Author's response to "Autonomous and efficient large-scale snow avalanche monitoring with an Unmanned Aerial System (UAS)"

Jaeyoung Lim[1], Elisabeth Hafner-Aeschbacher[2,3,4], Florian Achermann[1], Rik Girod[1], David Rohr[1], Nicholas Lawrance[1,5], Yves Bühler[2,3], and Roland Siegwart[1]

[1]Autonomous Systems Lab, ETH Zürich, Zürich 8092, Switzerland
[2]WSL Institute for Snow and Avalanche Research SLF, Davos 7260, Switzerland
[3]Climate Change, Extremes, and Natural Hazards in Alpine Regions Research Center CERC, Davos Dorf 7260, Switzerland
[4]EcoVision Lab, Photogrammetry and Remote Sensing, ETH Zürich, Zürich 8093, Switzerland
[5]CSIRO Robotics, Data61, QLD 4069, Australia

Correspondence: Jaeyoung Lim (jalim@ethz.ch)

We would like to sincerely thank the editor and reviewer for the time and effort in thoroughly reviewing the submitted manuscript. The constructive feedback has been invaluable in improving the manuscript. We have invested significant effort in incorporating the feedback and improving the manuscript. This document includes the response to the editor and reviewers, changes made in the manuscript, and the difference on the revised version of the manuscript at the end. In Section A we summarize the overall changes. In section Section B we respond to the editor, and repsond to reviwers in Section **??** Section D. The revised version of the text is visualized as blue, and the original text is visualized as red with a strike-through.

A Summary

The following points summarize the main modifications made to the revision of the paper:

- Reformulated route optimization section to use realistic values with an energy budget.
- Addition of quantitative analysis on the field test results.
- Improvements to formatting and writing for improved clarity.

B Response to Editor

B.1: Thank you very much for your interest in Natural Hazards and Earth System Science (NHESS) and the submission of your manuscript “Autonomous and efficient large-scale snow avalanche monitoring with an Unmanned Aerial System (UAS)”. I have reviewed your manuscript in detail, and I am happy to release it for peer-review.

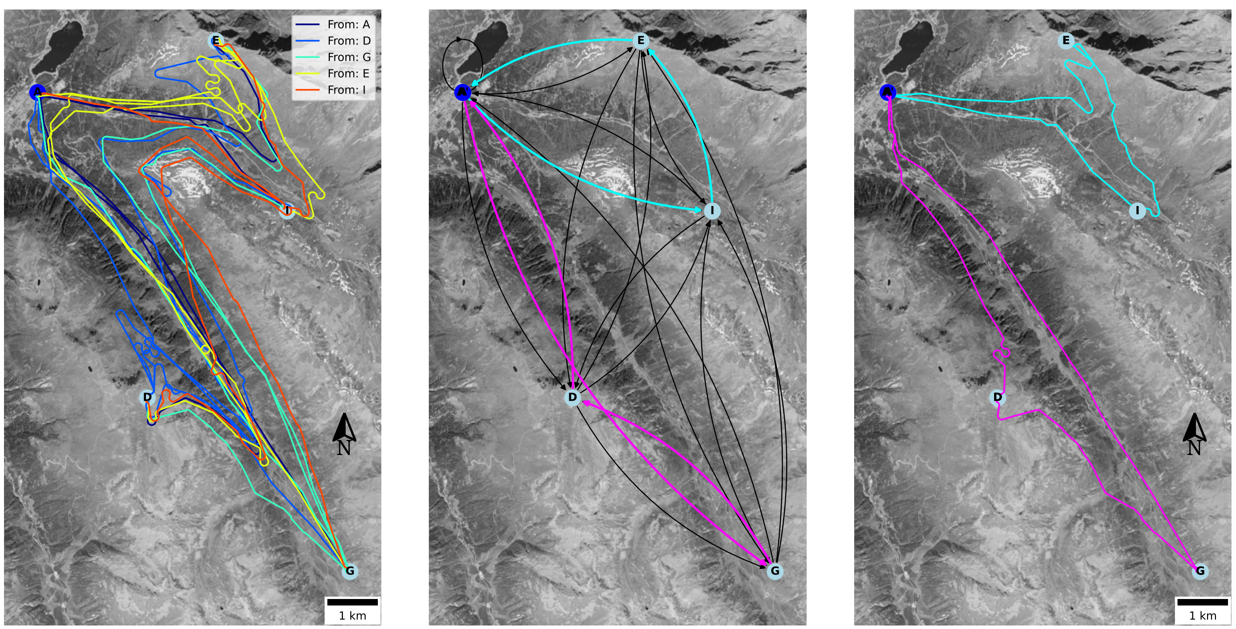
We would like to thank the editor for the time and effort in reading the manuscript in detail and providing constructive feedback. We have invested significant effort in improving the manuscript. We hope that the revised manuscript has improved in quality and is easier to understand for the reviewers and readers.

