Response to Comments on '*Evaluation of low-cost Raspberry Pi sensors for photogrammetry of glacier calving fronts*' by Taylor et al.

We'd like to thank both reviewers for their helpful, positive, and constructive comments which have substantially improved this manuscript. The most significant revisions have been to diversify the discussion on the applicability of this work to other fields, to offer further clarifications on our approaches, to produce a new Supplementary Information including a detailed list of components and our code, and to offer further distinctions between the Raspberry Pi and other sensors.

We offer replies to each comment, with our response to the comments given in red.

Reviewer 1 (Karen Anderson)

This is a nice piece of methodological work, which delivers insights on a new approach for low-cost unattended monitoring of calving glaciers via low-cost raspberry pi operated cameras. It's a neat idea and the proof-of-concept is done well. The piece was relatively uncomplicated to review, because it is quite clear in its layout. The major findings are that the raspberry pi-operated cameras can deliver quite good quality photogrammetric reconstructions of glacier fronts, and compared to equivalent data captured from a drone flying along the glacier front – the results are not hugely different, which evidences the capability of the cameras for this task. What is quite impressive is that the very low cost raspberry pi system delivers precision thresholds set for DSLR workflows. Monte carlo point-cloud to point-cloud methods are employed to perform a robust comparison between the raspberry pi and drone datasets. Overall the paper is uncontroversial but provides a useful reference point for those wanting to develop raspberry pi imaging for photogrammetry, or timelapse monitoring for glacial applications as well as in other fields.

Many thanks for your kind comments of our manuscript. We thank you also for your time in offering this review.

The main thing which I think needs a little finessing is that the piece has a title which is about photogrammetry but the paper is also focused on timelapse. And you can have timelapse functionality without photogrammetry on the pi – e.g. one camera instead of an array of cameras. So I felt that a bit more careful structuring of the argument could benefit the clarity of the paper and make that distinction a bit more visible. There are some minor points to address, largely relating to some areas needing a little more detail.

Following comments from Reviewer 2, we have removed 'photogrammetry' from the title in exchange for 'structure-from-motion' as this better reflects the manuscript. We have also attempted, throughout the manuscript (see minor points), to add this detail and nuance in which makes the distinction between time-lapse functionality (which this work is intended to help inform) and the results we present.

Minor points

Line 65 – 'we have designed…' – this sounds like a methodology point not something that belongs in introduction. I think the introduction should focus on reviewing the camera technology / hardware here rather than linking to your specific experiment or motivations. Maybe just lose the first sentence of this paragraph and start with 'raspberry pi computers are small…'

We have removed this sentence.

A general point is that timelapse capability can also be achieved very cheaply (less than £120) from wildlife cameras (e.g. the type that are typically used for motion-sense camera trapping). You do pick up on this a little in the discussion but not at the beginning of the piece (e.g. table 1). Not all trailcams have a timelapse capability, but some do, and many also have in-built solar trickle charge capacity. I've also seen papers using them as phenocams. It would have been interesting to see how data from these compared to the pis, but I appreciate that it's too late to ask for that. On that note I also wondered why you didn't do a like-for-like comparison to SLR method from the same vantage points with the pi? The drone may be the most widely used method for glacial front reconstruction but it is not for timelapse, I think… Perhaps there needs to be an explanation added about this distinction. I think the experiment described around line 140 is addressing this but the explanation is a bit opaque (e.g. "the monitoring network would be cheaper as fewer cameras are required"…)

We have now added a comparison to wildlife trail cameras to Table 1 to demonstrate the technical differences between a similar cost setup. The key difference between our work and that from trail cameras less than £120 is the connectivity. We have therefore provided this comparison to the cheapest available wildlife camera with MMS connectivity (coincidentally, the MMS version of the camera used by Mallalieu et al., 2017), which is $225 at time of writing.

We have added further clarity to the explanation about a monitoring network by describing instead that "*any time-lapse camera array produced using Raspberry Pis could be cheaper with fewer cameras required*" as this section pertains to the experiment to reduce the number of camera frames used to derive the model.

