# Response to Referees

Monitoring snow depth variations in an avalanche release area using low cost LiDAR and optical sensors

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Dear editor and referees,

Thank you for your constructive and thorough feedback. This helps to improve the manuscript considerably. We copied your comments into the blue boxes and enumerated them, so we can answer each part separately below.

Yours sincerely,

Pia Ruttner-Jansen & co-authors

## Response to Katreen Wikstrom Jones

### GENERAL COMMENTS

R1-1: The paper titled "Monitoring snow depth variations in an avalanche release area using low cost LiDAR and optical sensors" presents a compelling project where high-end technology from the automotive industry is explored and adopted to enhance our understanding of snow processes for avalanche hazard applications, with the long-term goal to improve road safety. The paper is focused on describing the instrumentation, and lessons learned from the first three months of operation. I truly enjoyed reading the manuscript. The scientific significance, the scientific quality and the presentation quality are all ranging from good to excellent. Terrestrial lidar is typically cost-prohibitive and avalanche safety programs rarely have the funds to invest in monitoring networks that can provide near real-time information about the snowpack in the release areas. Here, the authors have designed a low-cost autonomous terrestrial lidar/meteorological station network that shows promising potential in providing high spatiotemporal resolution of snow distribution. I look forward to following this project which, by no doubt, will be of high interest by the global avalanche community. The goal of the project is clear, the background (literature review) is quite thorough, however, as pointed out by the community reviewer Thomas Gölles, it should be updated to include recent implementations of low-cost lidar systems for geoscience applications in Austria. While the purpose of the study is clear, I think the value of the study could be even more emphasized – there is only one sentence in the introduction that touches on why snow depth variability in the release area matters for avalanches – please elaborate on this a bit further. The selected methodology is well motivated and considered (please see request below for additional brand/sensor details in Table). I commend the authors for their skill in keeping the chapters concise, yet adequately detailed. Chapter 2 Monitoring provides all the details necessary to understand the motivation behind selecting the suitable sensors, where and how to install the stations, and how the setup is configured. Anyone interested in implementing a similar system will find this section of the methodology very satisfying! I would like to point out that it would be important to include a brief paragraph that describes the UAV system that was used for generating photogrammetry-derived DSMs and how that data was processed. If these data were not acquired and processed by the author team, then please provide a reference to the data release/publication. For the most part, it is easy to understand the lidar Data processing (Chapter 3), however some clarification regarding some of the processing steps would be needed prior to publication (see specific comment and line comments below). I also suggest making the Data Processing (Chapter 3) a sub-section of chapter 2. Naturally, given the early stage of the project, the authors are cautious with drawing too many conclusions based on their results, nevertheless they provide some interesting discussion points which deserve further exploring. In addition, they have attempted to assess the system performance and they openly state some challenges and limitations that they have encountered this winter. I appreciate the authors determination in making the effort to assess the system performance thoroughly, to [especially more so in the future] analyze the derived products, and comparing the lidar results with other methods available (photogrammetry-derived DSMs using UAVs for example). The text generally flows well and the language in the paper is mostly good, though there are a few sections with a bit clunky or convoluted sentence structure, and where I would suggest rephrasing or removing unnecessary words (see line comments below). There are also a few typos that need correction, some abbreviations that need to be spelled out the first time they are being used, issues with hyphenation, and some consistency issues using certain terminology (e.g. drone vs UAV). These language issues are relatively minor and should not be a problem for the authors to tackle prior to publication. My suggested rewording or rephrasing aim at improving the flow of the text, to make the content clearer and ultimately strengthen the paper. If you have any questions regarding any of my comments or suggested edits, please feel free to contact me at katreen.wikstromjones@alaska.gov.

Thank you for your in depth review with constructive comments and suggestions. While you find our answers to all specific and technical comments below, here are some general points:

- We understand that the literature and state-of-the-art section is missing some current and recent projects. We will include further relevant literature, including the literature pointed out by Thomas Gölles.
- The detailed specifications and processing of the UAV was not the aim of the paper, but we understand that it should be included for the sake of completeness. We will add a sub-chapter to chapter 2 named "Validation with photogrammetric UAV data" where we will include all system specifications and processing steps of the data used.
- According to your suggestion, we will restructure the content of our paper. The study site will be discussed first and the hardware and software components of the setup will be placed in the same section.
- Thank you for your detailed corrections of typos, grammar and language. We are happy to adapt all changes to improve the readability of the manuscript.