C Response to Reviewer Comment 1

C.1: Thank you for your work and taking the time to share this research. The paper is structured well and has high quality figures which show the potential for a significant improvement in UAV mapping techniques.

Thank you for the positive response and valuable feedback. We have tried to clarify the questions and respond to the valuable feedback received by the reviewer as best as we can.

C.2: It does make sense to try and maximize the number of ROIs visited per flight but since this can be calculated before take off I'd also like to see it optimized around the number of flights needed to cover all the ROIs. For instance since it'll take two flights to cover all four ROIs could the route optimization cover E and I with a greater % coverage (mapping cost = 6) in one flight and D and G in another? This would also help ensure there's plenty of flight time since the optimization route from I to D passes right next to A.



(a) Roadmap (b) Graph and solution of orienteering problem (c) Solution path

Figure 1. Visualization of the route optimization example with four regions of interest (ROIs). The start position is labeled as A, and the regions of interest (ROIs) are labeled as D, G, E, I. a) Roadmap of the full graph. Each edge is a safe path navigating from one vertex to the other. The edges are colored based on which vertex the edge is started from. b) Graph of the orienteering problem. The edge cost of the graph is the path length of the paths shown in the roadmap. The solution route of the orienteering problem is highlighted in cyan for the first flight, and magenta for the second flight. c) Path of the solution path. Source of orthoimage: (swisstopo, 1998).

We thank the reviewer for the valuable feedback regarding the route planning. The route optimization section was written to a) show that using fixed-wing type vehicles provide the endurance necessary for the target application, unlike multirotor vehicles, and b) demonstrate the importance of mapping cost for route optimization. We have simplified the problem to highlight these aspects while keeping the problem realistic. For example, we have simplified the allocated mapping time to be the average rather than varying by the size of the region of interest (ROI). Practical mission planning and route optimization may require considering many more factors, such as operational procedures, local regulations (e.g. no-fly zones), and weather conditions.

While global route optimization (optimizing over number of flights) would be an interesting direction, it is a challenging problem, possibly worthy of more detailed future research. Moreover, global route optimization spanning over multiple flights can no longer be considered as a single-tour orienteering problem. While this aspect was not fully explored in the manuscript, it would be an interesting direction to expand the formulation of the problem to extend the route optimization using novel formulations such as multi-path orienteering. An in-depth exploration of this would be beyond the scope of this work.

As an intermediate approach without tackling the complete multi-flight optimization, we have updated the manuscript to apply the single-tour orienteering problem sequentially over multiple flights (Fig. 1b, Fig. 1c). This allows us to demonstrate how many flights would be required to cover all ROIs, and its sensitivity to the cost of mapping an ROI. We believe that this is still a valuable extension, as the main value of being able to visit multiple ROIs is the fact that the mapping can happen within a narrow weather window.

C.3: I'd also like to see some discussion about using a somewhat flexible but realistic flight time/range estimate to inform the route planning optimization instead of these being hard-coded values.

Thank you for the valuable feedback. To make the example more compelling, we have changed the budget to be the energy that is stored in the battery of the vehicle. The energy onboard is stored in a 6S $23\,000\,\mathrm{mA\,h}$ lithium polymer battery. To provide better intuition on the energy budget, the range of the vehicle is calculated from the average power consumption $(20\,\mathrm{A})$ during level cruise $(18.7\,\mathrm{m\,s^{-1}})$ with a conversion efficiency of $70\,\%$. This amounts to a range of $51.6\,\mathrm{km}$. As we use the energy model in Duan et al. (2024), the 3D geometry of the path is considered for computing the energy cost. We consider zero wind conditions to keep the analysis simple. Moreover, we have changed hard-coded mapping cost to mapping time, which is converted to the energy used during mapping mission. This is evaluated against different ranges of the vehicle Fig. 2.