A like-for-like comparison with an SLR camera would, with hindsight, have been a good addition to this manuscript and is something that we will look to improve for future work in this area. However, we feel that by reporting statistics such as mean absolute precision, the reader can make comparisons to a broad range of sensors (including, as we do in Section 4.1, trail cameras, DSLR cameras, and terrestrial laser scanners).

If this is about time-series monitoring of glacier frontal dynamics – is the spatial reconstruction from the boat-mounted surveys a useful demonstration of the temporal case study? I am referring to the statement at the beginning of the paper where you state that "Arrays of fixed cameras can be positioned around a glacier front to capture images repeatedly over long time periods. The resulting imagery can then be used to photogrammetrically generate 3D models at a high temporal resolution and analyse change over days, months, or years." So I guess that one way would be to position multiple pis facing the calving front and trigger them simultaneously, to generate SfM products. I felt that the paper warranted a discussion about this high cadence mode of operation which seems to be largely what you're advocating – vs the boat mounted transect operation that you actually carried out.

We have added a paragraph to the discussion to demonstrate how we are advocating for the results from the boat survey to be applied to a fixed array approach. Here, we have also cited some other work conducted during the lead author's PhD in successfully running a Raspberry Pi camera for three months in a glacierised environment, to demonstrate that high cadence operation with these sensors can work.

Figure 4 – it shows the two comparative point clouds from the pi and the drone and I note that the colouration of the renderings is different. Is this due to some different camera settings used (e.g. exposure etc?) or something else? It made me think that the methods section needs some added information about these aspexts given that other papers have commented on the impact of camera settings on the quality of SfM outputs. I guess it may not be possible to change the settings on the pi camera but this is not the case on the drone camera, so does warrant some discussion.

The Raspberry Pi camera is more customisable than the UAV camera and, as a result, we left the exposure, saturation, and ISO settings all as 'auto' given we were moving throughout acquisition and had to ensure good quality images across the transect. We have explained this in text, and offered advice on adjusting these settings to improve the Pi camera if placed in a fixed position.

Line 125 – I read your argument for flying the drone closer to the glacier than the boat but I think if you want to compare pi to drone it would have made more sense to use a distance for each which did a better job of balancing the camera resolution capabilities with the distance. It seems like being further from the glacier with a poorer quality camera will give you a negatively biased estimate of the quality of the pi camera. Perhaps warrants some discussion.

We have added additional clarification that the boat was as close as possible while remaining at a safe distance to the calving margin. We have also added a citation to Esposito et al. (2017) who flew a UAV closer to a coastal cliff than a boat survey to gain a higher accuracy 3D model for cloud comparison. Finally, we have noted that this will likely give a negatively biased estimate for the Raspberry Pi camera. This ties to our general approach to be fairly conservative towards the Raspberry Pi throughout, so as to provide realistic estimates of its performance in sub-optimal conditions if positioned in a fixed array.

Table 1 – I think the cost given here is inaccurate – you did not use a Pi ZeroW so this price is not describing the system used. You could perhaps put a range of price here to indicate the low-entry point zero-W and the version you used.

We have given the range from $120 – 150 to reflect the more expensive model we used in this build.

The thing that is lacking from the paper is an open source sharing of the build recipe (e.g. list of components) and code for setting up the pi to run as timelapse camera. I think this should be added as supplementary information if the paper is accepted.

Many thanks, this has been added as a supplementary information so that anybody can recreate this build.

Line 120 – what is the minimum capability for timelapse in the pi camera? And why approx. 10 second intervals – is it uncertain how often it triggers (e.g. why 'approx').

The minimum capability, we believe based on documentation, is around two frames per second (500 m/s) however having not tested this we'd be unkeen to incorporate this figure. The approximate interval is that we were manually triggering in this setup to allow us to continuously monitor photos as they came through.