## SPECIFIC COMMENTS

R1-2: **Georeferencing the point cloud and aligning different models)** Please elaborate a bit on what was involved in the georeferencing step using the prisms. Can you also please explain how you “projected the 3D models in the vertical direction”? Did you calculate horizontal and vertical offsets and applied shifts to the point cloud or models? It does not appear that co-registration of the lidar model to the photogrammetric model was made. I apologize if I misunderstood any of your processing steps; it would be important to co-register the datasets using stable features, such as the prisms, prior to differencing, especially when comparing a lidar-derived DSM to a photogrammetry-derived DSM (based on Line 269 in the Discussion, it suggests that a co-registration was not done yet). Photogrammetric models tend to be less accurate horizontally, unless they are well georeferenced, which for this type of steep terrain may result in large vertical offsets when compared to another model.

The required steps for georeferencing the scans with prisms are as follows:

1. install prisms at stable locations in the area of interest
2. determine the global coordinates of the prism center (done with Tachymeter and tie points measured with RTK-GNSS)
3. detect prisms and determine prism center in scanner local coordinate system (2D-Gaussian fit using intensity values of points belonging to prism)
4. determine transformation matrix with known points in each coordinate system (prism centers)
5. transform scan points to global coordinate system

The photogrammetric data is georeferenced with Post-Processed Kinematic Global Navigation Satellite System (PPK-GNSS), similar as in Eberhard et al. (2021).

The discussed processing steps would allow an independent georeferencing. But the processing showed that the geometric distribution of the prisms is unfavourable and therefore not suitable for a valid comparison between the lidar and photogrammetric data. The comparison with each independent georeferencing would result in a tilt, mainly showing the georeferencing error of the lidar data, not allowing a fair comparison of the lidar and photogrammetric data. Therefore, we aligned the lidar pointcloud with the photogrammetric results by using the Iterative Closest Point (ICP) algorithm.

For further processing we decided to rasterize the point cloud, by "projecting the 3D models in the vertical direction". This was done after georeferencing, so the horizontal coordinates were used to define a regular grid. If more than one point fell into the grid cell, the height/z- values were averaged and in case of an empty grid cell we linearly interpolated the values from the nearest neighboring cells using Delauney triangulation, with a maximum edge length of 1 m.

We will clarify this in the manuscript.

R1-3: **Interpolation of voids in the lidar-derived DSM)** Did you evaluate other interpolation methods before choosing Nearest Neighbor? If yes, how did they perform?

We did not try any other interpolation method, but we will investigate this in the future.

R1-4: **Observed diurnal patterns in spatial coverage (by lidar))** This is an interesting observation! Line 209-215 in Chapter 4 Results, where you discuss potential explanations to this diurnal pattern, should be moved to Chapter 5 Discussion, and I would encourage you to elaborate on this a bit. I think you are on the right track – research has shown that the lidar sensor can be saturated from scattered sunlight. Even though this is a topic that you may investigate more in the future, I suggest you include a couple of these previous investigations to strengthen the outlook/discussion (e.g. Wu et al, 2011, https://doi.org/10.5194/acp-11-2641-2011). In the spring and summertime, I am curious to see if you'll continue to see a diurnal pattern as less dense air caused by warmer air temperatures could scatter the laser pulses and cause a reduction in reflectance.

The diurnal pattern is indeed a very interesting observation and in agreement with our expectation that we would have more favorable scan conditions during the night. As pointed out by Alexander Prokop in R2-10, ambient radiation with the same wavelength as used by the lidar causes a too low signal to noise ratio for points at far ranges or low incidence angles (Prokop, 2008; Wiscombe and Warren, 1980). The other influencing factor mentioned is the presence of liquid water on the surface or liquid water content in the snowpack. As discussed in Wiscombe and Warren (1980) a higher liquid water content leads to bigger effective grain size, which in turn enables more absorption and forward scattering. The influence of air temperature on the scatter of the laser pulse is discussed in the literature mainly for air and space borne lidar applications (Wu et al., 2011; Fahey et al., 2021). We will discuss the effect of air temperature on our short range setup in the revised version of the manuscript.

As suggested we will move lines 209-215 to Chapter 5 Discussion and add a brief discussion along the lines sketched herein.