> ~~This route optimization~~ We consider an energy budget based on the platform mentioned in Section 3.2,which is equipped with a 6S $23\,000\,\mathrm{mA\,h}$ lithium polymer battery. The route optimization problem for a single sortie can be formulated as an185 orienteering problem (Chao et al., 1996) and interpreted as a graph. For the graph, each ROI vertex is assigned a reward (the value of mapping that ROI) and a mapping cost (the approximate distance required to map the ROI), and each edge is assigned a traversal cost. The goal of the orienteering problem is to find a path from the start vertex to the goal vertex, visiting the set of ROI vertices that ~~maximize the reward~~maximizes the number of ROIs visited, while keeping the total cost ~~within a limited budget.~~ (or, effectively, the energy spent) within the limited energy budget. For a realistic long-range deployment scenario considered in this paper, we assume the start and end vertices to be at the same location.

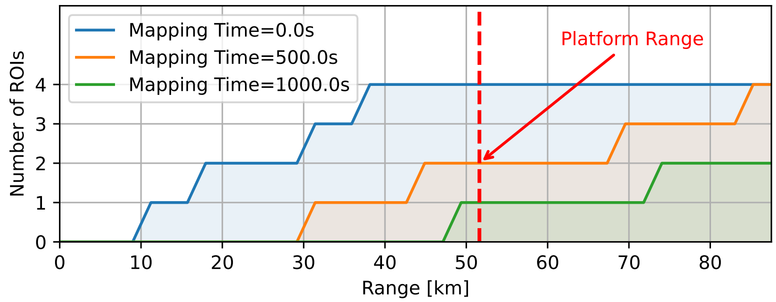


Figure 2. Number of ROIs reachable with different ranges of the vehicle, for the ROIs shown in Fig. 1a. Low mapping time allows the vehicle to reach more ROIs. The range of the platform (51.6 km) is marked as the red dotted line.

C.4: Does it cruise at the same speed when collecting data as when traversing between study areas?

The platform is assumed to be flown at a specific air-relative speed (typically the maximum in-air range speed) throughout the whole mission, as fixed-wing vehicles are normally optimized for a certain speed. This would mean that the vehicle will fly at different speeds relative to the ground, depending on the wind conditions. We specified this in our revisions for better clarity.

> The platform consists of the airframe and the avionics system. The airframe is a commercially-available tiltrotor vertical takeoff and landing (VTOL) aircraft with a mass of $5.7\,\mathrm{kg}$ and a wingspan of $2300\,\mathrm{mm}$ based on the Makeflyeasy Freeman (mfe)(Fig. 2b). The wing-mounted motors tilt upwards to hover during takeoff and landings, which eliminates the need for a runway and allows the vehicle to launch and land in confined locations. This is a significant advantage in mountainous environments where flat regions large enough for traditional fixed-wing take-off can be hard to find. After take-off, the front rotors tilt forward to operate as a normal fixed-wing vehicle for the remainder of the mission until landing. The fixed-wing flight modality uses $9.5\,\%$ of the power compared to hovering flight, and cruise speed of $18.7\,\mathrm{m\,s^{-1}}$, extending the range of the system significantly. We assume that the vehicle always maintains the air-relative cruise speed such that the vehicle maximizes its endurance, simplifying the planning process.

C.5: What is the DEM resolution and what terrain_spacing value was used?

The DEM resolution was selected as $10\,\mathrm{m}$, as this limits the amount of data storage required to be small enough for the onboard memory, but also high enough to accurately represent the terrain for navigation. The DEM is loaded as one file, therefore, there is no terrain_spacing value defined.

C.6: You mention a $50\,\mathrm{km}$ range but is this with $20\,\%$ of the battery remaining when landing or how was this estimated?

The nominal range of the vehicle is $51.6\,\mathrm{km}$ which is assumed with a sufficient margin ($70\,\%$). This was due to the high uncertainty given the large elevation changes and uncertain wind conditions the vehicle would experience during the mission.

We adjusted the feasible range to be calculated based on the platform specs, rather than hard-coded values, for a more realistic example with the concerned system (response of C.3). We hope that this provides a more compelling case for the target application.

