Geomorphology, 280, pp. 51–66, 2017

14. "However, when not using a reduced measurement setup it is also possible to determine object coordinates and camera orientation parameters solely using PhotoScan." What is a reduced measurement setup? Is this an option or something you have done in this study?

   In section 2.2 we introduced several possible geo-referencing setups which require different measurement equipment and effort. In the field or during expedition planning the choice has to be made which of these geo-referencing setups fits best depending on:
   - the topography of the individual measurement scene
   - how much measurement equipment we want to carry in the field
   - how much time we have to conduct the geo-referencing measurements
   - or even which kind of processing software we want to use

   The chosen geo-referencing setup than decides up to which state of the geo-referencing workflow we can use PhotoScan or need to switch to our own software. To use PhotoScan as much as possible (which might be something non-photogrammetrists would prefer) we need to choose the most extensive one from the proposed geo-referencing setups (a "non-reduced" measurement setup) because full 3D control points are required.

   For practical reasons we used "reduced measurement setups" during most of our studies because they save time and money. For their processing a flexible photogrammetric bundle is required. This can be combined with certain functionalities of PhotoScan to obtain the input data for the bundle (image coordinates, approximate values). In contrast, the full geo-referencing setup will work in any case and has the advantage that the bundle adjustment can completely done with PhotoScan but the measurement in the field is time consuming and equipment-intense.

   We restructured and rephrased some text in section 2.2 and 2.4 to make this become more clearly. We numbered the proposed geo-referencing options to more clearly refer to them in section 2.4.

15. "Thus, it is recommendable to measure the cameras positions in the field and to precalibrate the cameras..." I agree, but it is again not clear if that is a recommendation or something you implemented in this study. I there are more examples like this.

   This does not refer to a certain study. The pre-calibration is something we did during all of our measurement campaigns. From our photogrammetric point of view we recommend this. The sentence you cited above continues with the reasons why.

16. p.17, l.13: "In case of using PhotoScan, the exterior camera orientation parameters and a depth map can be exported for the time-lapse image." Above you explained that you use you own in-house bundle adjustment and in combination with pre-calibration of the internal parameters. Why would you then export these parameters from Photoscan?

   If we choose the most extensive one from the proposed geo-referencing setups (a "non-reduced" measurement setup) and measure 3D control points instead of height control points, we have the opportunity to use the bundle of PhotoScan and don't need to switch to our own bundle (compare answer to comment 14).

   If we pre-calibrated the cameras the interior orientation parameters are known and can be introduced as fix values into the bundle (in this case the PhotoScan bundle) as well as the 3D control points and the camera positions. The results we need to obtain from the PhotoScan bundle are the exterior orientation parameter of the time-lapse camera. From the dense matching step we need to obtain the depth map of the measurement object (a depth value for each pixel of the time-lapse image).

   This is what defines the interface between PhotoScan and our software in case of using a "non-reduced" measurement setup: Exporting exterior camera orientation parameters and a depth map from PhotoScan and importing them, together with the pre-calibrated interior parameters, into our software. Here they serve to scale the trajectories and define their position in a world coordinate system as explained in section 2.4.3.

17. p.18, l. 12: "The glacier flow direction can e.g. be obtained via flow-line patterns that are visible in satellite orthophotos. Does this imply that the glacier flow direction is constant across the scene (as shown in Fig 12A)? This would be a rather strong assumption for observations in areas where the glacier flow is bending with the topography. Please clarify and state possible limitations that may arise from this assumption.

   In section 2.1 we compared advantages and disadvantages of using a single time lapse camera and a multi camera time-lapse system. A full 3D motion acquisition (via multi-temporal laser scanning or multi-camera time-lapse) would directly offer 3D-motion vectors. Since we are using single camera systems, we have to make assumptions about the motion direction.

   The simplest assumption is orthogonality between glacier flow and camera viewing direction. The next step of improvement would be to introduce an overall mean flow direction of the measured glacier part (as we propose as a local approximation in the contribution). From our own experience, this will be sufficient for most of the tasks, as time lapse observations usually cover small parts of a glacier.

   Of cause there may be single cases (strong bending glacier + large observation section + wide angle lens + high accuracy demands), where we would need to go even further. In these cases the accuracy can be increased by introducing flow line polygons (again digitized from Satellite imagery) which provide an individual local flow direction for smaller parts of the measurement area.

18. p.19, l. 16: "For a sample trajectory from an image sequence measurement at Jakobshavn Isbræ in May 2010" I feel it would be helpful to first introduce the study sites with their respective measurement setups before providing results on the accuracy. At this point it is rather difficult for the reader to understand if the error budget estimation is representative for all sites.

   To complete the presentation of the method we wanted to name the main error influences of the method and exemplarily show the magnitude of accuracy that can be achieved.

   We added some more specifications of our measurement example.

19. p.20, l.20: "These individual errors were propagated into a mean total error of 9.2 cm "It might be useful to provide the formula for the error propagation. Why did you not also assess the measured velocities against independent in-situ measurements?

It would be out of scope of the paper to present the whole error analysis for the method. The general mathematical principals of geodetic error estimation theory can be found in textbooks (e.g. Niemeier, 2002 or Taylor, 1997). These references are given in the paper. An individual formula to calculate the error does not exist because the whole method cannot be described with a single formula. The error propagation is inherently incorporated in all photogrammetric routines used here, including bundle adjustment and least squares image matching.

Of cause we also compared the time-lapse measurements with independent measurements, including terrestrial laser scanner measurements, total station measurements, satellite based measurements. However, since these methods cannot be assumed to have a higher accuracy potential than the time lapse method, they cannot be used as a reference for absolute error calculation. This comparison only proofs that the results are plausible and in accordance with other methods. To derive an individual error value for each measurement value, we still have to rely on a thorough inner accuracy analysis of the method.

We are currently planning to write another paper that will cover the topic of error analysis for the presented method. The subject is too extensive to be described in detail here.

20. General comment related to section 3 Assessment of glacier motion fields: four case studies. I feel that a lot of important information regarding the case studies is missing including maps of the measurements setup, the type of deployed cameras, the duration and frequency of the acquisitions of monoscopic images as well as stereo views. Introducing the particularities of the study sites might also help the readers to understand which specific choices were made following the rather generic description in section 2.2. Another interesting aspect that might deserve some further considerations is the operation of the camera systems in the those rather harsh environmental conditions (e.g. power supply, data storage and submission, etc.).

This section was never meant to present the results of these applications as new results. As the introduction of the section tells we wanted to: "…present examples for different glaciology applications of the method to show its potential". It's a discussion about the suitability and possible areas of application of the method. For more details, references are given to application-oriented publications where more information can be found on the individual studies.

We admit that the headline of the section is misleading here. Subscribing the section with the Term "discussion" as referee 2 suggests will hopefully prevent from further misunderstandings.

21. 3.1 Horizontal glacier motion. Is the glacier motion in the presented case studies purely horizontal? If not your measurements may also comprise a vertical component. Please clarify.

We always do measure a horizontal and a vertical component of glacier motion. In section 3.1 we wanted to discuss examples of applications that focus on the horizontal component of the derived motion vector.

22. 3.1.1 Glacier motion velocity fields
Considering all the effort for setting up a time-lapse system it is more than unfortunate that you only present the aggregated means. Surely you derived some interesting timeseries that you could present? What can we learn from those time-series regarding the process of glacier flow? Section 3.1.2 is much more mature in this regard.

See answer to comment 20.

23. p. 23, l 14: "velocity increase decreased with increasing" There is a lot of increase and decrease here. Please reformulate.

We changed this.

24. Figure 16: I would be helpful to provide a scale for the upper figure (e.g. distance between to arbitrary points on the stable terrain). Please also provide the details on the smoothing filter (e.g. rolling mean with a window size of x?) used.

As Referee 2 suggested we now changed the sections headline into "Discussion", removed the figures and shortened it.

25. 1.1 Vertical glacier motion Something went wrong with the section numbering here.

Thank you, we corrected this.

26. 1.1.1 Grounding line determination
There are several issues in this section. The caption of Figure 17 refers to only two of the 3 subfigures and raises the impression that all the results presented originate from other studies.

Our objective was not to present the results of these applications as new results. We rather wanted to show the potential and value of the method for different types of glaciological applications. Thereby the results of our previous studies should serve as examples and proof of the methods suitability for diverse tasks with different demands. Thus, for each example that has been already published we added the accordant reference.

As Referee 2 suggested we now changed the sections headline into "Discussion", removed the figures and shortened it.

27. The letters A-C used to number the subfigures are not used at all. In Fig 17 A it is not clear which measurement is from which source. The y-axis gives the impression that both curves show the tidal range while one of them shows (I assume) the vertical component of the glacier motion. "Figure 17 (A) shows the vertical motion component of a single trajectory compared to tidal

height measured by a pressure gauge." Neither from the text nor in the figure it is clear which measurement is which. "In particular, the scale factor in vertical direction" The paper is not really self-contained here. Please explain how the scale factor is computed.

The figure has been removed following the suggestion of Referee 2 to shorten the section.

28. "Multiple time lapse measurements at Jakobshavn Isbræ in 2004, 2007 and 2010 even allowed for the documentation of the migration of the glaciers grounding line (Figure 17, C) (Rosenau et. al., 2013)." I finally had a look at the study by Rosenau et al. 2013 and came to realize that an important part of the presented material has already been published in this previous paper by the authors. This includes the measurements on the Jakobshavn Isbrae glacier, the corrections for camera movement, the projection into object-space, estimation of the error budget, the delineation of the grounding line, and the documentation of the calving event. I stop the review here.

We would really like to ask you to continue!

We never claimed that "the measurements on the Jakobshavn Isbrae glacier, the delineation of the grounding line, and the documentation of the calving event" are new results. We did not hide that they are already published but added the references. In section 3 we wanted to show and discuss the potential and value of the method for different types of glaciological applications. Thereby the results of our previous studies should serve as examples and proof of the methods suitability for diverse tasks with different demands. The same holds for the results of other pilot studies shown in this paper.

Of course we mention camera motion and transformation into object space in both of the papers. These are essential parts of each monoscopic time-lapse approach. In Rosenau-2013 only a short method overview (1 page) is given as add-on to better understand where the measurements, which are analyzed and interpreted in the paper, come from (the reviewers especially requested it that time). The part of presenting the individual measurements at Jakobshavn Isbrae and their analysis and interpretation was the intention and main focus of this paper, not a detailed presentation of our photogrammetric time-lapse method.

Our submitted contribution has about 20 manuscript pages of pure and detailed method description + 5 pages of discussion of the methods potential and suitability supported by application examples. And the review shows that there are still several open questions concerning the method. Isn't this in a certain contradiction to the statement that everything has already been published?

Answers to Anonymous Referee #2

29. I have read the paper with interest, and I think this is a potential interesting contribution for the special issue as it matches very well with the topic. My main concern about the paper is the very large similarities with the paper already published by Roseneau et al. 2013. Indeed this paper is not cited in the introduction when I think that it should be clearly stated that this paper exists and which is the exact contribution and adding of this new paper.

The contribution that we submitted is meant to be an overview paper on recent photogrammetric methods and applications in glaciology, written by photogrammetrists and addressed to a broader readership. The contents published in the Rosenau-2013 paper play only a minor role therein, and there is no identical text or identical figures. Rosenau-2013 was actually never meant to be a methodological paper, the focus was clearly on the interpretation of the velocity fields and not on the algorithms to determine them. Of course there is a chapter covering the photogrammetric method as well, but it is only one page.

We rephrased parts of the introduction to make the objective of our contribution become more clearly and to early address this previous paper.

30. It would also allow to prepare a revised version more focussed and shorter, as in its current state it seems to me that it results a little bit sparse and too long (18 figures is probably excessive for a paper). As a suggestion, I think that the paper will be more interesting for readers focussing in the detailed presentation of the methodology and validation that you do that exceeds the one offered in Roseneau et al.2013. Much of the sections dealing with applications and results could be removed and synthetized in a discussion section. I would avoid to exceed 10-12 figures in total.

