

**Note Author comments to reviewer #2 follow on from the author comments to reviewer #1.**

## **Author Comments to Review #1**

Overall comment to Reviewer #1

Firstly we would like to thank the reviewer for taking the time to provide a useful, comprehensive and detailed review of our methods paper. The reviewer raises many valid points and has identified ambiguous paragraphs. We have addressed these issues and updated the manuscript accordingly. For example, the flowchart and the specific ImGRAFT terminology now match up and several sections have been rewritten for clarity. In light of this the manuscript has been significantly updated according to comments from reviewer 1, and we believe this has improved the coherence, readability and quality of the manuscript.

Four main improvements have been made to the figures and tables. We have inserted an updated flowchart (figure 2) and have added a descriptive table of key terminology and added two new figures. A schematic of the template matching and a snapshot of the DEM smoothing process. These figures can be found at the end of the entire document.

The reviewer has also requested a detailed presentation and discussion of the results. We comply with this request and discuss our findings for Engabreen in more detail. However, we believe that presenting further results here is beyond the scope of this paper especially due to the technical/methodological scope of the GI journal. We have recently submitted a paper to the Cryosphere (<http://www.the-cryosphere-discuss.net/8/6235/2014/tcd-8-6235-2014.html>) that uses ImGRAFT to map velocities of 5 major Greenland glaciers. This paper is purely a results-oriented paper and demonstrates a potential use of ImGRAFT. We are also currently preparing a second results paper that combines an extension of the ImGRAFT results mentioned in this paper with a comparison of four different velocity estimates and a modelling study at Engabreen our test site. We include the reference to the new cryosphere discussions paper in the text, in order to direct the reader to the comprehensive results paper.

### **Interactive comment on “Image GeoRectification And Feature Tracking toolbox: ImGRAFT” by A.**

**Messerli and A. Grinsted**

**Anonymous Referee #1**

Received and published: 24 September 2014

#### *General comments*

*This paper presents an overview of a Matlab-based software package which provides a method for georeferencing and georectifying oblique imagery, and then carrying out feature-tracking from a series of such images, separated in time but collected from the same view-point. This is a tremendously exciting prospect, since as the authors state, time-lapse imagery is becoming more popular, but extracting quantifiable information regarding surface displacement is far from straightforward. Providing a package that puts this procedure more easily in reach is therefore of huge potential interest and of benefit to many (including myself!). Having said all that, I must therefore say that I was ultimately a little underwhelmed by what the paper contains. The paper starts well and promises much, but in actual fact, much of the technical details of how the software*

*works is omitted, and a fairly broad-brush approach is applied in which only generic details are provided. I accept that a blow-by-blow account of the precise process behind the technique is beyond the scope of the paper (particularly as the code is available for potential users to interrogate and use via the authors associated website), however I would have liked to have seen a little more detail here. I was also disappointed to see that there was very little discussion of quantified results, or much attempt to assess just how good the software is. General statements about flow patterns one might expect of a typical alpine glacier are not sufficient. Much more is needed. Overall then, I like this paper's promise, and what the software can do, but I feel that there is some work to be done to bring the paper up to a standard worthy of publication. Below, I outline the things that I believe need to be acted upon.*

#### *Specific comments*

- 1. P497, L4 – you say this ‘needs to be corrected for’ but it is unclear if you are stating this as a requirement before application of your methodology, or if this is done as part of the ImGRAFT package. This needs to be clearer. I would hope that it is done here, and I believe it is, but it needs to be stated as such, especially as the package is flagged up as ‘complete’.*

Yes these are both carried out in ImGRAFT and this is now clarified in the manuscript. The description has been updated and included in the appropriate methods section (section 4.3.1).

- 2. P498, L1 – I would like to know more about the background to the approach you take to your DEM – i.e. filling in crevasses. In other words, what is the justification for following this approach? There is ultimately an awful lot of smoothing of and manipulation of the DEM – what are the implications of doing all this for your results? Have you explored this?*

Yes, we did explore using the DEM without any filtering, which we mention in the text (first part of the first paragraph of section 4.2). Due to the anomalous velocity values caused by the high surface variability (crevasses) it motivated us to apply the crevasse filling approach we outline. To make this clearer we have expanded the motivational description in this section.