C.7: This is done in real-time using the onboard computer which is very cool and would definitely be a useful tool to ensure an area is fully covered before returning to home. In Figure 17 we see that the active mapping collected 67 images over the ROI instead of the 167 images mentioned before but both of these values are still significantly more than the 47 collected in the coverage mapping survey. Were these two surveys the same flight time and range so the resulting difference in the image count is solely because of how well the active mapping performed? Would a cross-grid coverage map have been a better comparison? Also, it should be mentioned somewhere what side lap % was used for the traditional coverage mapping survey.

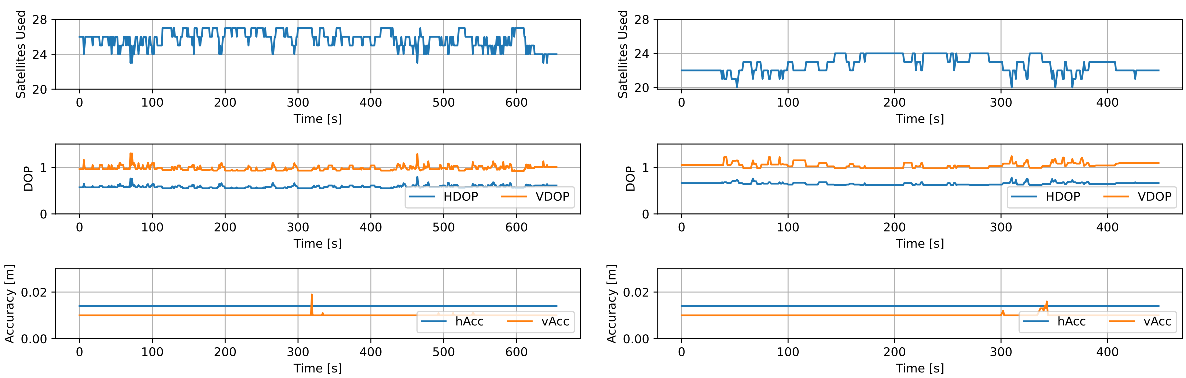
For the coverage plan mapping survey, the sweep spacing was set as $67.4\,\mathrm{m}$, which sets the overlap percentage at 70%. This is compatible with the industry standard of 60-80% overlap between sweeps. The trigger rate was set at $1\,\mathrm{Hz}$, in order to keep it comparable with the active mapping approach. As mentioned in the manuscript, a path planner was used to find a feasible path between the sweep lines. The active mapping approach triggers images consistently at $1\,\mathrm{Hz}$. However, given that the coverage map is not triggering on the path in between the sweep lines, the image count of the active mapping ends up being significantly higher compared to a coverage survey. Figure 15 shows the comparison of the coverage and predicted uncertainty as the flight time progresses. As there is no explicit termination criteria for the active mapping experiment, we can compare the evolution of uncertainty and coverage as if the survey and active mapping has started at the same time. We believe that it is more important to optimize for flight time, as this prioritizes information gathered during the survey, rather than optimizing the computation cost that is required for the photogrammetry reconstruction after the survey.

A cross-grid coverage map was not selected as a baseline method to compare for two reasons. a) It is not possible to fly in the normal direction of the sweep patterns in this particular case, as the terrain is steeper than the maximum flight path angle of the vehicle. b) Drawbacks of cross-grid coverage planning are identical to coverage planning, in the sense that cross-grid coverage would also be planned based on a 2D projection of the environment, and it is not able to react to external disturbances. The main advantage of using the active mapping is the adaptability to disturbances on-the-fly and the ability to efficiently map steep terrain without complicated expert planning, which can be tricky in steep environments.

> Note that a cross-grid coverage pattern was not considered, as the steep terrain prohibits the vehicle from following sweep patterns that are orthogonal to the main sweep patterns. As the active mapping method does not have an explicit termination criterion, the operator commands an *Abort* once the duration of the mapping state is longer than the duration of the coverage survey. In the mapping state, the vehicle takes images of the target region, which is post-processed for reconstruction after the flight. We compare the reconstruction quality and the time to get equal reconstruction results. Comparison with other sensing modalities was not included in the campaign, as the vehicle is not capable of flying other sensing modalities such as Lidar, and ground penetrating radar (GPR).