Our objective was not to present the results of these applications as new results. We rather wanted to show the potential and value of the method for different types of glaciological applications. Thereby the results of our previous studies should serve as examples and proof of the methods suitability for diverse tasks with different demands.

We followed your suggestion and transformed the case study section into a shorter discussion section.

31. I think it would be useful to add a figure showing a scheme with the complete workflow applied to the figures in a sequential way.

We added the requested figure in section 2.1.

Minor comments:
32. In general the methodology is presented in a clear way and it is possible to be understood by the majority of readers, but some sentences could be simplified to facilitatethe lecture for people not very familiarized with this technique. An example is. "We limit ourselves to monoscopic image motion capture and processing delivering two-dimensional velocity field information here, as the 15 glaciology phenomena observed in the practical experiments do not show significant across-track motion and can thus be well described in 2D."; or to explain better some concepts as "decorrelation" used in page 2 line 29.

We tried to rephrase these sentences.

33. It is necessary to read more than half of the paper to realize that you are using Photoscan and a library developed for yourselves for the analyses. I would mention this earlier in the paper and I would indicate if the library is open for all users.

We now mention it already in section 2.1.

34. P7 line 19: First, not fist.

Thank you, this has been corrected.

35. P6, line 23. "The cameras camera position...."

Thank you, this has been corrected.

36. How is corrected the distortion of the lens? Using the info provided by the producers or using some tool as the one provided by Photoscan?

For camera calibration we used the photogrammetric software "Aicon 3D Studio" and coded marks that can be measured with sub-pixel accuracy. We usually try to install a calibration area in the field and calibrate the cameras shortly before taking measurement images or installing them as time-lapse cameras.

We added this information in the text.

37. If I understood well, all the analyses were made with only one camera. In Figure 2 the inclusion of more photogrammetric cameras may lead to confusion.

The figure mainly illustrates the camera network that is necessary for scaling and georeferencing of the time-lapse measurements. Since the time-lapse camera has to be part of this network to obtain its orientation and position in relation to the 3D surface geometry of the glacier we integrated all camera positions in the scheme. With the image we want to show that the camera views need to have some convergence that, they should cover the area observed by the time-lapse camera and that control points should be visible in all of these images.

We would therefore prefer not to change the scheme and added some explanations in image caption and text to prevent from the confusion you mentioned.

38. Please check well the references-citations as there are several mistakes.

Thank you for the hint, we checked and corrected remaining formatting errors.

39. Indeed the reference of the paper Roseneau et al. 2013 is wrong.

We added the missing line break in the reference list. But in the reference itself we couldn't find any mistakes. The name of our colleague really is Rosenau.

Determination of high resolution spatio-temporal glacier motion fields from time-lapse sequences

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Abstract.

This paper presents a comprehensive method for the determination of glacier surface motion vector fields at high spatial and temporal resolution. These vector fields can be derived from monocular terrestrial camera image sequences and are a valuable data source for glaciological analysis of the motion behaviour of glaciers. The measurement concepts for the

10   acquisition of image sequences are presented, and an automated monoscopic image sequence processing chain is developed. Motion vector fields can be derived with high precision by applying automatic sub-pixel-accuracy image matching techniques on grey value patterns in the image sequences. Well-established matching techniques have been adapted to the special characteristics of the glacier data in order to achieve high reliability in automatic image sequence processing, including the handling of moving shadows as well as motion effects induced by small instabilities in the camera setup.

15   Suitable geo-referencing techniques were developed to transform image measurements into a reference coordinate system.

The result of monoscopic image sequence analysis is a dense raster of glacier surface point trajectories for each image sequence. Each translation vector component in these trajectories can be determined with an accuracy of a few centimetres for points at a distance of several kilometres from the camera. Extensive practical validation experiments have shown that

20   motion vector and trajectory fields derived from monocular image sequences can be used for the determination of high resolution velocity fields of glaciers, including the analysis of tidal effects on glacier movement, the investigation of a glacier's motion behaviour during calving events, the determination of the position and migration of the grounding line and the detection of sub glacial channels during glacier lake outburst floods.

1 Introduction

25   For almost a century, terrestrial photogrammetry has been an important measurement method for glaciology research. Early basics for the use of photogrammetric methods for velocity measurements on glaciers were provided by Finsterwalder (1931) and Pillewizer (1938). For glaciers in the Pamir, the Himalaya, Norway and the Alps, velocity profiles were derived by repeated measurements. With the advance of the technical development of the cameras, the acquisition intervals for the photogrammetric measurements were getting shorter. For the investigation of short-term motion behaviour of glaciers,

automatic analogue cameras were used from the 1970s onwards (e.g. Flotron, 1973). Further examples for the use of automatic cameras are the photogrammetric time-lapse measurements on Columbia Glacier (Alaska) by Krimmel & Rasmussen (1986), which were conducted with a temporal resolution of three images per day, and the investigations of the Variegated-Glacier (Alaska) by Harrison et al. (1986).

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With the appearance of digital cameras and the rapid development of their sensors, photogrammetric tools have been available since the end of the 20th century, which allow for an automatic acquisition of data sets with not only high spatial but also high temporal resolution. Because of further technical improvements of digital cameras and developments in automatic image matching techniques, terrestrial image sequence analysis became a valuable tool for the investigation of

10 glaciers during the last 20 years. Phenomena with short-term movement variations requiring a temporal resolution of hours (tidal influence on the glacier movement) or even minutes (calving events) can now be investigated efficiently. Early applications of photogrammetry-based methods for the determination of glacier velocities from terrestrial digital time-lapse measurements have been published by Maas et al. (2006) and Ahn & Box (2010). Since then, time lapse- measurements were increasingly used for glacier motion analysis (e.g. Eiken and Sund, 2012; Rivera et. al., 2012; Danielson and Sharp,

15 2013).

Beyond glaciology applications, time-lapse imagery is also of great interest for various geomorphologic investigations: Parajka et al. (2012) e.g. used time-lapse images recorded with an hourly time interval to observe the snow cover in small

20 catchments. Travelletti et al. (2012) evaluate the suitability of terrestrial time-lapse measurements for permanent land slide monitoring. For this purpose a landslide area was observed with a 4 day time interval and displacement rates were derived applying cross-correlation matching to the image series. Matsuoka et al. (2014) conducted a five year investigation with time-lapse images to observe soil movement due to frost creep and heave at alpine slopes, taking images every four hours. To monitor and analyse large wood loads in rivers, Kramer & Wohl (2014) recorded images every minute and manually

25 analysed them regarding the presence or absence of wood. Nichols et al. (2016) used time-lapse images to qualify gully erosion. They identified the subsurface erosion as a cause for gully headwall retreat. Thereby the time-lapse measurements were considered as an important supplement besides topographic survey with total station and Lidar. Stumpf et al. (2016) even used time-lapse measurements to determine river discharge.

30 The simple use of time-lapse cameras as a visual observation tool may already be a great help for environmental investigations. However, beyond that, they have the potential to also deliver precise measurements with high temporal and spatial resolution when applying appropriate photogrammetric image sequence processing techniques. Accordant tools have been e.g. provided by James et al. (2014) or Messerli & Grinsted (2015). In this paper we want to present a detailed methodological concept for the determination of motion vector fields from terrestrial time-lapse image sequences. In

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The main part of the paper will be about methodological issues of photogrammetric image sequence analyses (section 2). After introducing the basic concept of the method (section 2.1), several aspects regarding the measurement setup for time-lapse image acquisition will be discussed (section 2.2). The analysis of the image sequences consists of two main parts. The first one comprises the determination of motion vectors from the images (section 2.3) and the second one the scaling and geo-referencing of the measurement values (section 2.4). The methodological section will be completed with a discussion of the accuracy potential of the presented method (section 2.5). In section 3 we discuss the suitability and possible areas of application of the method at the examples on the basis of different glaciology research pilot studies that were conducted applying the presented time-lapse measurement method and image sequence analysis approach.

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2 Methodological Approach

2.1 Monoscopic image sequence approach - basic concept

In the monoscopic time-lapse measurements, a single firmly installed camera observes the area of interest and continuously records images at a pre-selected time interval. The obtained image sequence is the basis for the determination of glacier motion. Applying appropriate feature tracking algorithms, the position of a large number of moving glacier surface points can be obtained for each image of the sequence. Thus, the glacier point's motion vectors in image space can be derived for each individual pair of sequence images. A trajectory of a glacier surface feature is obtained by tracking points through multiple images of the sequence.

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The motion vectors or trajectories measured in image space have to be transferred into object space. This means they need to be scaled, and the 3D position of the trajectory origins need to be determined. In a stereo approach, a 3D position is determined for each homologous point pair detected in the stereo images (Figure 1). This 3D position also delivers the distance of the point to the cameras, which is required for scaling the measurements from pixels to metric values. However, stereo image measurements on rugged glacier surfaces will often suffer from significant de-correlation. This means, strongly different appearances of glacier surface features in the stereo images affect the automatic detection of corresponding points, thus limiting the precision and reliability of stereo image sequence processing. Therefore, monoscopic image sequences

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processing is more appropriate for phenomena, which are mainly two-dimensional due to the lack of significant transverse components in typical glacier motion patterns. Nevertheless, an approximate digital surface model (DSM) of the glacier as well as the camera position and orientation parameters are required for scaling and geo-referencing of monoscopic image sequence measurements. Based on this information, an image ray can be reconstructed for each pixel and intersected with the DSM (Figure 1). This delivers the distance between glacier and camera for the scaling as well as the 3D glacier point position for the geo-referencing of the measurement value. With knowledge on the time interval between consecutive images, metric velocity values can be calculated from the motion vectors or trajectories.
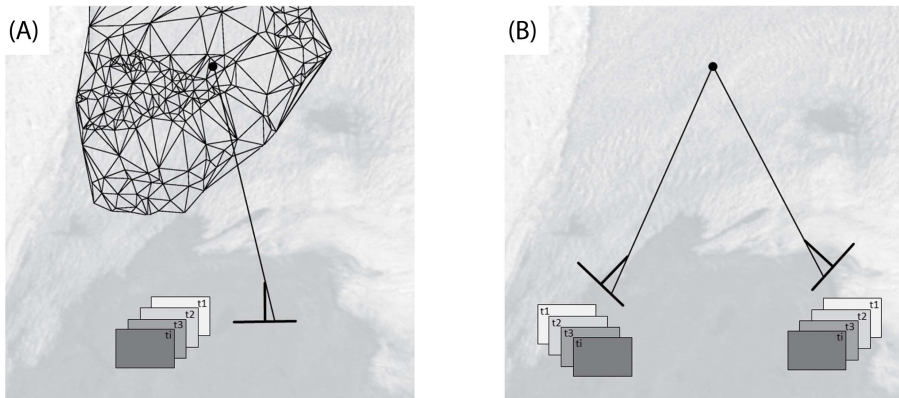
Figure 1: Monoscopic (A) vs. stereoscopic (B) image sequence analysis.

We limit ourselves to monoscopic image motion capture and processing delivering two-dimensional velocity field information here, as the glaciology phenomena observed in the practical experiments do not show significant across-track motion and can thus be well described in 2D (compare section 2.4.3). However, the method can be extended to 3D trajectory measurements from stereoscopic image sequences straightforwardly by inserting an additional stereo image matching step into the data processing chain.

Figure 2 shows the general workflow of the proposed concept for monoscopic time-lapse measurement and processing that will be described in detail in the following sections. The approach consists of two main tasks: The first one comprises the acquisition of the image sequences and their processing (also referred to as 'measurements in image space'). The second one comprises the acquisition of geo-referencing data and their use for scaling and geo-referencing of the image based measurements (also referred to as 'transformation into object space').