Note that we only apply the DEM preparation stages to the ice surface. The smoothing we apply is in a two stage process, where first we smooth the surface to remove the high variability in the surface caused by the crevasses using Gaussian spatial filtering. This results in a lower surface, therefore to retain the elevation of the surface we take the deviation between the original DEM and the smoothed DEM and pass it through a non-linear image filter, which preferentially selects the upper surface, i.e crevasse tops. We chose this method as it is computationally efficient. The final DEM surface which we use in the ImGRAFT processing chain is the smooth DEM plus the surface produced from the second stage of the processing. To illustrate this better we have reworded some of the text in the DEM preparation and added a small figure that illustrates this process, which we hope improves the understanding. We would also like to stress that this is one of many possible ways to prepare the DEM and as a result each DEM should be prepared according to each individual case. We have now stressed this in the text and mention that this is a suggestion of how to smooth the DEM and that this example was very specific to our needs. Whilst this may sound substantial, we are essentially only filling the crevasses to generate a constant surface, which better reflects what is “seen” in the images and therefore, we disagree with the statement that there is an “awful lot of smoothing”. This is particularly the case as we are able to choose the specific vertical and horizontal scales for the smoothing, which we obtain by measuring approximate crevasse widths and depths in the actual DEM and adjusting the smoothing parameters to fit these.

3. *P498, L5 – you talk about your weighting constant ( $a$ ) and that it is equal to 1 in this case. There is no explanation as to why this is, and what situations might arise where  $a$  is not 1. I think you need to explain this more fully, otherwise surely  $a$  could be omitted.*

We have removed the “equal to 1” part in favour of the following description which can be used as guide for other sites/studies. There is no fixed value for this. We have updated the text to the following:

Text insert after “largest crevasses”: “,and the weighting constant ‘ $a$ ’ has been chosen to be the same order of magnitude as the standard deviation between  $z$  and  $S_g$ .”

4. *P498, L16 – you say that there is 10 m of surface lowering in a melt season, but it’s not clear if you mean that you observed this in the field, or if you mean that your ImGRAFT approach reveals this.*

We derive this surface lowering from direct measurements. We have clarified this point further in the text, and the sentence now read: “*In this example we derive the elevation change factor for the ice from direct mass balance measurements taken at the glacier at monthly intervals throughout the operational period of the camera in 2013*”.

5. *P498, L25 – you indicate that there is a manual on your website – I cannot find this manual.*

We apologise for this inconsistency. On the ImGRAFT website the manual is referred to as “documentation” rather than manual.

The documentation for the software, along with full examples can be found on the documentation page here: <http://imgraft.glaciology.net/documentation>. We have made sure to change this in the text.

6. *P499, L2 – it is not clear to me what a ‘model camera’ is, and particularly how this relates to a ‘master camera’ (referred to later). Are these different, or are they the same thing? It is really important that the terminology used is clear.*

You highlight many areas of confusion about specific ImGRAFT terminology, in order to improve clarity have inserted a new table 1 that defines all the key ImGRAFT terminology. We hope that this along with the updated figure 2 and new figure 3 will reduce any further ambiguity.

7. *P499, L3 – similar to my first point above, it is not clear whether this determination of ‘camera view parameters’ is done here in the software, or if it needs to be done beforehand.*

Yes the determination of the camera view parameters is done directly in ImGRAFT. As mentioned above in response to the other comments this has now been made clearer with a new flowchart in figure 2 and a terminology table. In addition to this we have also split the method into two parts: firstly processes that are carried out, outside the ImGRAFT flow and second (section 4.3 onwards)

8. *P499-500 – the georectification section (4.2) is quite basic. You need to give more details as to what is done in ImGRAFT. Also, why doesn't this stage appear on Figure 2 at all? Figure 2 needs to be a complete guide to the processing stages.*

Figure 2 has been updated to be more complete and now outlines the key processes. The new figure 2d refers directly to the georectification section. The key variables and functions used in the georectification are now defined in the new Table 1 and some of the text in the georectification section (4.3.3) has also been expanded.