C.8: Because you're working in Avalanche terrain I'm understanding that there's no mention of ground control points for a qualitative comparison between these two mapping methods and their resulting point clouds. One advantage of the coverage mapping method is that (ignoring wind) the UAV is mostly level when imaging, which means the onboard GPS has a better sky view and position estimate. I'd be very interested to see some information about how imaging the hillside at an angle influenced your GPS accuracy which translates into your point cloud reconstruction uncertainty. Did you adjust for this difference in positional uncertainty between the methods in Agisoft? Since you used PPK were the images uploaded to Agisoft using their actual positional uncertainties? The Agisoft processing reports should also be included.

Thank you for the valuable feedback. The GPS position was acquired using RTK GPS. While this was due to the practical limitations of the platform, due to the lack of ground control points, the evaluation only requires relative accuracy. We used a helical GNSS antenna, which is quite resistant to orientation changes, and no significant GNSS outages were noted during the flights, in either banked or level flight.



(a) Active Mapping

(b) Coverage Planning

Figure 3. GPS accuracy data from the flight experiments.

In order to clarify the results, we compare the information of the GPS accuracy in Fig. 3. It can be seen that the GPS data does not show significant difference in terms of positional accuracy (Accuracy) nor the related metrics (HDOP, VDOP). In terms of number of satellites used, it appears that the coverage planning uses fewer satellites. Therefore we have no evidence that the abrupt viewpoint changes during active mapping are compromising the accuracy of the GPS.

For further development of this platform for commercial purposes, adding a PPK capability for the registration would be possible, but this would not influence the evaluation work that is done in this paper, as the PPK processed data would be unavailable for the onboard planner. We have submitted the Agisoft reports as part of the additional material.

C.9: Could this same mapping approach with high roll angles to image the hill side be calculated and used as a mapping tool in the mission planning software prior to taking off?

We appreciate the valuable suggestion from the reviewer. It would definitely be possible to plan high roll angle maneuvers to be included in the planning prior to the mission. However, because high roll angle maneuvers are typically states with high acceleration (inducing either a turn or a loss of altitude), it may be challenging to follow the plan robustly, especially if the wind conditions vary, or some disturbance causes the vehicle to deviate from its initial plan. One of the significant advantages of the active planning approach is to respond during flight to off-nominal image capture conditions caused by in-flight deviations.

C.10: For more autonomous operations Active Mapping and the on-board computer could still be used to calculate the estimated coverage and direct the UAV to add flight lines to fill in the gaps after the survey if needed and if battery levels are sufficient?

Thank you for the valuable suggestion. We considered two responses to your point, but we're not sure which one would directly address your concern, so we have included both.

First, adding sweep patterns would be a feasible approach, where the actions of the onboard planners would become addition of sweep patterns rather than planning maneuvers for the proposed approach. However, given that the vehicle is operating under tight altitude constraints, adding a sweep line that can be executed only at the end of the survey may require the vehicle to fly large detours. Moreover, coverage planning generates sweep lines based on a 2D projection of the ROI. It may be quite hard to find feasible sweep lines that can be added without significant detours due to the tight AGL constraints posed by regulation.

An alternative approach would be to allocate a reduced budget to the original survey plan, and use the remaining budget to identify gaps in the executed survey plan and attempt to 'fill' them with a new plan in the remaining time with new sweep lines. We believe this sequential approach could well be a viable strategy to improve executed coverage, but would require careful consideration of how much time to allocate to each phase. Effectively, it would require estimating the expected time required to cover missed regions (i.e an estimate of the amount likely to be missed and the time required to cover them). We have not fully explored this approach since we think it may require some hand-tuning and be difficult to estimate consistently. The active planner avoids this problem by constantly trying to maximize information in the remaining time.

We hope these points address your concerns, and apologize if we have misunderstood your concern.

C.11: "The field tests have also shown that the active mapping planner is capable of mapping an ROI with better reconstruction results, and potentially more efficiently." I do not agree that there's sufficient evidence provided to say that this method gives better reconstruction results. To do that you'd need ground control and validation points. This method has shown that with minimal user input active mapping can legally and safely fly a survey with good coverage.

Thank you for the valuable feedback. Our descriptions of 'better reconstruction' may have been too general. What we meant to say was that the active planning method aims at the whole target region from the beginning and does not rely on a finished mission to reconstruct the whole target region. We revised the manuscript to better specify what we mean.

> The field tests have also shown that the active mapping planner is capable of mapping an ROI with ~~better reconstruction results, and potentially more efficiently.~~ good coverage, while staying under the distance constraints.