Line 150 – this pre-alignment with the UAV data sounds great in this context, but what would happen if someone used the pi without the drone survey…? Presumably the registration would then be arbitrary. I realise that you did this for the purposes of cloud-to-cloud comparison in M3C2 but thinking more broadly does the lack of georeference information matter in the timelapse? Perhaps add some clarification to the manuscript in this regard.

We have added further discussion on the comparison of point clouds acquired by solely a Raspberry Pi in section 4.1, and outlined the need for information to georeference these clouds in the "Practical Recommendations" in section 4.3.

Figure 6 needs a colour bar scale legend

Added.

Can you comment a little more on the patterns of errors in Figures 4 and 6. You wrote that the jagged edges of ice result in higher errors but the nature of the patterns in the M3C2 results shows that there are patches of high positive errors neighbouring patches of large negative errors (e.g. blocks of blue and red next to one another). What is the cause of this systematic patterning of error – why are the differences in the point clouds organised like this?

To be perfectly honest… we're not sure! We have offered a suggested explanation that the jagged edge facing front is better modelled by the Pi (which only captured from one angle; front-facing) and the faces pointing away from the edge in either direction are not represented well by the Pi as a result. This has been added to the discussion section on the need for a variety of viewpoints and angles, with a caveat that this is a speculative explanation.

Thanks for the opportunity to review the paper.

Thanks for your time and effort in providing a helpful review of our work.

Reviewer 2 (Penelope How)

Taylor et al. present a Raspberry Pi system for capturing time-lapse images and producing glacial photogrammetry measurements. Alongside UAV surveying, the Raspberry Pi system is used to produce SfM models of a calving glacier in Iceland to evaluate its potential uses in glaciology. The study effectively shows the value of this system to the glaciology community, producing accurate SfM models and demonstrating its applications in operational monitoring of glaciers. I recommend publication of this work after minor corrections, with my main comments regarding the scope and focus of the paper, and the inclusion of a more extensive reference list. I was really excited to review this paper when I saw the request for reviewers, and it did not disappoint. Congratulations on an interesting paper that was very enjoyable to read.

Many thanks for your very kind comments, and enthusiasm, towards our manuscript!

Main comments

The use of the word photogrammetry in the title is slightly mis-leading given that much of the focus is on the application of the Raspberry Pi system in Structure-from-Motion (SfM). Photogrammetry more typically refers to traditional methods of scale factoring, tracking and georectification. SfM is a newer method that, although falls under the umbrella term photogrammetry, should be more clear here to avoid ambiguity. This is not to say that the Raspberry Pi system cannot be used for more traditional photogrammetry techniques (and you clearly demonstrate that it can), but given that the focus of the paper is on its SfM applications the title should be changed to reflect this. In addition, there are instances in the Introduction (L19, L59, L61, and L79) where the term "photogrammetry" should be changed to "SfM" as you are referring to specific SfM techniques.

Many thanks. We agree with this interpretation and we do not intend to mislead or overstate our results, and have changed these instances (including the title) to SfM.

2. In the Abstract and Introduction (e.g. L8-10, L31-34), it is stated that this work will be useful for monitoring small mountain glaciers in land-terminating settings and GLOF events. I think the scope of the authors' work reaches beyond this and is also very valuable for the monitoring of marine-terminating glaciers, where ice ballistics and tsunamis generated from calving are a major hazard to bystanders and cruise ships. The Discussion and Conclusion more effectively demonstrates the use of the Raspberry Pi across different glacier settings and for a variety of applications, however, I would like to see this also expressed in the Abstract and Introduction.

Thank you for your confidence in our results! We have added additional text to the discussion and conclusion regarding wider use of these data, and adjusted the wording of the abstract to move focus away from small mountain glaciers. We feel that the introduction is quite broad in its focus and tends to use a wide range of glacierised settings (including marine-terminating glaciers) to set-up the need for this system.