9. *P500, L11 – 'the initial version' – this implies there is another, more recent version. Is there? If so, how do they differ? Why mention an earlier version? What does the more recent version do?*

Thank you for highlighting this, we mean the current version. There is no other version of ImGRAFT. We have changed this accordingly in the text.

10. *P500, L16 – presumably ice flow is just inferred from differences between two images.*

Yes this is true we just mention here that we apply the same NCC algorithm to determine the offset of the stable bedrock (which we assume to be a result of camera motion) and that of ice displacement. We have altered the text to make this clear.

11. *P500, L24 – when you talk about 'camera B', do you just mean an image captured in the second of two time periods, as opposed to a camera in a different location, as is suggested here?*

We have updated the text to highlight that there is only one physical camera and that all references to the model cameras, refer to model cameras of images taken at different times.

12. *P501, L15-19 – in light of this limitation, why don't you show velocities along flow then?*

Due to the complex nature of the ice flow in our study site (the ice is flowing around a bend) we risk losing valuable information that is only contained within the full velocity component, if we only show velocities along flow. We have added a description of this in the updated velocity calculation section (4.3.4). We now emphasise that this a suggestion for other studies rather than a limitation. We prefer to leave it up to the the user to explore if this is an appropriate display technique for their data. . Additionally, in the demonstration on the webpage we show both original and velocity projected along flow for comparison.

13. *P502, L5 – you mention 'offset to camera' here, but it does not appear in Figure2, despite pointing your reader to this. It is quite frustrating to have Figure 2 missing some key elements, and not tying up with the text.*

Thank you for your further comments regarding mismatches with the figure and the text. As mentioned previously and in other comments we have significantly updated the figure, new table and the text to be more coherent. We have removed the offset-to-camera phrasing as we feel this is too code specific and consider that people who intend to use the toolbox will interrogate the code accordingly to their needs.

14. P502, L6 – *what is the threshold for ‘high’ velocity? When does it become acceptably low? Similarly, on L8, you say that the velocity field is removed if the ‘problem persists’. This seems very subjective. You need to be more rigorous in your criteria.*

Thank you for raising this point. We agree that this appeared somewhat subjective according to our previous description, and we have now clarified the definitions of “high velocity” and how we assess this. Our assessment whilst “visual” is based on what values of velocity that can be physically expected in this glacial setting. For example, we do not expect the marginal area which experiences high drag from the valley sides to be flowing as fast, or faster than the centre of the glacier. As a result then if we continuously find anomalous results from an individual image pair, even after reprocessing each image and the image pair completely then we remove this velocity field from any further calculations.

15. P502, L19 – *‘effectively the same time period’. What does this mean? Is it or isn’t it the same time period? I also don’t really understand how you carry out this error estimate. How do you calculate velocity for the same time period using independent image pairs? Do you have multiple cameras, or are you using consecutive image pairs. . .in which case they are not for the same time period, in which case things could differ.*

Thank you for raising this as an area of confusion, we agree that this wording is somewhat confusing, and that it introduces further misunderstanding. We have now removed “*effectively the same time period*” from the error description in the results section and have updated the explanation of the entire error calculation section (5.1). We imply that the approach compared image pairs with a significant temporal overlap. Our description is now improved and we state that this method gives a conservative error estimate that includes any variance caused by the shift in image pair acquisitions time, therefore the error encapsulates both the variance (caused by the time offset) and total error. We therefore believe we are overestimating the error estimates as we take into account both the variance and the error.