The algorithms regarding image sequence processing, scaling and geo-referencing presented here have been implemented in C++. For the bundle block adjustment we used a photogrammetric in-house bundle library (Schneider, 2008). In section

we will also discuss how the processing steps for the geo-referencing can be solved using commercial structure-from-motion (SFM) software (e.g. Agisoft PhotoScan).
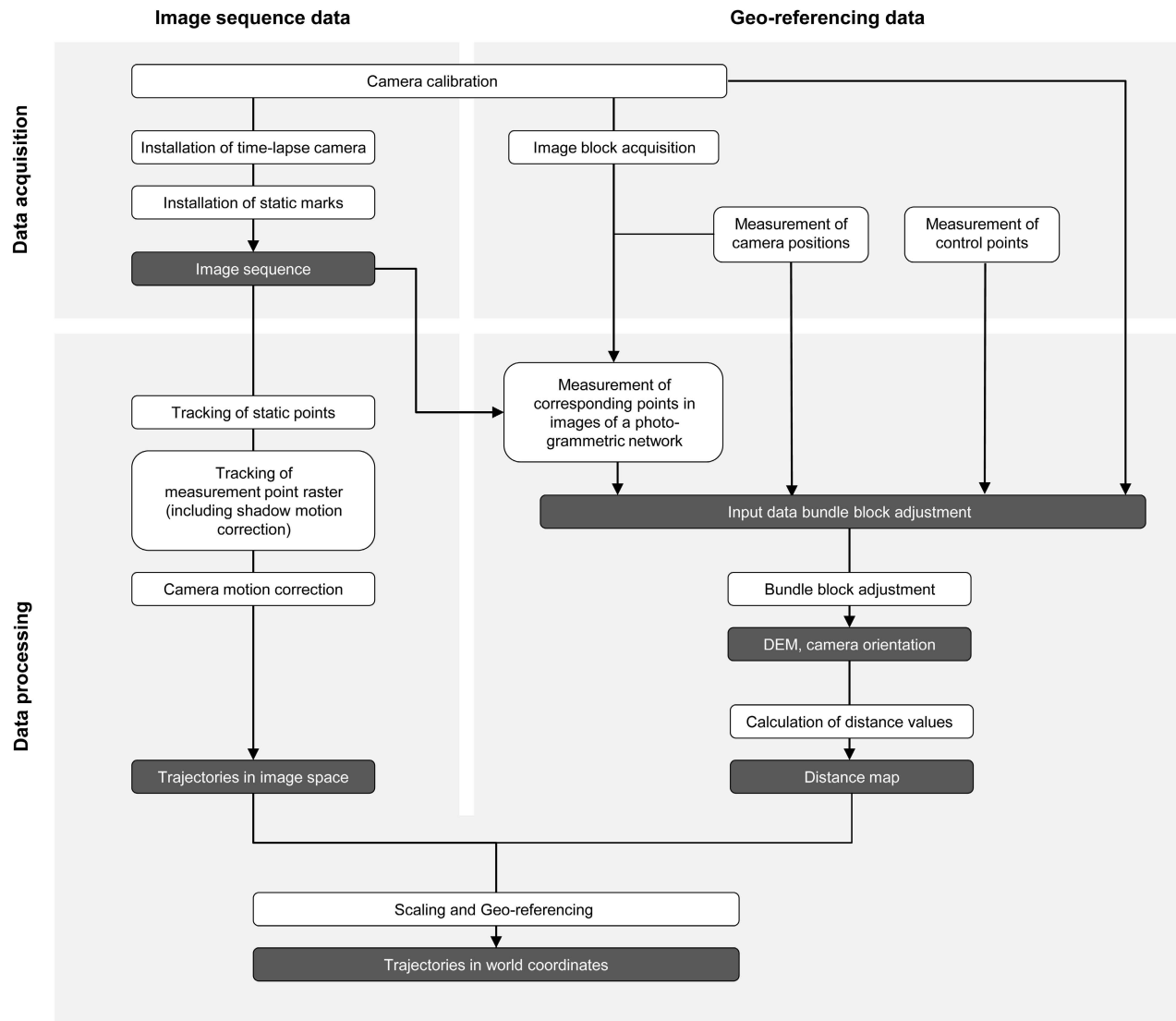

Figure 2: Workflow of monoscopic image sequence measurement

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2.2 Data acquisition concept

In order to guarantee a high inner accuracy of the final trajectories, we propose an integrated geo-referencing and time-lapse measurement approach. Thus the measurement setups for the time-lapse measurement and the geo-referencing cannot be considered independently from each other. Figure 3 shows the basic combined time-lapse and geo-referencing measurement setup (A) and the required visual content of the measurement image acquired by the time-lapse camera (B) to meet the demands of successful precise data processing.
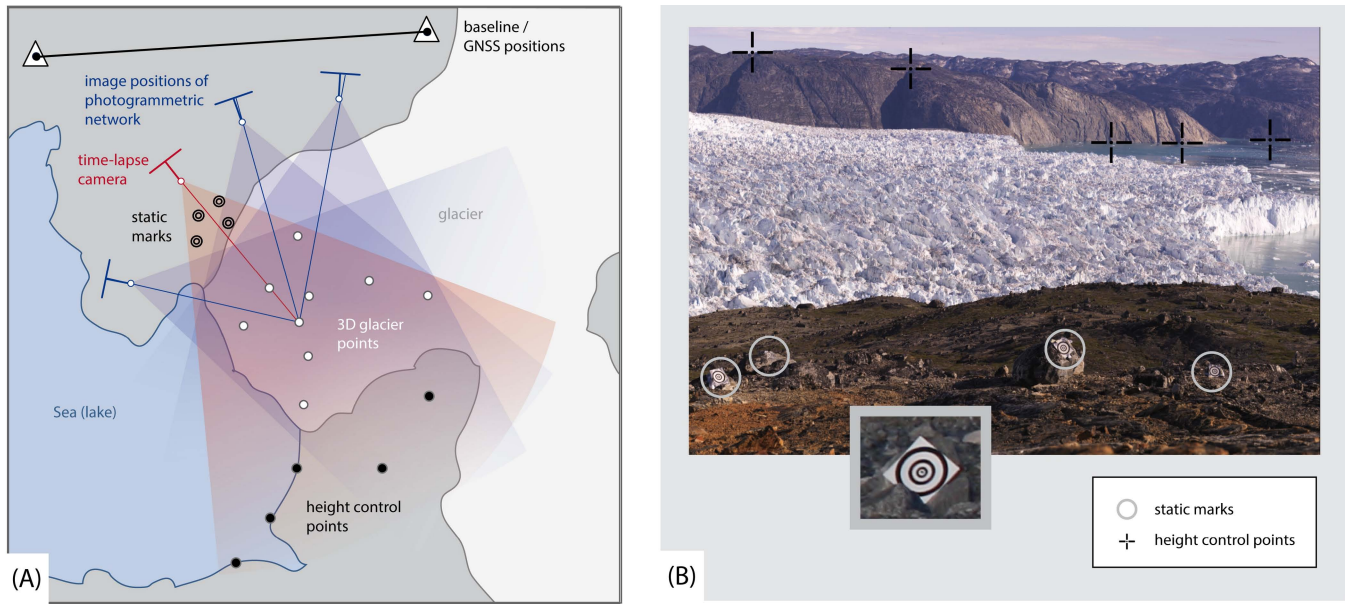
Figure 3: Combined scheme for the setup of a time-lapse camera and its corresponding geo-referencing measurement setup (A), measurement image of time lapse camera (B)

The main requirement for a camera to be used for glacier motion analysis is the ability to autonomously record images at defined time intervals over a certain period of time. It should therefore be equipped with a programmable timer as well as a weatherproof housing, sufficient power supply (e.g. a batteries supported by a solar panel) and sufficient data storage capacity.

For a flexible and stable installation of time-lapse cameras, tripods thoroughly covered with stones have proven to be suitable. To determine both horizontal and vertical components of glacier motion and to avoid occlusions on the glacier surface, an elevated camera position is required, which allows for an oblique viewing angle on the glacier surface. Despite the stable installation of a time-lapse camera, slight camera motion (mainly induced by wind and temperature effects) cannot be completely prevented. To compensate for this, it is necessary to have static points visible in the images, which can be

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used for correcting the influence of camera movement (see section 2.3.3). These may be natural features in the image fore- and/or background, but in most cases artificial marks placed in the foreground (Figure 3, B) turned out to be more accurate and reliable.

5   For the geo-referencing and scaling of measurement values of the monoscopic time-lapse camera approach, the geometric relation between image and glacier surface must be known. Thus, a digital surface model of the glacier and the orientation parameters of the time-lapse camera have to be determined. This can be achieved by establishing a local photogrammetric network (consisting of several convergent images taken from different positions as shown in Figure 3) plus some additional measurements. The acquisition of the accordant multi view images is conducted shortly after starting the time-lapse camera.

10   Together with one temporarily fitting image of the recorded time-lapse sequence, these images form a photogrammetric network, which allows for the simultaneous determination of glacier surface point coordinates and camera orientation parameters by photogrammetric bundle adjustment (see e.g. Kraus, 2007 or Luhmann et.al., 2006). A minimum constellation to transform the results into a scaled and horizontal world coordinate system (i.e. to establish a geodetic datum) is given by the knowledge of two camera positions (preferably those forming the longest baseline) and one height control point

15   (preferably at a far distance). However, it is recommendable to use redundant information in the process of geo-referencing. Therein, depending on the local topography, different variants of measurement setups are possible which require different measurement equipment and effort:.

Variant 1: A minimal geo-referencing measurement equipment consists of a hand held GNSS (global navigation satellite

20   system) device and a hand held laser distance measuring device. This instrumentation is sufficient, if a high accurate elevation reference is not required for a certain measurement task. Using the hand held GNSS, at least two camera positions (preferably those, which form the longest baseline) and at least one control point (ideally 5-10 for redundancy) in the background of the measurement object need to be measured. With the hand held laser distance measuring device precise distances between camera positions can be determined. The distance between the camera positions (called base length)

25   defines the scale for translating image measurements into object space, and errors in the base length will propagate linearly into the length of determined motion vectors and trajectories.

Variant 2: A special, advantageous case occurs when the shoreline of a lake or the sea is visible in the time-lapse images. The control point measurements can then be reduced to a single water level measurement that delivers the Z-coordinate for

30   several height control points along the shore line. These height control points form a good basis for defining the world coordinate system horizon.

Variant 3: If a higher positioning accuracy is required, the camera position determination via hand held GNSS measurements should be replaced by differential GNSS measurements. Besides an accurate elevation reference, camera positions measured

with an accuracy of a few centimeters ensure a more accurate scaling of the photogrammetric network, thus making additional laser distance scale measurements dispensable. Depending on the cameras resolution, it might still be sufficient to measure control points using hand held GNSS if they are located in adequate distance from the time-lapse camera.

Variant 4: The highest measurement effort is required for measuring environments in which the control points are inaccessible or very distant. In these cases control points need to be determined via triangulation. For this purpose a base line has to be established whose coordinates are measured via GNSS. From the base line positions, angle measurements are conducted by a tachymeter instrument to determine coordinates of control points via spatial intersection. Camera positions can then be transformed from a local horizontal coordinate system into a global coordinate system by the GNSS measurements.

2.3 Image Sequence analysis

This section will focus on the measurements in image space. The basis is a recorded image sequence of a moving glacier. To derive motion vectors from an image sequence, an appropriate feature tracking algorithm is required as well as an appropriate tracking strategy. To obtain reliable results, suitable methods need to be developed to compensate for the main error influences, including the effects of camera motion as well as effects of the motion of shadows on the glacier.