3. The main advantage of the Raspberry Pi system stated throughout is that it is cost-effective compared to off-the-shelf time-lapse camera systems (e.g. L12, L48, L63). Whilst I agree that this is a cost-effective system, I think the main advantage of this system is that it has greater capabilities and adaptability than a standard off-the-shelf system. Such a system can have more sophisticated programming and functionality. Not only will near-real-time monitoring be an option, but also near-real-time processing of images, which could technically be conducted on-site in the Raspberry Pi - this could mean that light-weight processed data (e.g. GLOF water level, ice velocity, terminus position, supraglacial lake area etc.) could be transmitted rather than the bulky image data. This capability is seldom found in a typical DSLR camera, or provided by time-lapse installation distributors. I think this is more clearly explained in the Discussion section of the paper, however, I would like to see these advantages focused on in the first sections, rather than its cost-effectiveness.

We have added additional commentary throughout the manuscript (with a focus on the Introductory sections) regarding the potential flexibility offered by using a Raspberry Pi sensor.

4. I would like to see more previous glacial photogrammetry work referred to throughout the paper. The literature is heavily weighted to UAV studies, and I would like to see more terrestrial time-lapse papers referred to, given that this is the main application of the Raspberry Pi system. I have provided many in the minor comments and reference list at the end of this review, and I would also like to see others added by the authors.

Please see the minor comments section, as we believe this has been addressed throughout the manuscript now with the additions suggested.

Minor comments

L8-10: See major comment #2 regarding broadening the scope of the paper, and not just focusing on land-terminating calving glaciers. You could include more examples here of hazards caused by calving, such as ice ballistics, tsunami waves and iceberg collapses.

We have added these examples.

L12: High equipment costs are just one reason that monitoring systems are difficult to implement. Monitoring systems are challenging to set up as well because of the lack of infrastructure (e.g. cell/Iridium coverage) for near-real-time data transmission, and challenges in implementing tracking/detection with fully-automated workflows. See main comment #3.

We have added 'highly adaptable' to this summary sentence, and presented more around the potential for this system within the text.

L18: "Raspberry Pi cameras represent..." >> "Raspberry Pi cameras present..."

We have changed the wording to 'Raspberry Pi cameras are an affordable…'.

L28-34: Same as comment on L8-10 (see main comment #2)

We have added the examples and an associated citation.

L35: Calving rate can not only be calculated through iceberg detection, but also by knowing the ice velocity and terminus change (e.g. Luckman et al., 2015; Schild et al., 2018; and many others)

In order to keep this sentence succinct, we have removed the nuance of "*through iceberg detection*" and added in the Luckman et al. (2015) citation to demonstrate multiple methods of deriving calving rate from satellites.

L37: "smaller mountain glaciers" >> "calving glaciers"

Changed accordingly.

L43: Measured glacier velocities from oblique time-lapse images are three-dimensional measurements, transformed from the image plane to three-dimensional space through the process of georectification. Equally, two-dimensional areas of calving events have proved a good measure of calving event size (e.g. Bunce et al., 2021; Holmes et al., 2021). Therefore, I think the statements that single stationary cameras have limited 2D measurements and offer little in the detection of calving magnitude is misleading and should be corrected.

Thanks – this sentence was unintentionally harsh and we have clarified our meaning here (that 3D is needed to quantify calving volume size) with reference to the two citations you mention.

L45: Whilst multi-camera, Structure-from-Motion set-ups are ideal for constraining calving volumes, the physics of a calving event can also be captured with high-temporal-resolution single time-lapse sequences (e.g. Holmes et al., 2021).

See above comment.

L48: I think that while start-up costs for UAV surveying are indeed expensive, it can become cost-effective in the long-term (as long as the UAV is maintained correctly and is not damaged). Personnel and fieldwork logistics are likely the biggest costs, which are common across most glaciology research with a fieldwork component. The value of the Raspberry Pi system is that it could reduce the number of re-visits, as data could be processed and transmitted in an automated manner rather than downloaded on-site. See main comment #3 regarding the cost-effectiveness of the Raspberry Pi system.