R1-5: **Terrain impacts for wind-induced redistribution of snow)** In "4.4 Case study II: Snowfall event with wind" – I suggest adding a sentence at the end of this section that emphasizes your results, something like "The clear pattern of eroded and deposited snow agrees with the recorded wind direction at nearby weather stations on this day." Additionally, in this section, I encourage you to analyze the interaction between topography and snow distribution a bit further and add a sentence or two that describe how this redistribution (erosion and deposition) was influenced by small terrain features within the ROI, such as scouring on taller small sub-ridges and deposition in lee-ward depressions/small gullies. In the discussion you could, for example, make a point that your results support the idea that it is important for avalanche safety experts to study the avalanche terrain in the summer to enhance their understanding of snow distribution in the winter (i.e. where the deep pockets of snow are vs. shallower potential trigger points).

We will clarify the sentence, also based on the suggestion in R1-22. The text will read:
*The snow redistribution was influenced by small terrain features within the ROI, such as erosion on taller small sub-ridges and deposition in lee-ward depressions and small gullies. This snow redistribution is also visible in the snow depth changes from the lidar data and agree with the recorded mainly westward wind direction on this day.*

A more detailed analysis on the relationship between topography and snow distribution is out of the scope of this study. In future research we want to investigate an approach to model and predict the snow depth distribution, which will require a detailed analysis of the correlation between snow depth distribution and terrain features.

We agree with the idea that local terrain knowledge is important for practitioners, but we would be careful with a clear recommendation that the avalanche terrain in summer explains the snow redistribution in winter, as other variables (wind, snowfall) play an essential role. We will adapt the discussion and write more about the implications for practitioners.

R1-6: **Discrepancies vs. potential of the system)** In Chapter 6 Discussion you state “While the discrepancies between the UAV-based acquisitions and the early processing results from our system are larger than the expected potential of our system…”, what do you mean by this? Can you please explain what you mean by the “expected potential”?

The revised manuscript will contain a better description of the expected potential of the system. The statement in Chapter 6 is meant to show that additional post-processing steps (noise filtering, improved alignment) will increase the quality of the results of the lidar measurements. This will be adjusted.

## TECHNICAL CORRECTIONS

We will implement all proposed changes to language, grammar, punctuation and almost all proposed details to be added. For brevity, we only list and comment the few other recommendations herein.

R1-7: Line 10 a mean of what? mean vertical/height difference?

We refer to the mean of vertical difference between the models and will clarify this in the text.

R1-8: Line 82 elaborate a bit "we installed sensors at the stations to record"

We will adjust the text to:
*Additionally, we installed meteorological sensors at the stations to observe wind speed and direction, air temperature, relative humidity, and snow surface temperature. These data will later serve as input data for a modelling approach, where we aim to predict the snow depth variations.*

R1-9: Line 91 what’s the unit here? Hz?, "application, the" (comma needed)

The unit is the number of scanlines. For clarification we will rephrase to: *... most of the devices are solid-state sensors, which are operating with usually 32, 64 or 128 scan lines (...).*
We will insert the missing comma.

R1-10: Line 92 Not sure what you mean here. Do you mean "the spatial coverage increases as the sensor operates farther away from the target features/surface"?

For clarification we will rephrase to:
*In a mobile application, the scan lines sweep across the scene as the sensor itself moves, thereby increasing the spatial coverage. In a static setup the fixed angular spacing between the scan lines of solid-state sensors results in relatively sparse coverage of the scanned scene, especially at far ranges.*

R1-11: Line 111 Having a figure here that shows the location of all these instruments would be valuable to the reader!

We will better highlight this in figures 3 and 5, and add some related clarification to the text.

R1-12: Line 128 add "to ensure that the station would not get buried", point #3 Was this a ground assessment? Maybe specify what you were looking for - stable bedrock?

We will change the phrasing as suggested, and add *... 3) checking the surroundings of possible locations on-site, in the field to find suitable mounting possibilities, such as stable bedrock.*

R1-13: Line 142 “derived results” - vague wording

With the derived results we meant raster data, such as DEMs. We will include the term for clarification.

R1-14: Line 161 Not clear on what “local system” means? Local coordinate system?

The "local system" refers to the "local scanner own coordinate system", we will include the extended phrasing in the sentence for clarification.

R1-15: Line 166 I do not understand what is being done in this step. Can you please explain?