16. P503, L3 – *this is very vague. What are the expected flow patterns for an alpine glacier, and what do you mean when you say your measurements ‘match’? You need to tell us much more precisely what you mean, and also to tell us something about the velocities measured. Give us some numbers too.*

We have now included a more detailed explanation of the results in the beginning of the results section, along with a more quantitative assessment. See also our replies to comment #14, and the general comments above.

17. P503, L21 – *again, this is vague – what are the ‘distinct time periods’ for which no detectable motion is likely (or expected)?*

This has now been removed from the results section to avoid further confusion and a more descriptive text has been added, as part of the reworking of the entire section, in connection with the error section.

18. P503-504 – *I think the explanation of the effects of illumination is a bit long-winded and repetitive. I think you can say (much more simply and quickly) that illumination is important and that the area you chose to focus on is not really affected by changes in illumination*

Thank you for pointing this out, we have cut down and refined the explanation of the effect of illumination.

19. P504, L10 – *I disagree with your statement regarding what Figure 4c shows. This figure does not say anything about the effects of shadows – what it shows us is that in the specific area, there is minimal variation in velocities. You may choose to infer from this that shadow has minimal effects, but the figure does not ‘clearly’ show this in its own right, as you suggest.*

We agree that we do infer this rather than demonstrate this, and the wording has now been altered accordingly to make it clear that we are assuming this instead of “clearly showing this”.

20. P504, L12 – *do you mean Table 1 rather than Figure 1?*

Yes this has been updated accordingly (Table 1 is now Table 2)

21. P504 – *I’m a bit disappointed not to see a more detailed analysis of velocity patterns across the study area – surely the value of the approach is to produce a detailed, distributed data-set. In which case, it’s a shame not to discuss it more. I’d also like to know more about how good the method is in reproducing real velocities.*

See the response to comment 16. Additionally we have included the citation to our new Cryosphere paper which is purely an ImGRAFT results paper, which we now reference in the text and link to in the general comments.

22. P505, L9-11 – *it would be preferable to explain the section about the ability to use lower-quality cameras earlier on, rather than here in the conclusions.*

Similarly to the next comment we have added this explanation of the low quality camera to section 4.3.1

23. P505, L17-19 – *I don’t know why you start discussing filters and signal-to-noise ratios here. This material should appear much earlier on. Conclusions are where you summarise what has gone before, not introduce new material.*

The filtering discussion has been moved from the conclusion and added the filtering discussion to the velocity calculation section 4.3.4.

24. P505, L25 – *I am disappointed that your approach does not account for inaccuracies in DEMs. I understand that in your case, this is not relevant as you were fortunate to be able to get a DEM at exactly the right time. However, for most applications, this will not be feasible.*

*Given you claim that ImGRAFT is flexible and user-friendly, I think you need to consider the implications of DEM accuracy more fully, so that other users can apply this tool.*

This is always a challenge with terrestrial time lapse feature tracking and one that does not have a simple solution. If you want to achieve quantitative estimates of velocity a good quality DEM is essential input, as are good quality images.

We do mention, briefly one simple method of dealing with DEM uncertainties (section 4.2), and have now expanded this to provide a clearer description.

Whilst we appreciate that in many cases a perfect DEM is not available we believe that providing solutions for inadequate input data is beyond the scope of this paper and the direct functioning of the toolbox, as each case must be handled individually.

25. *Figure 2 – I think a lot of work is needed to improve this. I have mentioned in various places above that there is a mismatch between what is mentioned in the text and what is mentioned in the figure. There are even more examples of this. You mention ‘rock template match’ in the table, but this does not appear in the text. Instead, ‘template match rock’ appears on L3 of P502 – is this the same thing? Presumably it is, but you need to be consistent with your terminology. Similarly, there is no mention in the text of the ‘optimise secondary camera’ phase. What does this mean? I thought you were using imagery from a single camera. Further, you mention ‘master camera’ in the figure but not ‘model camera’. Are these the same? It is fundamentally important that the text of your manuscript should track the boxes in this image, so that the figure is actually useful.*

See earlier comments. This figure has now been completely remade and the text has been updated accordingly throughout. We have now split the figure into the four main sections and added a specific table (table 1) to describe the key terms. We thank you for your suggestions and comments with regard to this and hope that our changes to the figure and text have made it more cohesive.