We have added that personnel and fieldwork costs make up a large proportion of this 'high cost' that we attribute to UAVs.

L54-56: There are many more examples and applications where DSLR cameras have been positioned at glaciers to capture a plethora of glaciological measurements (e.g. glacier velocities, supraglacial lake change, snow coverage/snowline positions, crevasse tracing, terminus position change, calving). Please include more examples, starting with the reference list at the end of this review (see main comment #4).

Thanks – we chose here to only include DSLR cameras that had been fixed in place for photogrammetry of glaciers specifically, but we have included these citations elsewhere to diversify the manuscript in its applications following your main comment.

L62: Other monoscopic photogrammetry toolboxes in glaciology: ImGRAFT (Messerli and Grinsted, 2015), EMT (Schwalbe et al. 2017), and Pointcatcher (James et al., 2016)

We intentionally only directed readers to How et al. (2020) as we believe this is the most user friendly and accessible toolkit which covers a broad range of applications. Given this was not a focus of the manuscript, we have added 'e.g.' to the citation to imply that this is not the only one available, but we believe it to be the best for our readers to follow up on this comment.

L63: I think the trail cameras from the Kangerlussuaq set-up by Mallalieu et al. (2020) were not very expensive, so please consider changing this statement.

This statement is carefully curated with the caveat of "trail cameras with cellular connectivity are many hundreds of dollars per unit". The cameras set up by Mallalieu et al. (2020) each cost ~$120 at time of purchase (comparable to the Raspberry Pi setup), but do not have cellular connectivity. With this connectivity, the cheapest model (at time of writing, with comparable specifications to Mallalieu et al.) was ~$225 plus associated data costs of transmitting photos via a cellular network. The advantage of the Raspberry Pi is that is has the connectivity component at the cost of the non-connected trail cameras. We have added this comparison to Table 1 also.

L80: "incorporating low-cost sensors in glacier monitoring systems." >> "incorporating low-cost, high-functionality sensors in glacier monitoring systems."

Changed accordingly.

Table 1: Please include camera focal lengths, to indicate how you arrived at the horizontal field of view (FOV) angles. In the case of the Canon Rebel T5, you could provide the focal length of the kit zoom lens, 18-55 mm. I'm actually surprised that the Raspberry Pi FOV is so narrow, given that the lens has a small focal length (16 mm).

This has been added.

L120: I see you interchangeably refer to the system as "Pi" and "Raspberry Pi". I would suggest sticking with one to be consist through the paper.

Apologies! This has been corrected, including in multiple following locations further in the paper.

L130: Whilst I like this figure, I would like to see the field photos alongside an annotated photo/diagram of the Raspberry Pi system, outlining the key components. I would suggest removing photo B and replacing it with a close-up photo of the Raspberry Pi that clearly shows the system.

This is a good suggestion, but unfortunately our equipment was damaged in transit following this fieldwork. We hope that the suggestion from Reviewer 1, of a detailed list of components, build instructions, and code given in as supplementary information can satisfy this comment?

L149: What is the accuracy of the RTK system?

Added.

L154: "high quality points clouds" >> "high quality point clouds"

Changed accordingly.

L155: What is a mild filter in Agisoft Metashape? Is this a low-pass smoothing correction? If you could define the filtering method then it should be included here.

The Agisoft Metshape manual gives little information on this, only that this is a mild depth filter which removes points not connected to a surface. This has been added to the manuscript.

L214: I think this is the first instance that the acronym "SfM" is used. Please can you define this earlier in the manuscript, the first time you use the term "Structure from Motion (SfM)" in the main body, and then use "SfM" throughout the rest of the manuscript.

This is defined towards the end of the introduction as SfM (though, as this sentence was removed following other comments, we have re-added this in a new location).