D Response to Reviewer Comment 2

D.1: The authors have presented a good discussion on the importance of balancing efficiency and safety of UAV-flight operations in rough terrain with achieving the objective of reliable remotely-sensed imagery for avalanche monitoring and mapping. The presented methods may prove to be highly beneficial to reduce scientific data loss when a sensor trigger fails in flight or optimize flight paths to reduce uncertainty / increase image resolution based on real-time feedback of conditions. However, further field testing and quantitative image analysis is needed to fully demonstrate the advantage of the optimization algorithms. Below are minor considerations for the authors.

We thank the reviewer for the positive response. We agree that further field testing would fully demonstrate the advantage of the algorithm. While additional flight tests this season would not be possible due to the snow season being concluded, we plan to work on future research directions to advance the platform.

D.2: L35: Replace 'manned' with 'crewed' considering UAS is an uncrewed aircraft.

Thank you for the recommendation. We have corrected the terminology for UAS from 'manned' to 'crewed' in the revised manuscript.

> However, ~~manned~~crewed airplanes have high operating costs and limited deployment availabilities per season.

D.3: L88: Discussion on photogrammetry is presented, however there is no mention in the paper on the implementation of LiDAR and the resolution of photogrammetry to LiDAR, which would be relevant as a potential dataset for validation/comparison. For example: Solbakken, E. et al. (2024) Repeated UAS Lidar Scanning of Snow Surface to Support Site Specific Avalanche Warning.

Thank you for the valuable feedback. We agree that LiDAR data would have been a good data source for validation and comparison. However, we believe that the suitability of photogrammetry for snow depth mapping has been thoroughly investigated and shown by previous works (e.g., Bühler et al., 2016; Eberhard et al., 2020). The platform we used is unfortunately not capable of flying a relevant LiDAR. We would like to stress that the goal of our work was to show the potential of an active mapping approach for photogrammetric snow depth reconstruction and avalanche mapping. In this context the platform demonstrates the first regulation-compliant autonomous flight in steep terrain, under the new EU regulations (European Commission, 2019).

D.4: L168: "We describe the system by describing the system".

Thank you for pointing out the error in the manuscript. We addressed this mistake in the updated manuscript.

> We ~~describe~~break down the system into ~~describing~~ route optimization, platform, autonomous planner, and operational processes.

D.5: L198: The mapping cost is highly variable, where it will differ per ROI. Further, there is no mention on flight direction, which is highly impacted by head or tail winds, especially within valleys.

The comment on mapping cost being highly variable is accurate. We have simplified the example to only consider 3D distance, considering the kinematics of the vehicle. In realistic scenarios, many more factors should be accounted for, as pointed out by the reviewer, such as the area of the ROI and the wind direction. However, with state-of-the-art methods, these anisotropic costs can be challenging. First, wind fields are highly non-uniform due to the rugged terrain around avalanche risk terrain, but current weather predictions typically only provide kilometer-scale wind information. Therefore, using a predicted wind field for planning may not yield realistic conditions. Second, there is no reliable coverage planning method that can automatically produce complete coverage paths that respect the vehicle kinematics with tight AGL constraints as required for the regulation. Moreover, the active mapping path reacts to unknown disturbances, modeling all possible disturbances at random for mapping cost calculation would make this process very complicated. Therefore, the analysis was simplified to demonstrate using long-range aerial vehicles is advantageous for the vision we are presenting. We have tried making these assumptions on the analysis clearer in the revised manuscript.

> The energy model accounts for the 3D geometry of the path as well as wind. Therefore, the edge costs can be updated based on wind conditions, if available. In this work, however, we assume zero wind, noting that accurate local, low-altitude wind-estimates are very challenging to obtain, especially in the considered terrain. To accommodate the respective uncertainty, we instead plan with a conservative energy budget for simplicity.

D.6: L263: Acknowledgement of "unaccounted trees and obstructions not included in DEM", however pointing out relevant 'obstructions' is recommended. As this is a paper focused on avalanche terrain, there is no mention of the impact of snow height (except 'snow cover' in conclusion) and avalanche debris. The DEM will represent a 'snow free' interpretation of the surface, however the UAV will be operated above snow covered terrain. This additional height above surface should be acknowledged earlier in the paper and impact on flight altitude above ground level. Additionally, in zones of high avalanche activity, the surface is dynamic and large rock debris may exist causing the DEM to be out of date.