2.3.1 Feature tracking

For glacier surface point tracking a wide range of algorithms is available (see e.g. Brown, 1992 and Zitová & Flusser, 2003). Generally they can be separated into feature based and area based methods. Area based methods establishing correspondences between small image patches by minimizing some cost functions are able to provide results with sub-pixel accuracy and allow for a dense and regular distribution of measurement points over the image area of interest. Feature based techniques extract discrete features from the image and track those by comparing values of a defined feature vector. We chose an area based method for the task of glacier motion determination due to the higher accuracy potential. The chosen method depicts a combination of cross correlation (e.g. Lewis, 1995) and least squares matching (LSM) (Förstner, 1982; Ackermann, 1984; Grün, 1985). The cross correlation method is a fast option to obtain approximate values that are required for LSM. The advantage of LSM is that it is an adaptive, robust and accurate approach. It directly estimates sub-pixel accuracy patch translation parameters and simultaneously delivers figures on their accuracy and reliability. Furthermore, LSM is also capable to consider rotations and linear distortions of patches.

In order to determine glacier motion fields, a dense raster of points needs to be defined in the first image of the image sequence. For each of these measurement points a patch has to be defined as well as a search area before applying the actual tracking algorithm. The patch contains the area of pixels around the measurement point to be tracked, and the search area

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defines the region were the corresponding point might be located in the subsequent image. There are special demands on both of them when monitoring glaciers:

The resulting motion vector for a certain patch will be an interpolated value for the area on the glacier surface that is covered by the patch. When terrestrially observing glaciers the view to the glacier surface will usually be rather oblique. Thus a quadratic patch that contains an adequate amount of pixels will cover an area on the glacier surface that has a large extension in depth direction (i.e. across glacier motion). This is especially critical for remote measurement points. In order to address this problem, a specific rectangular shape is chosen for each patch (Figure 4). To automatically define the optimal patch size, two parameters are predefined. The first one is a number of pixels a search patch should contain to ensure stable matching, and the second one is a maximal difference in depth a patch should cover to avoid interpolation over large areas. While the depth parameter restricts the extension of the patch in y-direction, the given number of pixels lets the patch proportionately grow in x-direction. The DSM of the glacier surface that is required to obtain the necessary distance information for patch shape restriction can be provided as described in section 2.4.2.
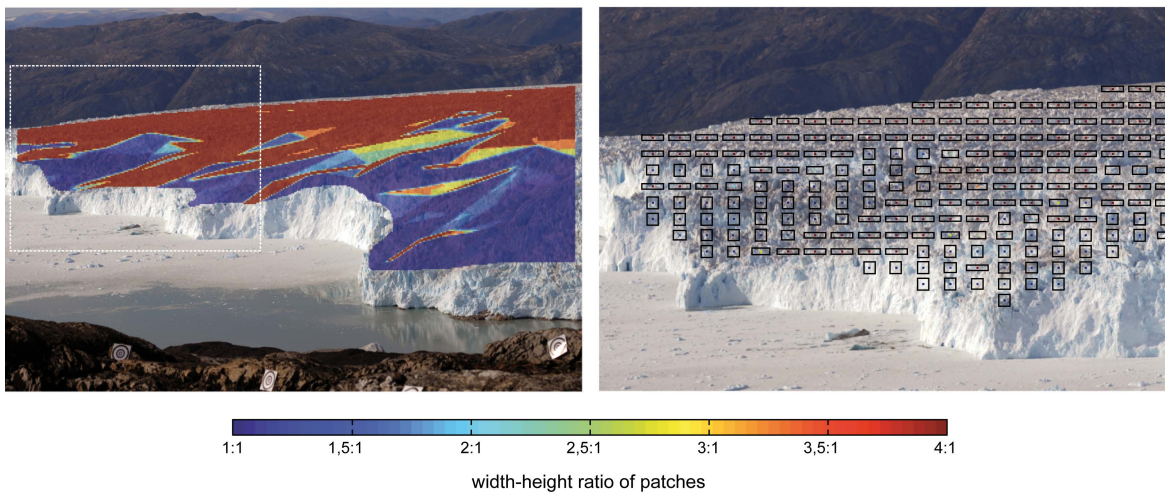
Figure 4: Locally adaptive patch sizes. The figure shows the result of the automatic patch size definition taking into account distance differences in the patch. On the left, the determined aspect ratios for a patch are shown colour-coded at the corresponding position in the image. For a smaller image excerpt (white rectangle), the resulting patches (black contour) are superimposed on the sequence image on the right.

For the purpose of glacier motion measurements, the search area can be strongly limited in most cases. It mainly depends on the chosen time interval of the image sequence. Usually, the temporal resolution of the image sequences is high enough to keep the glacier movements between subsequent images small. In most cases the motion direction is predictable and the velocity of a glacier surface point does not change rapidly between subsequent images. Furthermore, the search area also

depends on the influence of the camera motion, which can be determined beforehand (see section 2.3.3). This a-priori knowledge can be used to restrict the search area in order to reduce mismatches and ambiguities during tracking.

Depending on the application, different temporal or spatial strategies can be applied for the tracking points in an image sequence. Temporal strategies can be distinguished depending on how images of a sequence are combined for tracking. For instance, a trajectory can be determined by always tracking a point from the first image of a sequence into each of the other sequence images, or it can be determined by successively tracking the point from each image into the subsequent one. The first version in comparison to the second one is stronger regarding error propagation but weaker regarding image de-correlation. Thus, the first strategy ~~might~~ has to be applied when tracking signalised points - as for camera motion determination (see section 2.3.3) - and the second one when tracking natural points like glacier surface points.

Spatial strategies mean that either a certain feature (e.g. a specific crevasse) can be tracked through the image sequence (Lagrangian approach), or the tracking is performed at a fix position for each image of the sequence (Eulerian approach). The advantage of the first method is that it provides good visual control over the success of the tracking. Advantageous of the second method is that it is independent on the loss of features (e.g. because of calving). This is especially imported for long-time observations. However, for most applications motion values are required that refer to a fix position in space, which makes the Eulerian approach the standard for the tracking of glacier surfaces. For a subset of the measurement image, Figure 5 shows trajectories resulting from feature tracking on fix position. The single measured translations of a trajectory, which are depicted here arranged one after the other, all refer to the starting point position of the trajectory.
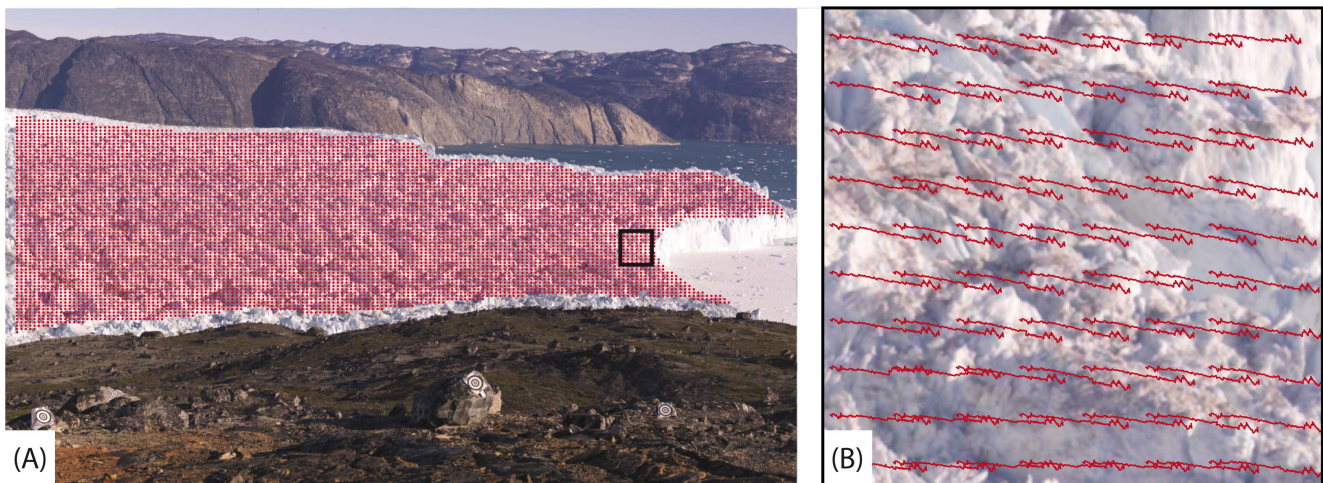

Figure 5: Raster of measurement points on the glacier surface (A) and resulting trajectories obtained from feature tracking (B). The figure shows the grid of the measuring points (red dots) as a superposition of a sequence image (A). For the black-marked area, the corresponding image section is shown on the right. It is superimposed by the measured trajectories (red lines) for a 24 h image sequence (acquisition interval 20 min) (B).

2.3.2 Handling of shadow motion effects

The changing positions of the sun during a day as well as moving clouds generate moving shadows on object surfaces. In case of environmental monitoring time-lapse observation, the motion of shadows may be a rather imported issue. It influences the tracking method described above in such a way that the obtained motion vectors will be a combination of actual glacier motion and shadow motion. More specifically, it is not the whole area covered by a shadow that causes matching errors, but the image areas that change from shadow to non-shadow and vice versa (see Figure 6). Thus, to obtain pure glacier motion the pixels of these areas need to be detected and excluded from the matching (see Figure 6, B).
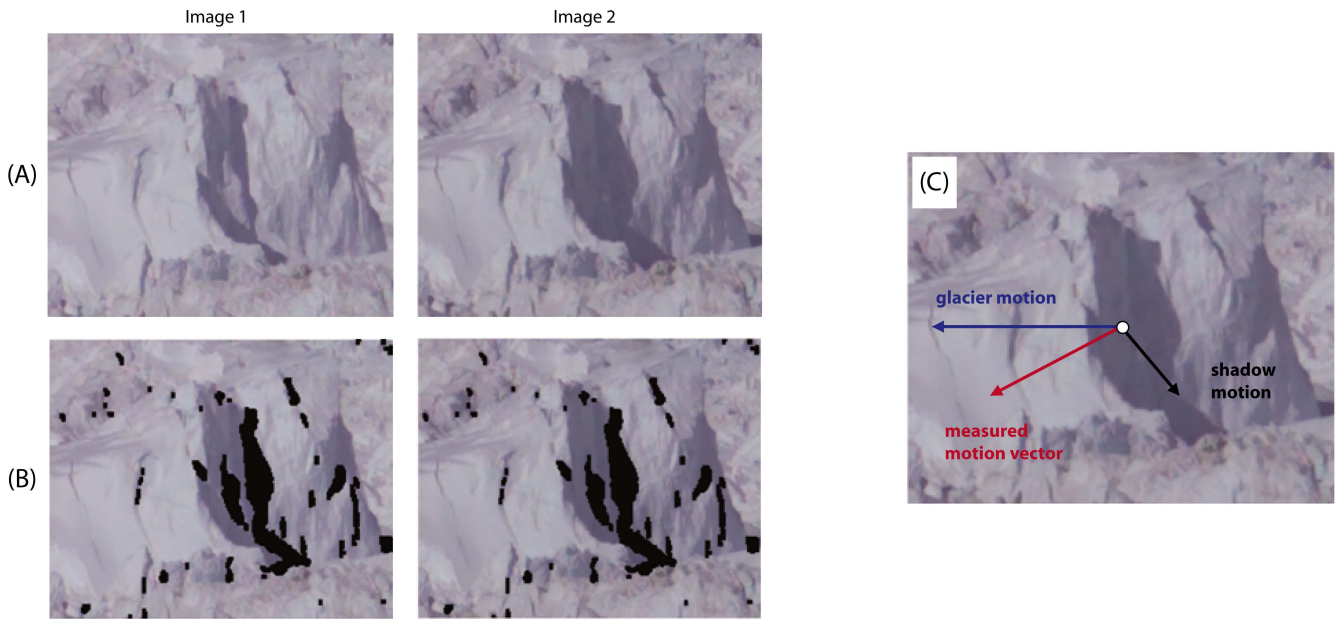
Figure 6: Influence of moving shadows in image sequences. The figure shows corresponding image sections from two sequence images recorded at a time interval of 30 min (A). In the same image pair those pixels were marked black, which are influenced by shadow motion (B). These pixels falsify the result of the feature tracking because the tracked glacier movement is overlaid by the shadow movement (C).