L245-L252: Camera positioning is often a big limitation in glaciology studies given that you have to fit the set-up to the environment you are working in (e.g. working around proglacial lakes, inaccessible areas and differing ground stability). Therefore, positioning cameras at precise heights and angles is sometimes not possible. In fact, the majority of glacier photogrammetry studies have cameras positioned above the glacier front in order to yield the most accurate data (e.g. Holmes et al., 2021; How et al., 2017; Medrzycka et al., 2018; Schild et al., 2016) - please include more examples to demonstrate that many studies have adopted this approach.

We completely agree and have made this more explicit, with additional citations to demonstrate that this is a standard approach.

L254-260: What are these alternate methods? Can you give some examples of where alternate methods have been used, and do they yield measurements that are as accurate as GCPs? My understanding is that precise GPS positioning has been used as a good alternative to GCPs in UAV studies (e.g. Chudley et al., 2019; Jouvet et al., 2019), but not so confidently in terrestrial SfM studies (e.g. Mallalieu et al., 2019). I think the Raspberry Pi set-up also has applications in broader photogrammetry and not just SfM studies. That being said, GCPs are essential for oblique terrestrial photogrammetry (e.g. a single time-lapse camera placed on land at a calving front) because the camera pose (i.e. its angular position in the real world environment - yaw, pitch, roll) has to be estimated from GCPs (Messerli and Grinsted, 2015; Schwalbe et al., 2017) in order to produce an accurate projection model. Additionally, GCPs are an effective way to define and constrain the error of the projection model (How et al., 2020). I think this is an interesting point and you are correct in tackling it here, but perhaps there is scope to open this up to a bigger discussion.

Thanks for this discussion. Apologies for the confusion, this was supposed to be an opening sentence for the rest of the paragraph which does this discussion on ‘alternate methods’. We have added ‘For example’ to the next sentence to demonstrate the point leads on and it doesn’t end with no further clarification. We have also added further discussion on broader applications of Raspberry Pis in photogrammetry studies where GCPs are essential.

L264-273: I think you are discrediting your Raspberry Pi system too much here! Yes, the spatial coverage of a terrestrial camera is limited compared to a UAV; however:

1. Terrestrial cameras can be placed higher up on the glacier tongue in certain settings to capture processes such as ice flow, crevasse propagation, and lake drainage (e.g. How et al., 2017; Fahrner et al., 2021)

2. A key advantage is that it can be placed in the field for long periods of time and produce much longer, higher-temporal-resolution time-series

Additionally, this Raspberry Pi system has the potential for operational monitoring in an automated manner. It is highly unlikely that the glaciology community will ever be able to use UAVs operationally in an completely automated manner (i.e. no pilot).

Thanks! We have added some text to this section from Reviewer 1 which we hope softens the discrediting too much, but we’d still like to remain a little cautious in overstating our results given how challenging it is to position cameras optimally in glacial environments. We have added further emphasis on the automation capabilities of our approach.

L288: "timelapse" >> "time-lapse". This is the convention adopted by the glaciology community generally, so please also change all other instances of this.

We have changed all instances of timelapse to time-lapse – apologies!

L294-315: This is a great two paragraphs for showcasing the advantages of your Raspberry Pi system. I think you have conveyed its potential in operational monitoring very clearly. Please can you include more examples of potential applications in glaciology to demonstrate the potential of its far-reaching impact, specifically in the section L295-300; such as monitoring GLOFs (e.g. Muslow, Koschitzki and Maas, 2015), supraglacial lake drainage (Danielson and Sharp, 2013), iceberg tracking (Kienholz et al. 2019), grounding line position (Rosenau et al., 2013), and seasonal snowline migration (Messerli et al., 2022)

We have added these suggestions (in a slightly different position owing to a new paragraph being introduced here).

L330-345: I think another recommendation should be that whilst SfM-generated models can be produced without GCPs, it is advisable to collect GCPs in order to produce accurate photogrammetric measurements from a Raspberry Pi system (especially if only using a single system instead of an array of systems)

We have added this recommendation – thanks.