#### *Technical corrections*

1. P493, L16 – remove ‘be’ after ‘otherwise only’.

Corrected.

2. P493, L22 – ‘a own’? Not sure what you mean here. Do you mean ‘our own’?

Corrected.

3. P493, L23 – comma after ‘rectified’.

Corrected.

4. P497, L12 – I would say that section 3.2: ‘DEM preparation’ is part of the methodology.

We originally didn’t include the DEM preparation as part of the method, as we only discussed ImGRAFT specific processes in the Method, however we have now changed this and now clearly split the method section into two main parts, which now include the image and DEM preparation as pre-processing steps and then the second part for only ImGRAFT processing.

5. P498, L13-15 – you say that on a surface where melting occurs, ‘it is important to consider the effect on the accuracy of the result’. However, you’ve said virtually the same thing in the previous sentence. There’s therefore a bit of repetition here which could be removed and tidied up.

Thank you for pointing this out, we have reworded and tidied up this section.

6. P499, L10 – insert ‘is’ between ‘previously’ and ‘caused’.  
Corrected.

7. P500, L17 – ‘and to and reduce’ doesn’t make sense. I think you just need to remove the second ‘and’.  
Corrected.

8. P501, L22 – remove ‘are’ from after ‘regions’.  
Corrected.

9. P504, L17 – ‘then’ instead of ‘then’ after ‘Table 1. . .’  
Corrected.

10. P504, L20 – I don’t understand how an error of 5 cm d-1 when the velocity is 60cm d-1 equates to an error estimate of 7%. Surely it’s 12%?

Sorry for the miscalculation, this has now been removed and individual error estimates are given in table 2 for each velocity estimate.

11. P504, L21 – what is the point of the ‘(or < 10)’?

This has been removed.

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END OF AUTHOR COMMENTS TO REVIEWER #1

Author comments to Reviewer #2 on begin on next page:

## Author Comments to Reviewer # 2

Thank you very much for taking the time to provide a complete review of our methods paper. Reviewer 2 makes many useful comments and highlighting some key areas of potential confusion.

In response to reviewer 1 comments we believe that we have updated the manuscript in a way that answers both reviews. One particular aspect that reviewer 2 highlights, which is not raised by reviewer 1, is the need for a clearer schematic of the “features”. In response to this we have included a new figure (see figure 2 attached) that illustrates the “features”, which we define as templates. We have also added a small illustration of our crevasse filling technique that follows the DEM preparation, again providing a more visual aspect to the paper. We believe that these additions along with the updated flowchart and the definitions table have significantly improved the usability of the paper for potential users. As reviewer 2 quite rightly suggests, our code and online ImGRAFT documentation is likely to be updated through time with addition of new features and examples, as ImGRAFT develops within the user community. Nevertheless we hope that our updates have made the paper a more useful guide for potential users.

### Anonymous Referee #2

Received and published: 16 November 2014

In my view the paper presents very useful tool not only for glaciers velocity and mass balance measurements, but for many other Natural processes related to moving masses (solifluction, permafrost development/degradation, land slides, etc.). There can be many technical questions to the authors. However, since there is supposed to be a manual on-line, I am, personally quite satisfied by the present technical details and support publishing the paper in GID and later in GI.

The problems I have and can expect from other readers are as the following:

1. I do not see clearly what are the “features” automatically recognized by the package and used as the reference “points” for velocity estimations. A lot is described about the shadows, crevasses, and so on – but would be useful to see closer (enlarged area from the photographs) example(s) of a “point” (rock) on a glacier surface with corresponding area around, and how same looks like at a next image. There is also additional transformation of such recognized “features” into “spaced grid”. How this transformation looks like relative to the actual features (rocks) at the glacier surface? The reason for asking this is to give possibility to a reader to evaluate if such image processing procedures can be useful in his particular application, not necessary related to a glacier surface change. Figure 3 does not allow this.