Thank you for pointing out the accuracy of the DEM. Indeed, unmodeled objects in the terrain, such as vegetation, artificial buildings or other objects may result in obstructions as pointed out in the manuscript. The snow height is typically smaller than those objects, and all of them will not exceed the safety margin of 50 m. For the photogrammetric reconstruction snow on the surface will affect the actual (not planned) overlap of the images. Through several years of regularly documenting snow/avalanches with coverage mapping we have not encountered problems with these rough assumptions. An accurate DEM with a resolution of 10 m or finer is a sufficiently good representation of terrain for safe path planning.

D.7: L345: "The extent was outlined by hand". On what dataset (aerial, satellite) was the extent determined?

The extent of the ROI was outlined by hand where the avalanche had occurred.

D.8: L438: Consider a comparison with at least a grid difference where areas of disagreement or lower uncertainty can be more clearly identified. Perhaps the areas of disagreement are correlated to slope or flight angle, etc.

Thank you for the valuable feedback. We agree that comparing the grid difference would be valuable. However, given that the uncertainty metric does not take into account the appearance or texture, low predicted uncertainty may not necessarily correlate with the predicted uncertainty. Moreover, the Fisher information metric represents the aggregated information, incorporating viewpoints from diverse distances and flight angles, finding correlation to a single quantity may be challenging.

Incorporating the valuable suggestion, we have tried analyzing the population of uncertainties through a histogram

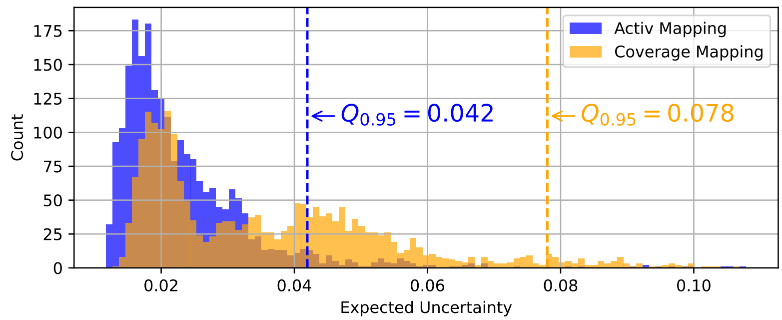


Figure 4. Distribution of uncertainty across the mapped surface inside the ROI. 95 quantile of expected uncertainty with active mapping is 0.042, significantly lower compared to coverage mapping of 0.078

D.9: L444: "fraction of the time" - What is the time difference needed to accomplish the 67 active mapping images versus the 47 coverage mapping images?

The flight time comparison between active mapping and coverage mapping is shown in Figure 15. The time it took to acquire 67 images for active mapping was at 45.63 s and 47 images for coverage mapping at 135.73 s. The full active mapping was run up to a similar time needed for the coverage planning, such that the incremental mapping capabilities of the active mapping planner could be compared.

We will explicitly mark the timestamp in Figure 15 for the reconstructions shown in Figure 17, such that the flight time and number of images gathered are more intuitive.

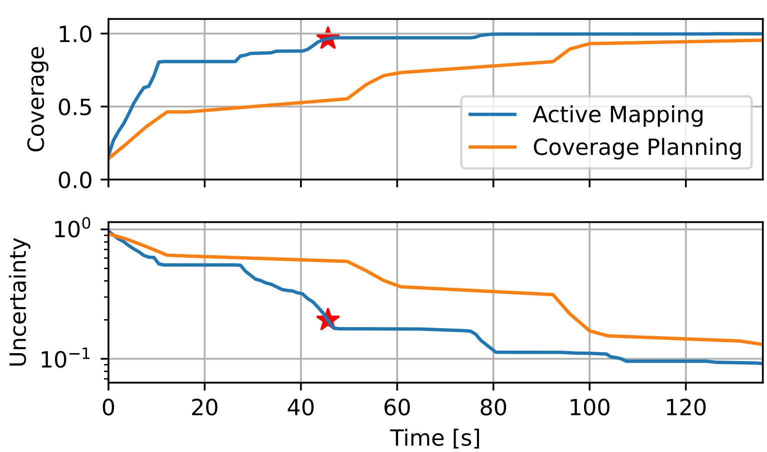


Figure 5. (Top) Coverage comparison of active mapping and coverage mapping. (Bottom) Expected uncertainty comparison with active mapping and coverage mapping. The point with 67 images is marked with a red star symbol.