Lines 167-170 are the explanation of the projection step, which we also tried to explain in different words in R1-2. For clarification we will change the phrasing to: *... where we project the 3D point clouds along the vertical direction, using the open source software CloudCompare, performing the following steps: We define a grid ...*

R1-16: Line 172 Use either 1 m x 1 m or 1 m2. "one" instead of "1". Regarding statement of "points with horizontal coordinates" - Do you have points without any horizontal coordinates?

We will change the expressions as suggested. We have no points without horizontal coordinates, for clarification we will reformulate to: *.. scan point where its horizontal coordinates are within the cell.*

R1-17: Line 207-209 Your observation of a difference in lidar reflectance during nighttime vs daytime is very interesting! Please provide some numbers here - these diurnal patterns, how significant are they?

In the analysis until end of February, as shown in the present manuscript, we found differences of up to 20 % region of interest coverage between day and night, e.g. on February 5th, 2024. In our extended analysis (until mid April), we found differences of up to 30 %, e.g. on March 20th, 2024. We will add the specific numbers in the corresponding section in the results.

R1-18: Line 212-213 I'm also wondering if the less dense air caused by warmer air temperatures (though still subzero) were enough to scatter the laser pulses and cause a reduction in reflectance.

We refer here to our answer to R1-4.

R1-19: Line 217 How was the comparison done? Did you compare the resulting DSMs or was it a point cloud comparison?, write out MP as "megapixel"

We will write out megapixel, and clarify in the text: *We compare the DSM derived from the lidar point cloud to a photogrammetric ....*

R1-20: Line 220 Mean difference between the two?

Exactly. We will reformulate to: *The two DSMs have a mean ...*

R1-21: Line 231-231 Here you state that there is disagreement between the models "where the pattern changes from ablation to accumulation, which can be due to errors in the alignment of the systems." Was no horizontal alignment done between the models?

We performed a horizontal alignment between the models (see R1-2). However, the unavoidable imperfections of the estimated alignment result in deviations most visible in the mentioned areas. We will clarify this better in the text.

R1-22: Line 255 You have the opportunity here to analyze the interaction between topography and snow distribution – I suggest adding a sentence that describes how this redistribution (erosion and deposition) also was a result of topography within the ROI, such as erosion from taller small sub-ridges and deposition in depressions/small gullies. Suggest adding a sentence at the end emphasizing your point "The clear westward pattern of eroded and deposited snow agree with the recorded wind direction on this day."

We refer here to our answer to R1-5.

R1-23: Line 266 What do you mean by "potential"?

We refer here to our answer to R1-6.

R1-24: Line 290 remove “limitations of the system” unless you’ll give examples!

We will keep the "limitations of the system" in the manuscript and add some specific examples.

R1-25: Line 310 suggest replacing “state-of-the-art” with “current”, add “that are mainly”. Regarding “its benefit”, I’m wondering, would you provide all the data, such as providing real-time access to the monitoring stations, or would you compile a product based on the data that you’ve collected, or maybe both?

We will change the phrasings as suggested.

We do not plan to provide real-time access, but the data and compiled products will be made available after each season. We will clarify this in the text.

# Response to Alexander Prokop

## General Comments

R2-1: The paper titled “Monitoring snow depth variations in an avalanche release area using low cost LiDAR and optical sensors” explains how a low cost automotive lidar system is applied to measure snow depth variations in an avalanche release area. Currently several research groups are working on the topic, as such low cost lidars are promising to increase the application of terrestrial lidars for avalanche safety applications. The presented paper is an easy read and the presented analysis are done well , so in this context it is very worth publishing those results. However, the paper seems to be written a bit in a rush, which is too bad, as the scientific content could be increased and give even more valuable information to the reader. Here are some examples on how to improve the paper:

Thank you for your in-depth review with constructive comments and suggestions. You find our answers to the respective general and specific comments below.

R2-2: The data presented ends after 3 month in the middle of the winter. I think in particular the spring season with wet snow decreasing the range of lidar sensors and melt/freeze cycles challenging the stability of the set-up would have been great to analyze the full potential of the system. There is no reason to stop the analysis at this point as any future application would certainly like to apply the system for the whole winter season. You have been mentioning in the text yourself that the spring season would reveal further information, so why not showing the data. I guess it is possible to still do it. In this way you could also elaborate on that one of the systems was taken out by an avalanche later on in the season, so that would point out another very important limitation of the system and would support your comment that positioning of the lidar sensor is crucial in terms of the application regarding the limited measurement range achievable.