Thank you for highlighting this point we have updated the text and figure. We achieve this in the form of a new figure that provides an overall visual schematic illustration of the “templates” and how they are used in the “templatematching” process. We have also significantly updated the

flowchart, so it now includes all the key functions and is clearly split into the separate processes. The flowchart also corresponds much closer to the text now. We have also included a new table of definitions which we hope will add a more detailed description of these key variables.

2. The vectors of such “points” movements are the results of vertical (melting) and horizontal (glacier flow) displacement. Both results in change of the shapes around reference “points”. Some scheme/example of this multi-step transformation from a distance calculated from the images to the surface velocity of the glacier would also be helpful (with the same aim as in 1). Logically this are the procedures between “Rock template match” and “Template match ice” at Figure 2 – the most important part of the paper for a glaciologist.

We have updated the flowchart figure to include more details about the specific processes and in this case the “Templatematching” is used in two key processes in the toolbox. Firstly to determine the camera motion caused by external factors like wind and thermal expansion. In this case we track stable features like bedrock to determine this motion (note that this was previously referred to as “rock template match”). Secondly the “templatematching” is used to determine the displacement of the ice (for example). We have updated our description of each use of “templatematching”, and hope this has reduced the ambiguity of the terms. To avoid further confusion the use of “Rock template match” and “template match ice” terminology has been removed and instead we have added a clear description of the specific use of “templatematching” to the new definitions table.

3. I understand the complexity of defining velocity for such calculations. It shown in Table 1 that the velocity was calculated always comparing image b with image from 17 Jul 2013 (this is “Master image”). Not clear how all the images listed in Table 1 are related to the August 25 DEM (are they?). Also, it is not stated but look like we cannot compare, say, image from 22 Jul 2013 and 27 Jul 2013. Quite a limitation, because the velocity can change day by day.

Thank you for raising this area of confusion with regards to the possibility to compare different image combinations. We can compare any possible combination of images (not listed in the table) and are not limited to comparing every subsequent image to the “master Image”. We have now updated the error calculation section and the results section to include a clearer formulation of the role of the Table. The Table only lists the images and image pair combinations that we used to estimate our error and which are presented in the velocity field in figure 4. This is **not** a full list of all the images that we can compare. We hope that the updated description in the text clarifies this.

In conclusion: The technical details of image processing can be cleaned up infinitely. I would not be surprised if in couple years the routines of an updated version of Im-GRAFT would be very different from what is described now. However, for successful use of the software by others, at least in the first paper describing the suite, there should be some simple illustrations in “human eye” language of what can be used from the images as reference points and what can be expected limitations.

Thank you for your final comments, we agree with the comments above and have now included some more schematic illustrations to aid in the explanation of the toolbox along with the updated flowchart, which we believe has much improved the manuscript.

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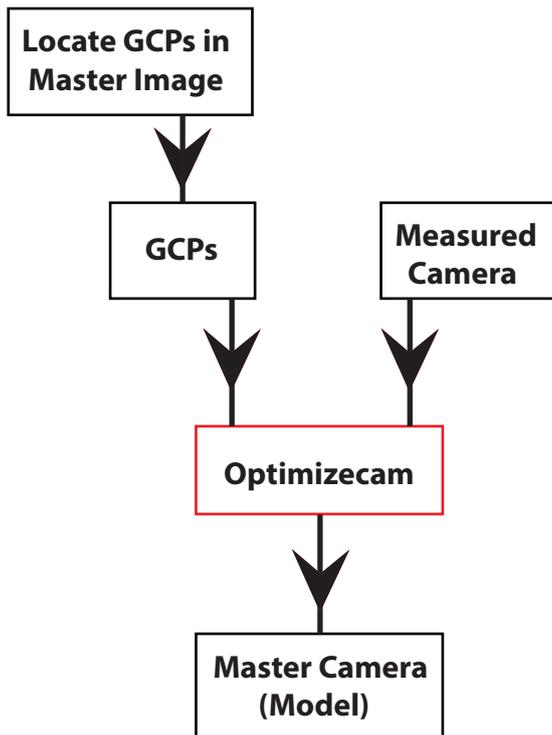
New Figures:

1: Updated flowchart:

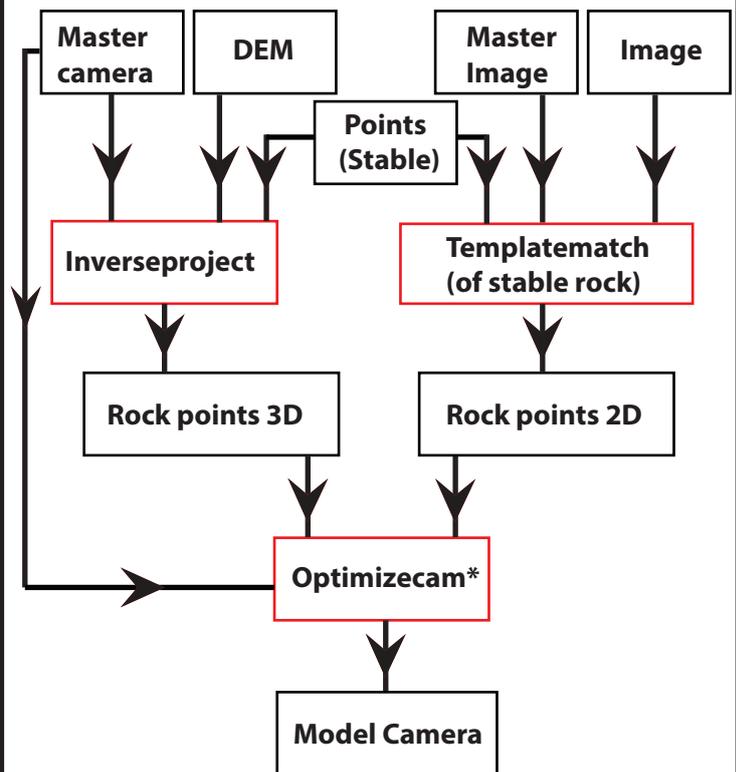
2: DEM smoothing snapshot

3: Templatematching template schematic

### a) Master Model Camera Determination

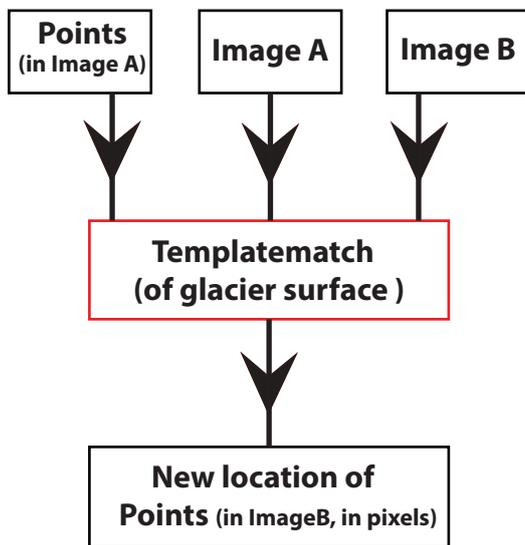


### b) Camera Motion and model camera determination

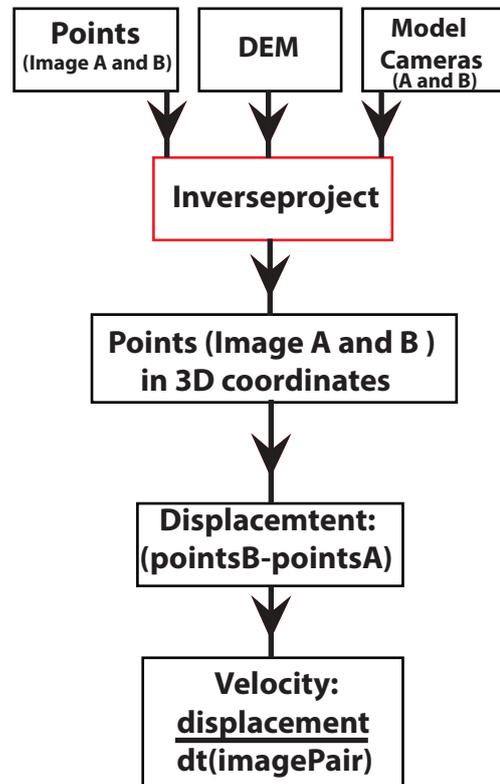