The method developed to exclude shadow influenced pixels during the matching will be described with the aid of a synthetic image pair as shown in Figure 7, wherein the slave image is a copy of the master image, but shifted in a predefined way (glacier motion simulation). Additionally, both images are overlaid by a transparent black square whose position in the slave image is shifted by a certain amount in comparison to its position in the master image (shadow motion simulation). In this way a shadow overlaid glacier motion is simulated where reference values for both motion components are available.
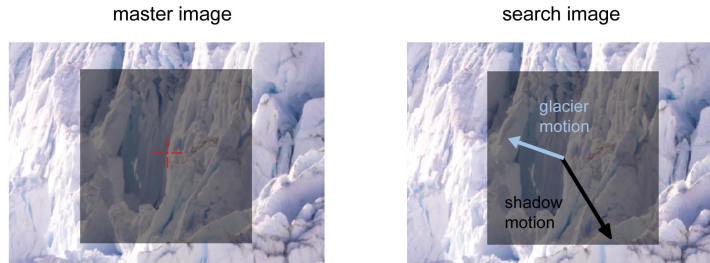
Synthetic image pair:

simulated glacier motion:

Δx_{G_Ref} = -5,00 pixel
Δy_{G_Ref} = -2,00 pixel

simulated shadow motion:

Δx_S = 6,00 pixel
Δy_S = -10,00 pixel

master image

search image

glacier motion

shadow motion

Measurement - LSM with shadow pixel exclusion:

difference image

excluded pixel

**1. Iteration
(LSM without exclusion):**

measured glacier motion:
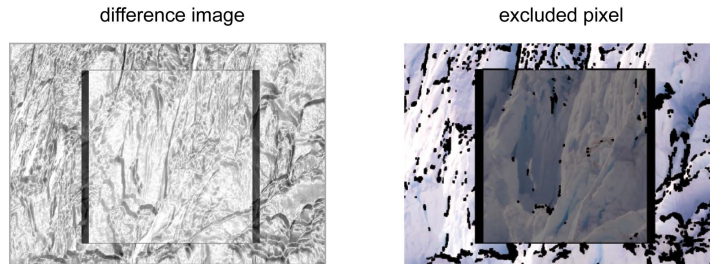
Δx_{G_LSM} = -0,98 pixel
Δy_{G_LSM} = -9,52 pixel

**2. Iteration:
(LSM with shadow pixel
  exclusion)**

measured glacier motion:

Δx_{G_LSM} = -4,06 pixel
Δy_{G_LSM} = -5,02 pixel
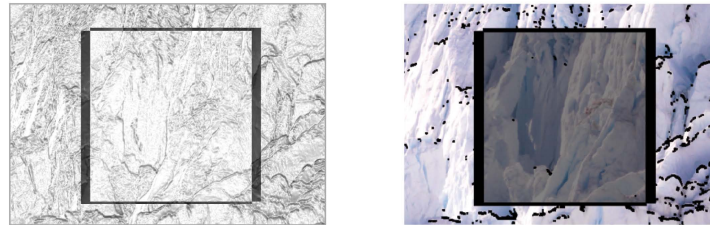
**3. Iteration:
(LSM with shadow pixel
  exclusion)**

measured glacier motion:

Δx_{G_LSM} = -5,00 pixel
Δy_{G_LSM} = -2,00 pixel

Figure 7: Least Squares matching with shadow pixel exclusion. The figure shows a synthetically generated image pair, which simulates a glacier motion superimposed by shadow movement, for which reference values are known (top). A method which iteratively detects and excludes shadow motion pixels from the matching is applied to this image pair (below). For each iteration step, the calculated translation parameters (left), the difference image between patch and transformed search patch (center), as well as the resulting exclusion pixels for the next iteration, which are superimposed as black pixels on the patch (right), are shown.

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12

In order to determine shadow motion pixel, the following iterative approach is applied: Initially all pixels of a patch will be incorporated into the matching process via LSM. The corresponding patch at the thus determined position in the slave image is still completely influenced by the shadow motion. In the ideal case the gray value differences between original and corresponding patch would be zero after LSM transformation. In the first iteration step this perfect match cannot be achieved

5   because the influence of moving shadows leads to an erroneous position of the corresponding patch. Thus high grey values occur in the difference image of the master patch defined in image 1 and its corresponding patch detected in image 2 especially at the margins of the shadow areas (Figure 7, 1st iteration). This information can be used to detect and exclude shadow influenced pixels to guarantee a better solution in the next iteration step. Since high difference values do not solely cover shadow shift areas but also some important glacier texture we have to find an appropriate threshold that removes

10 disturbing shadow influenced pixels but keeps enough good glacier texture for the matching as well. When looking at the histogram of the difference image the difference values are approximately normally distributed in most cases. The shadow influenced pixels show the highest grey value differences and accumulate at the upper and lower margin of the histogram. Thus, using the single standard deviation of the difference values as a threshold ensures that no more than ca. 30% of the pixels of a patch are excluded and enough texture remains in the patch. Pixels with grey value differences higher or lower

15 than the single standard deviation are defined as potential shadow motion pixels and are excluded from the matching procedure during the second iteration step. In this way the recalculated position of the corresponding patch is drawn to its real position. After the first iteration some real shadow motion pixel but also a noticeable amount of non-shadow pixel is excluded. This ratio improves during the next iteration step along with the improvement of the matching result. The process continues until either the matching result does not change anymore or no more new shadow motion pixels can be found (for

20 the example shown in Figure 7 this was achieved after the 3rd iteration). The comparison of the reference values of the synthetic example in Figure 7 with the tracked glacier motion values after the last iteration step show, that the influence of the simulated shadow motion could be completely eliminated.

Of course, image sequences of natural scenes are influenced by illumination differences as well as by random noise of the

25 sensor. This will also affect the quality of the matching result. Nevertheless the results can be significantly improved applying the method described above (Figure 8).
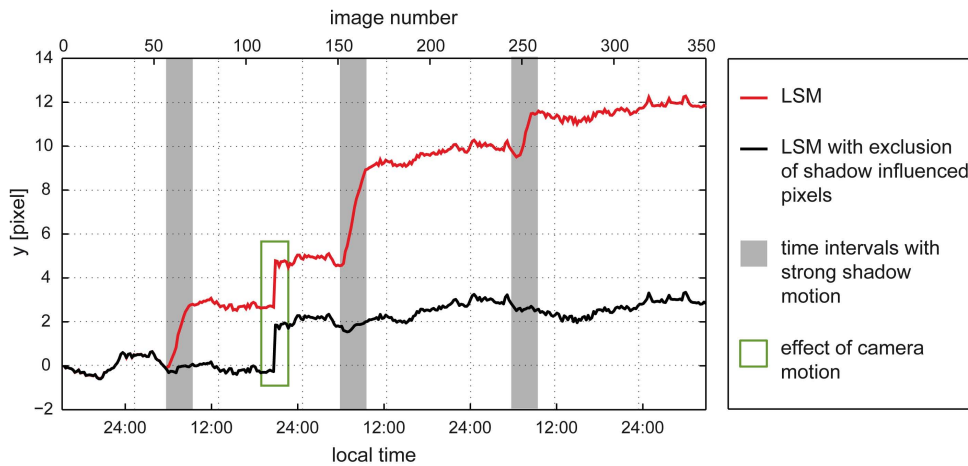
Figure 8: Drift effects during the measurement of a trajectory due to shadow movement. The figure shows the vertical component of a glacier trajectory measured using least squares matching (LSM) with and without shadow pixel exclusion. At certain times of the day (gray background) particularly strong shadows occur. Both motion curves still contain the influence of the camera motion.

2.3.3 Camera motion

The second main error source that might impact the motion vectors or trajectories is the effect of the motion of the time-lapse camera itself. Even if a camera system is firmly installed, small movements caused by wind and temperature changes cannot be avoided. Thus, their impact on the measurements needs to be determined and corrected. As techniques such as LSM are capable of measuring image motion with a precision <0.1 pixel, camera motion has to be corrected for at an equivalent level.

The effects of camera motion can be determined (and corrected) by tracking static points in the images. These can either be signalized targets or natural points (Figure 9). To facilitate camera motion compensation, a sequence image must not only contain the dynamic measurement object (e.g. a moving glacier), but also some terrain in the foreground and/or background. While signalised points can usually only be installed in the foreground area and are limited in number, natural points may be defined all over static image areas. Although natural points basically provide a better distribution for the modelling of camera motion, their disadvantage is often a lower contrast and their sensitivity to illumination changes, moving shadows and visibility limitations. This will often lead to a lower precision and reliability potential for tracking natural points as compared to signalized targets. However, using the high redundancy of natural points in combination with a robust estimation method such as RANSAC (Random Sample Consensus, Fischler & Bolles, 1981), this can be compensated to some extent. Thus, for applications where tracking intervals of 24 h (i.e. minimized influence of illumination and shadow variations) are sufficient, natural points might be preferred. For tracking tasks with higher temporal resolution signalised points are often recommendable.

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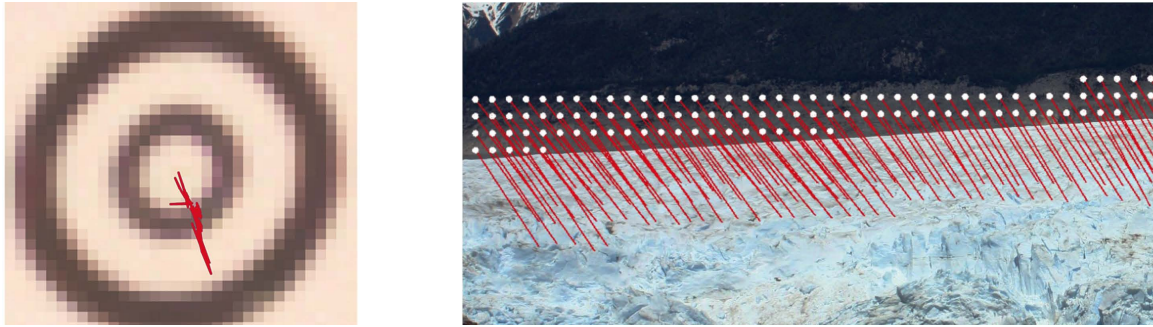
Figure 9: Tracking of static fiducial marks and/or static natural points. On the left, the figure shows an example of a signalised static point as it is visible in a sequence image. The red line here shows the motion path of the mark during a 24h image sequence (acquisition interval 20 min). On the right, an example for the use of natural static points is shown. The white dots represent a raster of static points that have been defined on the mountain slope in the background of the glacier. The red vectors (enlarged) represent the results for tracking these points from one sequence image into another one recorded 24h later. The red motion lines of the static points (signalised or natural) correspond to the effect of camera motion.

The tracking of static points results in displacement vectors for each subsequent image pair representing the camera motion between the two consecutive image recording times. These vectors can be used to derive parameters that appropriately describe the influence of camera motion for each individual pixel of the image. In general, two options to model camera motion are possible: The first option is to mathematically describe the real physical motion of the camera in object space defining position and orientation changes of the camera as model parameters. The second option is to mathematically describe the effects of the camera motion in image space by a planar transformation. Applying the first method provides a higher accuracy potential, as also distance depended effects can be modelled, which is not possible when applying a planar image transformation. However, in most cases it is sufficient to describe the effects of camera motion in image space via the two image shift parameters and the rotation parameter of a 2D rigid transformation.