Due to the submission deadline of the special issue it was only possible to process the measurement data to the point in time as presented. At this time of the review process we have data from the whole winter season and we are eager to extend our analysis with data from the spring season for re-submission. We will also report on the loss of station Braema1.

R2-3: As already mentioned by the other reviewers the literature research can be improved. The work of the other groups that currently work on the same topic has not been mentioned. Moreover extensive work from different research groups about lidar applications you like to achieve with your system should be included, I have mentioned some in the specific comments, but feel free to cite others as well.

As we indicated in R1-1 we will add more relevant literature, including the references mentioned in your specific comments.

R2-4: The comparison of the lidar data to SfM-photogrammetry is not optimal. Here it would have been better to validate with state-of-the-art lidar sytems (e.g. Riegl VZ-6000). I think it is not necessary to do this for this paper, but please elaborate on the referencing of both techniques and what the error introduced by the referencing process is as there is certainly an error when comparing 2 totally different measuring approaches (active and passive measurement)

We agree that a comparison of the presented system with a state-of-the-art lidar system, such as the Riegl VZ-6000 TLS, would be highly interesting and would allow for a better benchmarking within the lidar measurent methods. However, while planned for the future, it was not possible for us to organize a VZ-6000 for reference measurements already during the past winter/spring season, and we chose to compare to a UAV-based photogrammetric model instead. The common output (point clouds) obtained using different measurement principles and different viewing directions, with sensors and processes affected by different sources of uncertainty, indeed make the comparison more difficult than using TLS, but on the other hand may also strengthen the comparison through technological complementarity. Finally, in our perception, photogrammetric acquisition using UAVs is the current state-of-the-art method for areal snow depth distribution mapping in practice. For the future we plan to compare to both UAV-based photogrammetric results and TLS-based ones.

As suggested, we will elaborate more on the referencing processes and error quantification coming from the different systems and measurement approaches.

R2-5: Other to reviewer 1 Katreen, I think the important scientific content of the paper is how the low cost lidar system works in comparison to the existing expensive ones. All applications in the snow and avalanche community have been extensively discussed in the past 20 years, so what is really interesting is what kind of information you can actually gather from the low cost lidar systems. In this context I mentioned in particular for the discussion and conclusion section some improvements in the specific comments. E.g. while calculating full avalanche release volume seems to be not achievable by the limited measurement range of the system and the data presented, still very valuable information can be given to avalanche forecasters. So I suggest a more thorough discussion on the results achieved leading to certain applications, that would improve the paper significantly.

We aim to showcase a new low cost setup to observe snow depth variations in avalanche release areas. We will extend the discussion on the results and highlight possible links to specific applications.

## Specific Comments

As above, we implement most of the concrete recommendations regarding clarifications and formal improvements of the text. We only report the other recommendations and responses here, for brevity.

R2-6: Line 31: change to "of snow depth across a slope and are less accurate than spatial measurements" (Prokop et al. 2008)

Prokop, A., Schirmer, M., Rub, M., Lehning, M., Stocker, M., 2008. A comparison of measurement methods: terrestrial laser scanning, tachymetry and snow probing for the determination of the spatial snow-depth distribution on slopes. Ann. Glaciol. 49,210–216.

In the context of this paragraph we are referring to different methods of single-point measurements of snow depths and it would be misleading to state that single point measurements in general are less accurate than spatial measurements.

R2-7: Line 67: to my knowledge the VZ-6000 is not that costly, its above 150k (USD) and if necessary you can run it in an eye safe mode even though its not the optimal mode. Those scanners (e.g. Riegl VZ-4000) are often run operational in mines, so an autonomous operation is not complex., there are ready made (not cheap) solutions provided by Riegl . The group at Hintereisferner you are citing suffered from a poor foundation of their measurement cabin and therefore a rather instable set-up.

We will remove the price indication of the Riegl VZ-6000 in the manuscript, and clearly relate the assessment as 'costly' to the use case anticipated in this paper. We will correct the statement regarding eye-safety, and improve the formulation of the sentence to better express that autonomous operation is not complex as such, but that the listed challenges make it complex to achieve during winter in alpine environment, close enough to the avalanche release areas and under the financial restrictions of public administration.

R2-8: Line 110: Skip the part of explaining that you measure the temperature in the snowpack in different heights, you do not use this data for any analyses.

We see this as relevant information for other scientists who might consider to use our data for their own investigations. However, we will shorten this part and mention explicitly that the data are not used in the present investigation.