\*Only the view direction is optimized in this stage of the processing, as all other parameters are unchanged.

### c) Feature Tracking (e.g. Glacier surface)



### d) Georectification and Displacement



\*Note: at this stage we generate 2D pixel displacement

Slice through crevasse filled dem.

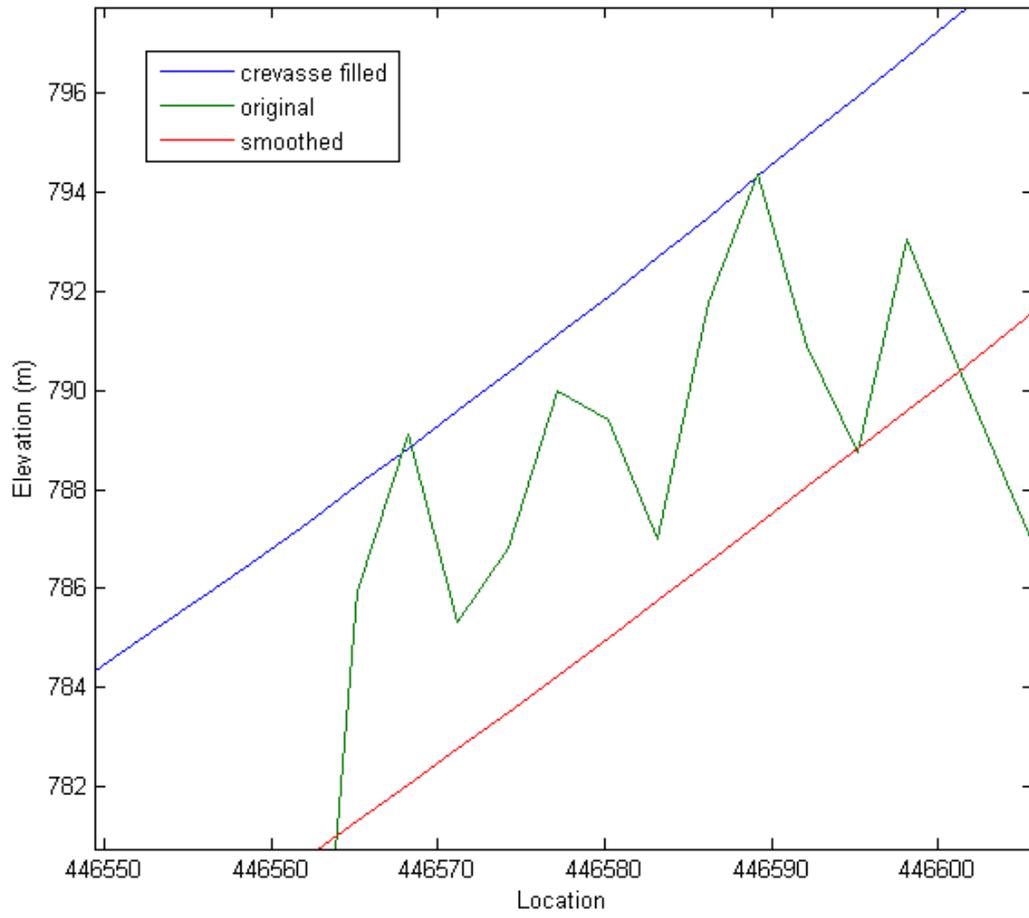


Image Pair