D.10: L513: Consider additional quantitative means to validate the quality of the reconstruction. In addition to simple grid differencing, other remotely sensed/geophysical data sets may be acquired by drone. LiDAR, as suggested above, may have a very high resolution result that can act as a baseline to which active and coverage mapping results is compared. Another is ground penetrating radar, GPR. Although GPR is suited for rotary-wing and not ideal for extended coverage by a FW, it can be used for a small scale validation of photogrammetry results. It can also validate the DEMs since GPR will provide a snapshot of the current ground conditions below the snow cover.

Thank you for the valuable suggestion on evaluating the quality of photogrammetry results. Unfortunately, we are no longer able to access the avalanche terrain, due to the fact that the season has passed. We also believe that using photogrammetry for snow depth estimation has been sufficiently shown (see comment to LiDAR above), and the primary goal of this paper is to demonstrate a method for efficiently collecting photogrammetric data using a UAV. We plan to continue our research on this topic and further evaluate the quality of the photogrammetry using different modalities of sensors.

D.11: Figure 1. Captions under each image pane in addition to the full caption is redundant, and can be minimized to a, b, c Figure 2. Although mentioned in text, the addition of a scalebar to b) to provide context on wingspan / aircraft size. Figure 3. ROIs are labeled

We thank the reviewer for pointing out improvements regarding the formatting of the paper. We have improved the aspects pointed out in the revised version of our manuscript. We have added the scalebar to the platform figure, as can be seen in Fig. 6.

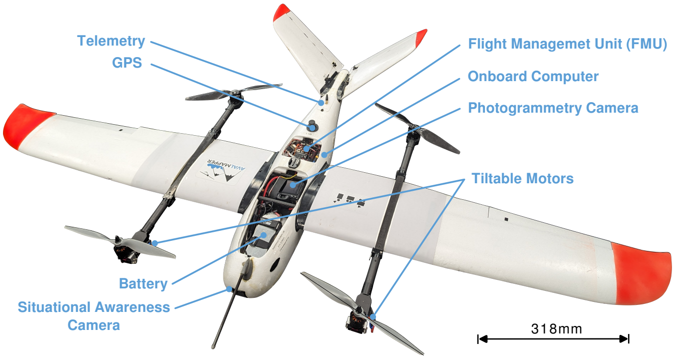
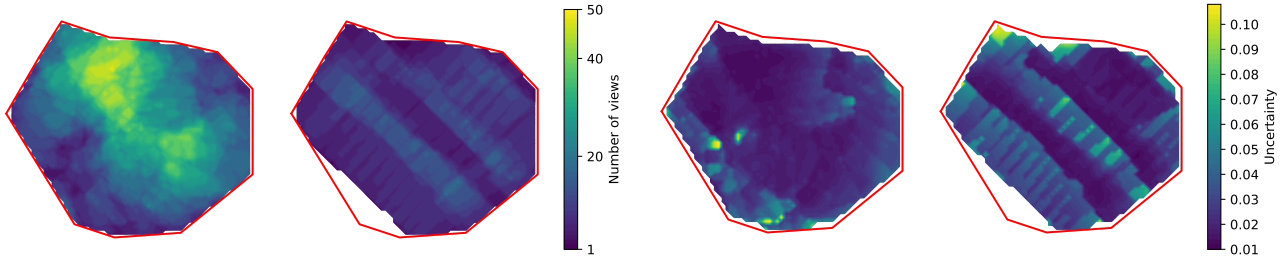


Figure 6. Overview of airframe and components.

D.12: Figure 16. Label which sides of the figure are active and coverage mapping with a, b or left, right. Recommend same colour scale for all grids, as viridis is perceptually uniform sequential but rainbow/spectral is not, so anomalies are presented differently.

We thank the reviewer for pointing out improvements regarding the formatting of the paper. We have improved Figure 16 as recommended by the reviewer, by using the same color scale.



(a) Number of Views (Left: Active Mapping, Right: Coverage Mapping) (b) Expected Uncertainty (Left: Active Mapping, Right: Coverage Mapping)

Figure 7. Comparison of the number of overlapping views and expected uncertainty between active mapping and coverage mapping after flight test. The ROI outline is marked as a red line. Regions with no color inside the ROI are regions on the surface that have zero views visible.

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