R2-9: Line 191 or before: Just a comment: It would to have been great to measure snow depth automatically with an alternative sensor such as an ultra sonic ranger or an 1D-laser for validation of the snow depth data at least at a single point. Taking HN from 5,5 km away is not really reliable in particular in windy snowy high alpine terrain.

We are fully aware of this limitation and will clarify it in the revised text. It is part of our ongoing investigations to find out whether HN measured at a single location within the monitored area or at the instrument site would be more representative for the entire monitored area than the approximation of snowfall intensity which we now obtain from the existing sensor 5.5 km away.

R2-10: Line 210-215: Already the first lidar snow measurements showed that solar radiation plays a role in the intensity of signals received from the snow surface. See e.g. Prokop 2008 Fig 4. The reason is that there is ambient radiation in the same wavelength as the lidar wavelength and the signal to noise ratio is therefore not as favorable and weak signals (e.g. from targets in a long range to the scanner, or with low incident angles) are not anymore detected by the receiver (too weak and lost in noise). Here a full waveform analysis helps, where the threshold of when the receiver detects a target can be set, however, I guess that is not possible with such low costs lidar systems.

Another factor of reduced received laser intensity is water content at the snow surface, see also Wiscombe and Warren, 1980; Prokop, 2008 Fig. 5.

We will include the extended explanation and suggested references in the discussion. Indeed, our low-cost system does not provide full waveform data.

R2-11: 4.2 Comparison with photogrammetric data:

A comparison to a Riegl VZ 6000 measurement would have been great instead of a comparison with photogrammetric data, as it would have pointed out the differences in laser behavior, different footprint size, different range, and so on. However, it leaves room for the other groups working on the topic to deliver such a comparison. As reviewer 1 pointed out already it is a bit unclear how you referenced the lidar and the photogrammetric data, please elaborate on this.

We will improve the description (see also R1-2, R2-4).

R2-12: Discussion and Conclusion:

Focus should be more on what is actually achievable with the proposed system in comparison to existing methods discussing the technical specifications and measurement behavior. For example it is mentioned through-out the text that an application of the system would be to collect data for avalanche dynamics analysis e.g. Line 273 you state that you are able to measure release volume. However, the data you present only shows a part of an avalanche release area, so you are not able to calculate full release volume. Here you could mention that the range of your lidar system is too short to cover full avalanche release areas, in particular when talking about road safety. Avalanches that endanger roads need to have a certain size, so the release area of such avalanches can not be covered by the presented system. It's still valuable information for an avalanche forecaster to know if there is actually something released and on what weak layer in the snowpack the avalanche has been released, so the application of the system is still very valuable, however it can certainly not used to calculate the full release volume in the current state (not mentioning even the avalanche track and the full accumulation area) as it is done at avalanche test sites e.g. at the Col du Lautaret (France), at Valle de la Sionne (Switzerland), or in Rygfonn (Norway). So to point out the current limitations, you could say that you covered an area of that much square meter, and that helps to asses conditions in the release area for avalanche forecasting in particular to determine snow drift patterns and in case an avalanche is released, in what depth of the snow the weak layer was identified (by the way that would have been another great analysis if you would have pointed out what weak layer was actually identified in your case example using available data).

We will extend the discussion to include more comparison to other existing methods and focus on the potentials and limitations in the context of practical implications.

R2-13: Another point of discussion could be what area you could cover under all types of measurement conditions, and what under optimal conditions. I think it is very interesting for the reader that wants to apply such a system, what is the impact of the incident angle, the range and the snow conditions on measurement behavior. The manufacturer always indicates optimal measurement results in the specifications, however, those are never reachable in high alpine terrain under harsh measurement conditions. So please go more in detail about what was actually reached and what are the real applications in the current state.

In the revised version of the manuscript we will include an analysis on the impact of incidence angle and range, and try to better cover the aspects mentioned in this comment.

## Response to Community Comment Thomas Gölles

C1-1: Dear Authors,

The state of the art section needs to be updated. We have been working on low cost lidar applications in geosciences and specifically for snow and avalanche applications for years. The paper describing our MOLISENS system already mentioned snow and avalanche applications in 2022. Also, more specifically the paper "Automated snow avalanche monitoring for Austria: State of the art and roadmap for future work" has a section about low cost lidar.

During the "5. Lawinensymposium Graz 2023" we also presented first results using low cost lidar for avalanches.

For data processing we have our own open source Python package called pointcloudset, which would be useful for your future work and we could collaborate on adapting/testing it for you're the Livox Avia lidar.