In order to calculate the transformation parameters, the start and end coordinates of each tracked static point displacement vector are introduced to the equations of the affine transformation. Since each vector provides two equations, two static points would be sufficient to solve the equation system. Using natural static points, the rate of outliers among the tracked displacement vectors may be significantly higher than for signalised points. However, this can be compensated by using a larger number of the natural points, eliminating outliers by robust techniques such as RANSAC. Applying these transformation parameters to the image coordinates of tracked glacier surface features, an individual correction value can be determined and applied to each of the measured motion vectors (Figure 10).
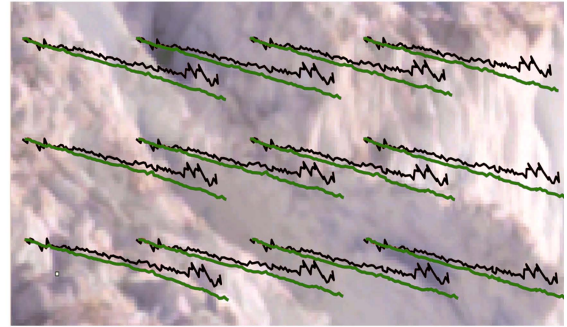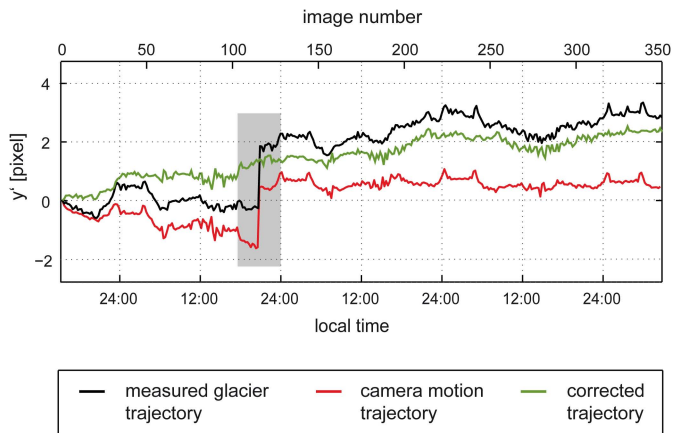
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Figure 10: Application of camera movement compensation. The chart on the left shows the vertical component of a measured trajectory (black), the camera motion trajectory (red) and the corrected trajectory (green). The gray area indicates where a jump in the camera movement occurred. On the right a small subset of a sequence image is shown overlaid by some measured trajectories (tracked trough a 24h image sequence).The originally measured trajectories (black) clearly show fluctuations caused by camera motion. In contrast, the corrected trajectories (green) finally represent the smooth glacier movement.

2.4 Geo-referencing

After feature tracking, camera motion and shadow correction, glacier surface motion vectors and trajectories are available in image space. However, to allow for a reasonable interpretation of these motion vectors and trajectories, they need to be scaled from pixel to metric space (Figure 11, A) and linked to their absolute 3D position in object space (Figure 11, B). Obviously, each vector or trajectory has its own scale factor due to their varying distance to the camera. While proper scaling is required for motion analysis, absolute geo-referencing is a precondition to fuse measurements with other data (e.g. remote sensing image overlay) or to compare measurements of different epochs or measurement techniques. This section describes how the geometric reference between image and object space can be realised.

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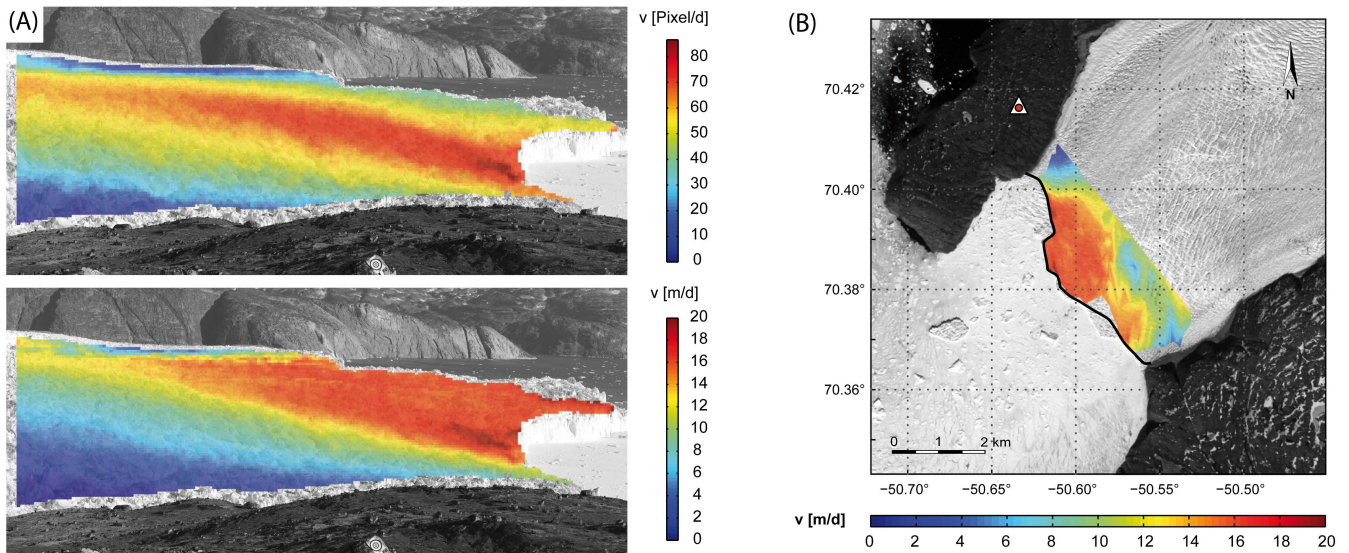
Figure 11: Result of scaling (A) and geo-referencing (B) at Støre Qarajaq glacier. The figure shows the color-coded superposition of velocity values derived from measured trajectories. They are shown as unscaled values in image space (A, top) and scaled values transferred into object space (A, bottom), as well as geo-referenced values that can be overlaid on satellite images (B).

5

2.4.1 Camera orientation and 3D elevation model of the measurement object

The basis for all further evaluation steps is the determination of object coordinates on the glacier surface. These are used to calculate a coarse digital surface model for the glacier area visible in the image sequence, which forms the basis for the determination of the distance between camera and glacier surface points as needed for scaling. For this purpose, further

10 knowledge on the position, orientation and intrinsic calibration of the time-lapse camera is required. In order to determine these parameters we make use of a photogrammetric network setup as described in section 2.2.

The recorded multi-view images, including an image from the time-lapse camera, are processed via photogrammetric bundle block adjustment (e. g. Kraus 2007), allowing for simultaneous determination of camera orientation parameters and glacier

15 surface point coordinates at a high accuracy. In contrast to other approaches (e.g. Box & Ahn, 2010 or Messerli & Grinsted 2015), which use an external DSM that needs to be registered with the time-lapse image, we propose an integrated solution to derive the DSM and its registration with the time-lapse image in one step. This offers high inner accuracy and avoids registration errors. The thus obtained glacier surface elevation model is optimally adapted to the time-lapse camera field of view and its oblique viewing angle.

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For the processing we originally solely used a photogrammetric in-house bundle library (Schneider, 2008). With the advancing development of structure from motion tools we also started to integrate some of the SFM-functionalities into our

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workflow. For this purpose we now use a combination of Agisoft PhotoScan and the photogrammetric in-house bundle. We e.g. took advantage of PhotoScan to automatically measure image coordinates of corresponding points in the images of the image block, which were exported into the bundle block adjustment. Going a step further and calculating the sparse cloud while providing the measured camera positions to PhotoScan, the thus determined 3D coordinates of object points can also be exported and used as approximate values for the bundle block adjustment. The major advantage of an open photogrammetric bundle is in the fact that it allows for a thorough error analysis and flexibility regarding different measurement configurations. It can be adapted to different types of control points as well as different sets of camera calibration parameters, scale conditions can be defined, and it provides the possibility to define each variable as fix or parameter to be estimated. Since many SFM tools are rather optimized for fast processing and 3D-visualization than for accurate measurement purposes, some limitations may have to be taken into account, when applying them for measurement tasks (compare e.g. Eltner and Schneider, 2015; James et al., 2017). However, when using a geo-referencing setup that allows for the measurement of 3D-control points instead of height control points it is also possible to determine object coordinates and camera orientation parameters solely using PhotoScan. Preconditions for this are, a network configuration of at least 3 images and 3-5 3D control points.

Due to restrictions posed by the terrain, the intersection geometry of the photogrammetric network established in the field is often rather poor. Thus, it is recommendable to measure the cameras positions in the field and to pre-calibrate the cameras in the lab or in the field. For camera calibration we used the photogrammetric software "Aicon 3D Studio" and coded targets that can be measured with sub-pixel accuracy. To warrant up-to-dateness of the camera parameters and to avoid changes of the interior orientation due to transport, it may be beneficial to install a calibration area in the field and calibrate the cameras shortly before taking measurement images or installing them as time-lapse cameras. The cameras camera position coordinates and the parameters of interior orientation and lens distortion are then introduced as fix values into the bundle block adjustment to stabilise the network and to minimize correlations between parameters. Seven degrees of freedom need to be fixed for the network (3 translations, 3 rotations, 1 scale). This can be achieved with at least two 3D control points and one height control point. Thus, the minimum setup, which can be used, consists of an image network of two images with known positions and a single height control point. However to ensure a successful and accurate processing of the photogrammetric network 5-10 control points that are well distributed within the field of view are recommendable.

As result of the photogrammetric bundle block adjustment, the orientation parameters of the time-lapse camera and 3D coordinates of a large number of object points on the glacier surface plus an individual error value for each parameter and coordinate are obtained. In case of solely using PhotoScan, camera orientation parameters and very dense 3D point clouds of the glacier surface are derived as well but without an integrated error analysis.

2.4.2 Distance map

In order to generate the DSM, the calculated 3D object points are meshed to a TIN (triangular irregular network, e.g. Delaunay, 1934). Using the DSM the individual distance between the camera and the corresponding object point on the glacier surface is assigned to each pixel in the time-lapse image. For this purpose, the image ray for each pixel can be reconstructed based on knowledge about the exterior and interior orientation of the time-lapse camera and intersected with the DSM. From this intersection point and the camera projection centre, the distance value for the corresponding pixel is obtained (see Figure 12). The distance image thus created forms the basis for scaling the individual trajectories and can also be used for automated parameterization of individual patch shapes in image sequence analysis (compare section 2.3.1).
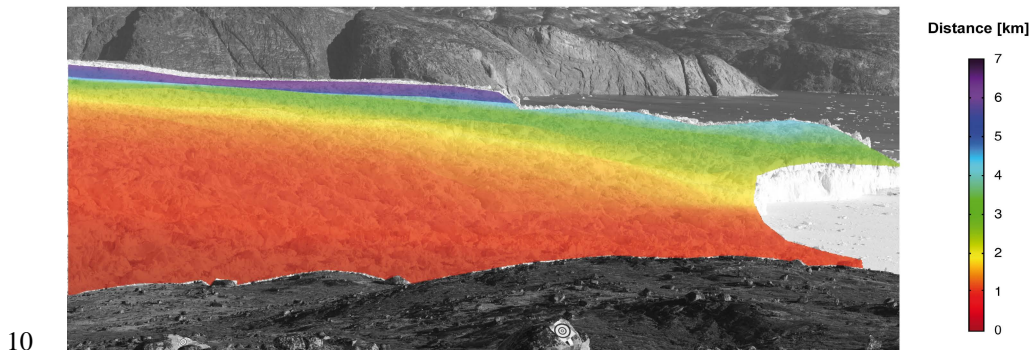

Figure 12: Distance map

In case of using solely using PhotoScan for bundle block adjustment and distance calculation, the results we need to obtain from the PhotoScan bundle are the exterior orientation parameter of the time-lapse camera and from the dense matching step we need to obtain the depth map of the measurement object (a depth value for each pixel of the time-lapse image). Both can be exported for the time-lapse image. After converting the depth map (containing depth coordinates of object points referring to the camera coordinate system) into a distance map (containing distance values between object points and the cameras perspective centre), the output can be further used as described in the following.

### 2.4.3 Scaling and position determination

In case of a horizontally oriented camera and an orthogonal viewing direction of the camera to the flow direction of the glacier, the motion vectors can simply be scaled by the distance values. However, this can usually not be perfectly realised in the field and is often not desirable either, since the sequence cameras field of view should cover the measurement area optimally, which often necessitates an oblique viewing angle. When applying a simple scaling by distance, erroneous vectors (red vectors compared to the correctly scaled vectors in green) would be obtained as shown in Figure 13 (A). The size of the

error depends on the motion vectors position in the image and the deviation of the viewing angle from orthogonality to the glacier motion direction Figure 13 (B).

(A)   (B)
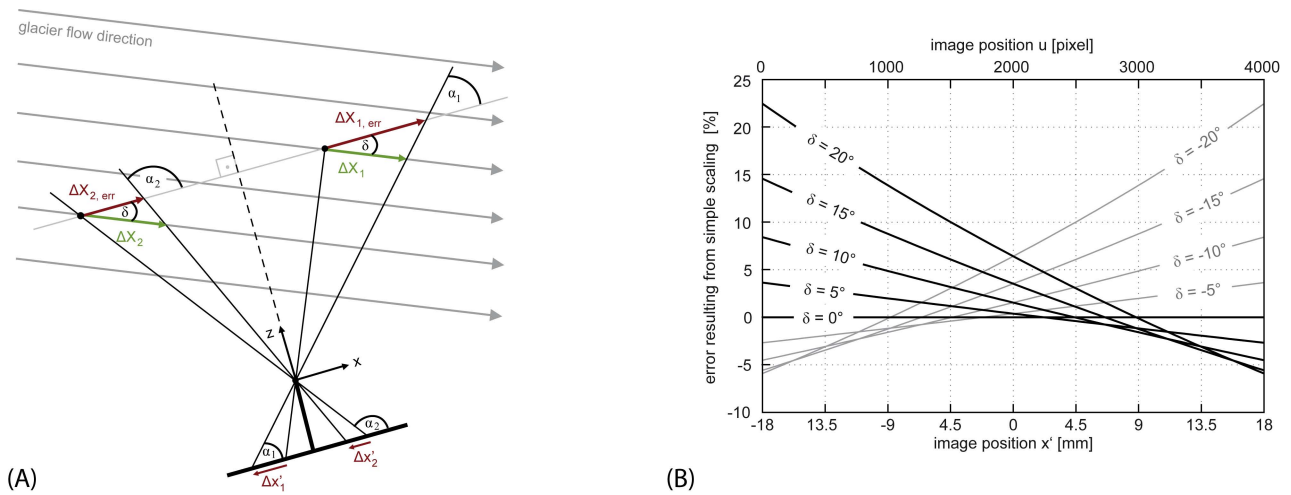
Figure 13: Scaling error in case of a deviation δ from orthogonality between the glacier flow direction and the viewing direction of the camera (shown for the horizontal motion component).

Thus, a more comprehensive method for the transformation of a vector or trajectory into object space is required. In the monoscopic approach, model assumptions have to be made about the direction of movement of object points. It is assumed that each glacier point moves in a vertical plane oriented along the flow direction of the glacier, i.e. that there is no significant motion across the moving direction (see Figure 14). Starting from the first point P' of a motion vector or trajectory given in image coordinate system, the image ray is reconstructed and the corresponding 3D object point P is determined by means of the known distance. The object point P, the vector of the glacier flow direction and its perpendicular define the vertical movement plane for the measured point. The glacier flow direction can e.g. be obtained via flow-line patterns that are visible in satellite orthophotos. By intersecting the image ray of the second motion vector point or of each further trajectory point with the thus defined vertical plane, the 3D object coordinates can be determined for all points of a motion vector or trajectory.
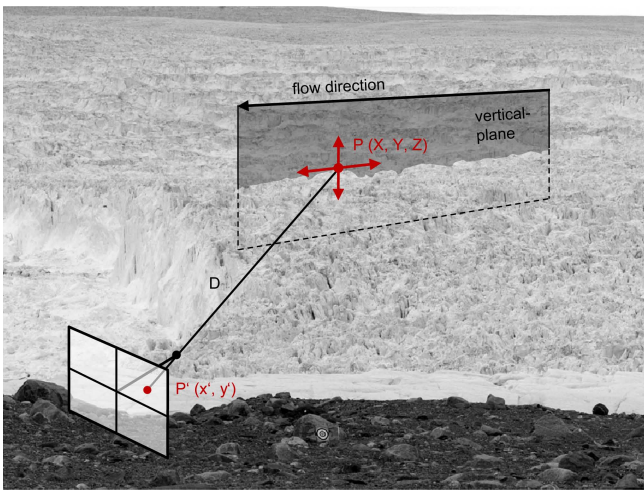
Figure 14: Transformation into object space.

2.5 Aspects of accuracy

5   The error of a determined motion vector is composed of several individual error influences. According to the individual steps of the image sequence analysis, four main error sources can be distinguished: The error of the image point tracking, the error of the camera movement correction and the scaling error as well as the error of geo-referencing. Whereas the three first mentioned errors have an influence on the accuracy of the determined translations, the geo-referencing error affects the accuracy of the spatial reference of the translation values. The errors of image point tracking and camera movement

10   correction occur during the measurement in image space, the errors of scaling and the geo-referencing while transforming the measurements into object space. The effect of each of these errors on the measured translations is also influenced by parameters of the time-lapse measurement setup, namely the principal distance and sensor size of the camera, the recording interval of the time-lapse sequence, the distance to the object, the local position of the measurement point in the image and the amount of the measured translation itself.

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At the example of an image sequence measurement at Jakobshavn Isbræ in May 2010 we exemplarily want to show the magnitude of accuracy that can be achieved with the method. For this time-lapse measurement a Canon EOS1000D (pixel size 5.7 µm) has been used equipped with a 35 mm lens which recorded images with an interval of 20 min.

20   For a sample trajectory (in a distance of 3000 m from the camera) of this dataset, the main error effects mentioned above have been estimated for each translation value of the trajectory applying statistical error estimation techniques (compare e.g. Niemeier, 2002; Taylor, 1997):

For the determination of the error of image point tracking the error analysis that is integrated part of the LSM procedure provides accuracy values that result from the statistical evaluation of gray-value differences between two patches. The standard deviation for a matching is thus a measure of the influence of the sensor noise and how accurately the transformation model of the LSM approximates reality. Although the influence of shadow motion is significantly reduced by the method explained in section 2.3.2 a remaining error of shadow motion influence and in case of the vertical translation component also refraction effects have to be considered additionally. Thus, on average, an error of 0.05 pixel for the horizontal and 0.17 pixel for the vertical motion component were estimated for the single translations of the trajectory. These errors in image space translate into error values of 2.3 and 8.1 cm in object space referring to the distance of 3000 m between measuring point and time-lapse camera.

The accuracy with which the camera motion correction can be applied is influenced by the tracking error of the static targets as well as by the quality of the functional model, which is used to mathematically describe the camera motion (see section 2.3.3). On average, we estimated an error of camera motion correction of 0.14 pixels for the measured translations of the example trajectory. Regarding to the distance of the measuring point from the camera, this corresponds to an error of 6.8 cm for each motion component.

The error of scaling is influenced by the scale error and inner accuracy of the photogrammetric network as well as by the error of the angle that describes the deviation from the orthogonality of camera direction and glacier movement direction. The latter is strongly dependent on the position of the measuring point in the image (section 2.4.3) and mostly influences the horizontal motion component. The scale error of the photogrammetric network depends on the accuracy of the measured camera or baseline positions and thus on the chosen geo-referencing measurement setup (see section 2.2). The inner accuracy of the photogrammetric network depends on the network configuration (convergent angles between image views, number and distribution of image positions), the quality of camera calibration and the cameras sensor resolution. The total scaling error was estimated with 7.27% for the horizontal and 0.34% for the vertical motion component. For a measured motion component of 0.5 m this corresponds to a scaling error of 3.6 cm (horizontal) and 0.2 cm (vertical).

These individual errors were propagated into a mean total error of 9.2 cm for the horizontal translations of the example trajectory and 10.7 cm for the vertical translations. Note that the major error components are of absolute nature; that means that the relative error (i.e. error divided by velocity) will almost linearly drop with increasing velocity. It should also be noted that the camera movement and geo-referencing related error components show a local and temporal correlation; that means that spatial or temporal velocity gradients will have a higher precision, as correlated error effects will cancel out.

These error calculations exemplarily described above for a single trajectory were conducted for each trajectory of the measured area on the Jakobshavn glacier. Figure 15 (A) shows the horizontal daily velocity values derived from the

measured trajectories and the corresponding error values for the velocities calculated from the trajectories translation errors. Figure 15 (B) shows velocity errors of 5 to 15 cmd^{-1} and the decrease of the accuracy with increasing distance between measurement point and time-lapse camera.

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(A)   (B)
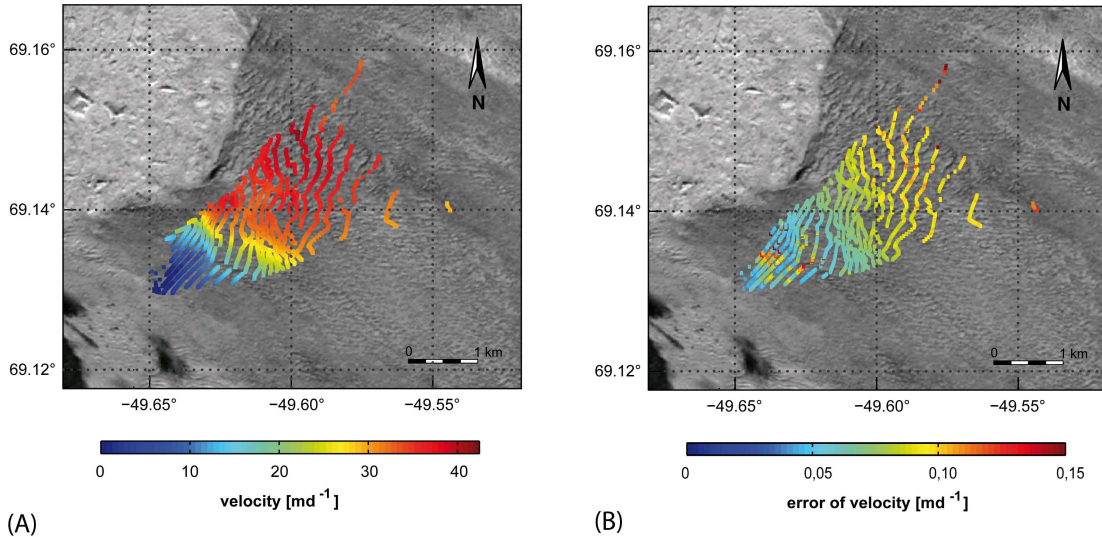
Figure 15: Horizontal velocity field (A) and corresponding error values (B) (example: Jakobshavn Isbræ, May 2010).

A further issue to consider is the error of the geo-referencing which does not influence the measurement values themselves
10 but is important when the measurements need to be compared with other data sets. This error strongly depends on the chosen method and instrumental setup for the geo-referencing (compare section 2.2). Generally we need to distinguish between lateral errors and height errors. Thereby the lateral accuracy of the spatial reference points of the individual trajectories and motion vectors is influenced by the position errors of the baseline (formed by the positions of the cameras of the photogrammetric network or by the positions of the total station measurements). The error of a height control point causes a
15 rotation error around the baseline and thus a height error of each measuring point. The error of a far-distant height control point thereby has a minor effect on the measurement points than the same error of a height control point with a smaller distance to the baseline.