Required citations:

Goelles, T., Hammer, T., Muckenhuber, S., Schlager, B., Abermann, J., Bauer, C., Expósito Jiménez, V. J., Schöner, W., Schratter, M., Schrei, B., and Senger, K.: MOLISENS: MObile LIdar SENsor System to exploit the potential of small industrial lidar devices for geoscientific applications, Geosci. Instrum. Method. Data Syst., 11, 247–261, https://doi.org/10.5194/gi-11-247-2022, 2022.

Kapper KL, Goelles T, Muckenhuber S, Trügler A, Abermann J, Schlager B, Gaisberger C, Eckerstorfer M, Grahn J, Malnes E, Prokop A and Schöner W (2023) Automated snow avalanche monitoring for Austria: State of the art and roadmap for future work. Front. Remote Sens. 4:1156519. doi: 10.3389/frsen.2023.1156519

RSnowAUT-Konsortium (2023). Das Potential von Automobilsensoren für die lokale Detektion von Lawinen im Rahmen des FFG-Projekts RSnowAUT, 5. Lawinensymposium Graz 2023, https://lawinensymposium.naturfreunde.at/files/uploads/2023/11/Tagungsband_2023_gesamt.pdf

Optional citation about pointcloudset:

Goelles, T., Schlager, B., Muckenhuber, S., Haas, S., & Hammer, T. (2021). 'pointcloudset': Efficient Analysis of Large Datasets of Point Clouds Recorded Over Time. Journal of Open Source Software, 6(65), 3471. https://doi.org/10.21105/joss.03471

best regards,

Thomas Gölles

Thank you for pointing this out. We consider the peer reviewed publications Goelles et al. (2022) and Kapper et al. (2023) as relevant references for our study and will include them in the revised manuscript.

## References


Eberhard, L. A., Sirguey, P., Miller, A., Marty, M., Schindler, K., Stoffel, A., and Bühler, Y.: Intercomparison of photogrammetric platforms for spatially continuous snow depth mapping, The Cryosphere, 15, 69–94, doi: 10.5194/tc-15-69-2021, publisher: Copernicus GmbH, 2021.

Fahey, T., Islam, M., Gardi, A., and Sabatini, R.: Laser Beam Atmospheric Propagation Modelling for Aerospace LIDAR Applications, Atmosphere, 12, 918, doi: 10.3390/atmos12070918, number: 7 Publisher: Multidisciplinary Digital Publishing Institute, 2021.

Goelles, T., Hammer, T., Muckenhuber, S., Schlager, B., Abermann, J., Bauer, C., Expósito Jiménez, V. J., Schöner, W., Schratter, M., Schrei, B., and Senger, K.: MOLISENS: MObile LIdar SENsor System to exploit the potential of small industrial lidar devices for geoscientific applications, Geoscientific Instrumentation, Methods and Data Systems, 11, 247–261, doi: 10.5194/gi-11-247-2022, publisher: Copernicus GmbH, 2022.

Kapper, K. L., Goelles, T., Muckenhuber, S., Trügler, A., Abermann, J., Schlager, B., Gaisberger, C., Eckerstorfer, M., Grahn, J., Malnes, E., Prokop, A., and Schöner, W.: Automated snow avalanche monitoring for Austria: State of the art and roadmap for future work, Frontiers in Remote Sensing, 4, URL `https://www.frontiersin.org/articles/10.3389/frsen.2023.1156519`, 2023.

Prokop, A.: Assessing the applicability of terrestrial laser scanning for spatial snow depth measurements, Cold Regions Science and Technology, 54, 155–163, doi: 10.1016/j.coldregions.2008.07.002, 2008.

Wiscombe, W. J. and Warren, S. G.: A Model for the Spectral Albedo of Snow. I: Pure Snow, Journal of the Atmospheric Sciences, 37, 2712–2733, doi: 10.1175/1520-0469(1980)037<2712:AMFTSA>2.0.CO;2, publisher: American Meteorological Society Section: Journal of the Atmospheric Sciences, 1980.

Wu, D. L., Chae, J. H., Lambert, A., and Zhang, F. F.: Characteristics of CALIOP attenuated backscatter noise: implication for cloud/aerosol detection, Atmospheric Chemistry and Physics, 11, 2641–2654, doi: 10.5194/acp-11-2641-2011, publisher: Copernicus GmbH, 2011.