3 Discussion

The velocity fields derived by monoscopic image sequence analysis can be further used for a wide range of motion analyses
20 tasks. Depending on the application and characteristics of the measurement object, the basic method as described above may be individually adapted. In comparison to satellite based analysis, terrestrial photogrammetric techniques cover only small

areas, but provide measurements at a very high spatio-temporal resolution and accuracy. Thus, the method is especially suitable for the investigation of objects, which show a high motion dynamic. The derived motion vectors or trajectories contain information about horizontal as well as vertical motion components, allowing for manifold glaciologic analyses. Since we are focusing on glaciology here, we want to discuss the potential of the method for different types of glaciology applications in this section. The discussion is based on the results of previous case studies on determining glacier motion data with the method presented here.

3.1 Horizontal glacier motion

Horizontal glacier motion fields derived from time-lapse imagery provide information about the motion of the glacier as well as spatial and temporal variations of velocity. They have proven to be a valuable database especially for the investigation of fast-flowing, high-dynamic glaciers, like many outlet glaciers of the big ice sheets.

Glacier motion velocity fields: Knowing the recording interval of the time-lapse images, velocity fields can directly be derived from the glacier motion fields. Depending on the time interval of the time-lapse series, velocity fields can be generated with very high temporal resolution. They are especially suitable for very fast moving glaciers such as many of the Greenland outlet glaciers that are of high scientific interest in the context of mass balance determination and sea level rise prediction. For these glaciers - with maximal velocities in the order of several tens of meters per day - the method is a useful supplement to glacier flow velocities derived by remote sensing methods which are hampered by their revisit time intervals. Figure 16 (A) shows velocity fields close to the front of Jakobshavn Isbræ (West Greenland) obtained by monoscopic terrestrial image sequence analysis over six years, displaying glacier surface velocities of up to 40 meters per day. Each velocity field consists of up to 4000 velocity vectors. Similar velocities have also been determined by 3D feature tracking in multi-temporal terrestrial laser scanner data (Schwalbe et.al., 2008).

Another advantage of the high temporal resolution of the terrestrial image sequences is that this allows for filtering the data. If e.g. daily velocities are required but the time-lapse camera is operated with a 10 to 20 minute time interval, the redundancy in the measurement values can be used to detect and eliminate outliers or to improve the precision by averaging. Thus, also investigations of glaciers with lower velocities may benefit from the terrestrial time-lapse measurements. This may especially be important for regions with changing weather conditions and frequent rainfall or fog as it is for instance the case for Patagonian glaciers. As an example Figure 16 (B) shows the velocity field of Glacier Grey (Southern Patagonian Ice Field) where each velocity value has been derived from about 300 single motion vector measurements (Schwalbe et.al., 2016).
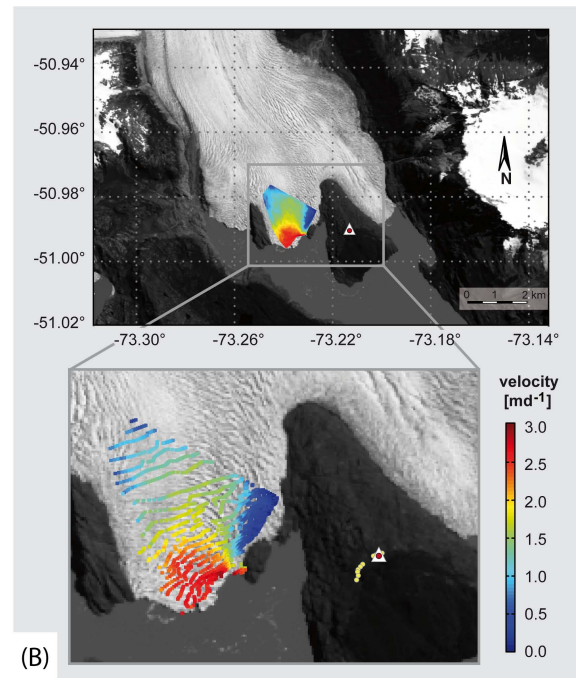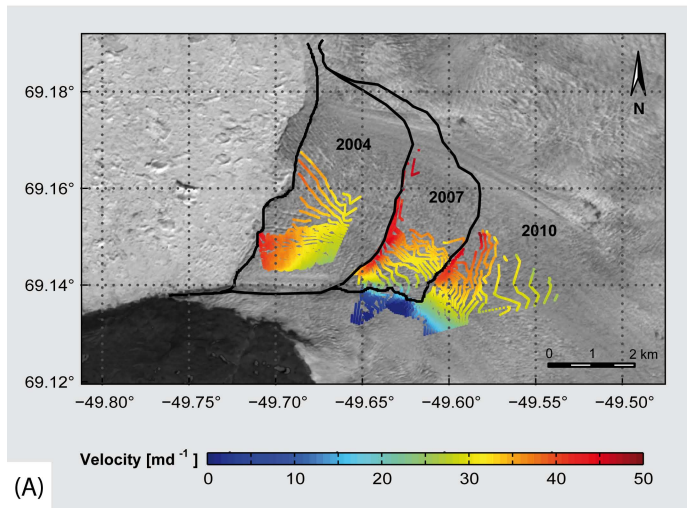
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Figure 16: Velocity fields of Jakobshavn Isbræ, West Greenland (A) and Glaciar Grey, (Southern Patagonian Ice Field (B))

Analysis of Calving events: Due to the (almost arbitrarily) short image (and thus measurement) intervals, the analysis of terrestrial image sequences also allows for the investigation of short-term changes in the velocity field during calving events. Calving events take place within a short period of time, thus requiring a high temporal resolution of the measurement method. On the other hand, the beginning of a calving event can hardly be predicted, which makes it necessary to autonomously record the glacier front area over a long period of time. An example for this kind of application is the case study presented in Rosenau et. al. (2013), where velocity fields during a large calving event at Jakobshavn Isbræ (West Greenland) were analysed on the basis of an image sequence over several weeks in May / June 2010 recorded with a temporal resolution of 20 minutes. During the calving event, the motion velocity close to the glacier front locally jumped towards up to 70 md^{-1} within a period of a few hours. The velocity thus almost doubled in the area of the new glacier front. The impact of the calving on the motion behaviour of the glacier could still be determined up to 1 km upstream.

3.2 Vertical glacier motion

The vertical component of the glacier motion field can be especially useful to draw conclusions on events taking place underneath the glacier surface and to recognize specific features that lie within or under the glacier. The vertical movement field thus has the potential to give an indirect view into the glacier.

Grounding line determination: When investigating outlet glaciers that terminate into the sea, the vertical motion component of the trajectories may provide information about tidal induced movements of the frontal area of the glacier tongue. Using tidal models or sea level measurements as a reference, various parameters such as vertical tidal participation, phase shift and inclination can be estimated for the measured trajectories. These parameters characterize the differences between the movements of the glacier surface compared to the tidal curve. In particular, the scale factor in vertical direction, which can be interpreted as a damping factor of the amplitude, can be used as an indicator for the detection of floating glacier areas. The detailed procedure for calculating the percentage of the vertical glacier movement compared with the tidal range (free float) is explained in Dietrich et al. (2007). The transition from the free float section of the glacier (with almost 100% tidal movement participation) to the grounded section (with no tidal movement participation) can be used for the determination of the glaciers grounding line. In Rosenau et. al. (2013) a case study is presented where multiple time lapse measurements at Jakobshavn Isbræ in 2004, 2007 and 2010 even allowed for the documentation of the migration of the glaciers grounding line.

Recognition of sub-glacial drainage channels: Another example for the possibility to obtain information about sub-glacial processes from vertical motion fields derived from terrestrial image sequences is the detection of a sub-glacial channel during a glacier lake outburst flood (GLOF) event. During a GLOF event, a glacier margin lake spontaneously starts to drain underneath the glacier, causing flash floods in downstream valleys. The event is triggered by the opening of a sub-glacial channel that drains the lake water and is quickly widened by erosion and melting. A typical GLOF event may take a few hours to days. After the outburst, the channel soon collapses and the lake refills until a new channel opens up and the cycle starts again (see Clague & Evans, 1994; Tweed & Russell, 1999; Dussaillant et al., 2010).

A time-lapse camera observing the water level of glacier margin lakes may be used as a GLOF early warning system if sudden water level changes can be detected reliably in the image data by a suitable image processing procedure (Mulsow et al., 2014). Vertical motion patterns of the glacier surface obtained from the same image data may depict a suitable basis to localize such a sub-glacial channel and to investigate the development of the channel during and after a GLOF event. As an example, in (Schwalbe et. al. (2016) a case study is presented where the high temporal resolution of the motion fields of the Colonia glacier allow for an analysis of the tunnel formation and collapse in relation to the changing water level of the lake Cachet II obtained from a GLOF early warning camera. By integration of daily subsidence fields of the glacier over a period of several days the drainage channel could be localized and visualized for several GLOF events at Cachet II.

4 Conclusion

The presented approach allows for the analysis of monoscopic image sequences in order to derive glacier motion vector fields with high spatial and temporal resolution based on tracking a large number of glacier surface points. These motion vector fields are of great value for the analysis of glacier motion behaviour particularly of glaciers showing high motion dynamics. Terrestrial photogrammetric time-lapse image measurements depict a powerful tool for providing glacier motion data with high accuracy at a high spatial and temporal resolution. Compared to other measuring methods, which are used for the observation of glaciers, automatic image sequence analysis also offers the advantages of a high flexibility and versatility at rather low instrumental cost. Obviously, there is the disadvantage that terrestrial measurement methods are not suitable for investigations of large areas. They are therefore to be considered as complementary methods to measurement methods based on aircraft or satellite imagery, which have the potential of covering large areas, but at a limited temporal resolution.

The methodology of monoscopic image sequence analysis consists of the determination of glacier surface point motion vectors and trajectories in image space and the transformation of the motion vectors into object space. The trajectories of the glacier points determined by sub-pixel accuracy image matching techniques may be distorted by migrating shadows on the glacier surface and by instabilities of the camera. The influence of the shadows can be eliminated during image point tracking by a technique of iteratively excluding shadow-influenced pixels from image matching. The influence of camera movement can be compensated by tracking fixed targets visible in the image sequences. In order to scale the trajectories from image space to metric measurements, the accordant distances between the camera and the according object points are required, which can be provided by a photogrammetric network adjustment approach. For the purpose of geo-referencing, different measurement setups are possible, which can be chosen depending on whether the focus of the measurement is on high positioning accuracy or light-weight measurement equipment and flexibility in the field.

The error analyses of the trajectories derived from the image sequences showed that the individual motion values can be determined with accuracy in the order of several centimetres for glacier surface points at a distance of several kilometres from the camera. The method allows for the measurement of both horizontal and vertical motion components. The described practical examples have shown that terrestrial time-lapse measurements can provide a suitable data basis for a wide spectrum of applications in glaciology. The determination of horizontal motion fields for fast flowing glaciers and the investigation of calving events have shown, that terrestrial time-lapse measurements may be a valuable supplement to satellite based observations of glaciers. While satellite images can cover large glacier areas, the terrestrial method takes advantage of its high temporal and spatial resolution and provides data for special local investigations of glacier areas which are characterized by highly dynamic changes. The studies for the detection of a glacier's grounding line or the localization of sub-glacial channels during GLOF events have shown, that vertical motion data of glacier surfaces obtained from terrestrial time-lapse measurements can be used to indirectly draw conclusions about events occurring within or underneath a glacier.

While the method of image sequence analysis as described here is optimized for the application for the motion analysis of glaciers, the use of the approaches is also conceivable for manifold other environmental investigations, e.g. motion analysis of landslides or even flow measurements of rivers.

5 Acknowledgment

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