Dear Dr. Williams,

Many thanks to you and the reviewers for the swift review of the manuscript. The helpful suggestions have greatly improved the manuscript. We have addressed these suggestions and comments below, paraphrasing or quoting them in bold, following with our response. Line numbers provided correspond to the new "clean" manuscript document (not the differenced PDF).

<u>Reviewer A:</u>

This manuscript presents an approach of using drone-based lidar to produce very high resolution point clouds and raster datasets of the Earth's surface. The presented applications focus on faults at multiple locations in the Canadian Cordillera that would be challenging to image with a drone and the more common structure-from-motion techniques.

The described approach and test cases are thorough and provide useful information for anyone interested in using a drone for fault related research. This manuscript is well written and the figures are of high quality. I recommend publication in Seismica after addressing the comments below:

The introduction could better motivate ULS lidar vs. airborne lidar or SfM. The introduction motivates high resolution topography and lidar broadly. But what is the importance of the spatial and temporal resolution of the ULV data specifically? A lot of manuscript focuses on the improved resolution of the ULS data, why is this important? What is the science that we can do better with this high resolution data. Is repeat time easier/ cheaper than with airborne lidar? What are the implications for change detection? Some of this comes later in the examples, but I would like to see a better motivation at the beginning of the manuscript.

Thank you for the positive and constructive feedback. We agree that motivating these points at the beginning will improve the manuscript. We have included the following text to the final paragraph of the Introduction, Line 103: *"One of the principal advantages is simplified and cheaper repeat observations, with the potential for imaging co-seismic rupture, off-fault deformation and post-seismic afterslip at finer spatial (<50 cm) and temporal (<1 day) resolutions. Additionally, the higher spatial resolutions attainable with ULS allow for more confident measurement and interpretation of subtle fault scarp morphology. The limitations of ULS systems include spatial coverage, which is restricted by battery life, flight constraints imposed by civil aviation authorities, and the necessity of road access to launch sites with good visual sightlines, and we finish the paper by discussing ways in which these limitations might be mitigated in the future.*"

Georeferencing point cloud data is very important and challenging and time-intensive. Did the authors evaluate the georeferencing accuracy via independent ground control points at any of the sites (beyond the 5 GCPs used in georeferening)? Can these be used to provide an uncertainty on the georeferencing from this technique without the use of other lidar data? This is not necessary for publication, but if the authors have this information, adding it would certainly strengthen the publication. If not, could the authors hypothesize briefly about the georeferencing quality, for example with knowledge of the location error in the published ALS lidar data.

This is a good suggestion, but we did not collect any independent control (such as monuments) for any of our sites. In most cases this is because none exist in the vicinity of our remote field sites.

To address your comment, we added the following text to the end of the paragraph discussing georeferencing, beginning on Line 237: "*Many of our field sites are in remote regions with limited options for additional, independent ground control, and we have therefore not performed testing of georeferencing uncertainties of our system against geodetic control monuments. However, we estimate uncertainties in the order of ~20 cm, based on random scatter observed in our point clouds (~15 cm) as well as expected accuracies of our GNSS ground control. We acknowledge that constraining these errors is important, especially for applications involving change detection between multiple acquisitions. However, our ~20 cm estimate compares favourably with uncertainties associated with ALS datasets, such as errors of ~21 cm observed by Hodgson et al. (2004) over a range of land cover types, and horizontal and vertical errors of ~29 cm and ~9 cm observed by Glennie et al. (2013) in helicopter lidar acquisitions.*"

We added the following sentence to Line 269 (Data Comparisons and Differencing Section) to include an additional source of error that might contribute to differences between two datasets, "*This step was taken in order to account for several sources of error, including random scatter within each point cloud* …"

Smaller comments:

Line 118: Approximately how far can you maintain visual line of sight?

On Line 180, in the section on survey planning, we write: "*In the absence of obstacles we find this visual limit to be around 1.5 km, though it is often challenging in forested areas to find ideal sight lines."*

Figure 2:

The green units look a lot alike. Use a different color.

Thank you for pointing this out, we had not realized how similar the vegetation greens in panel A were to the geological units in panel B! We have changed the colors for the geological units to prevent confusion between panels A and B. We have also added titles to panels A and B for clarity. In case there was still some confusion between the greens in the Vegetation Zones, we adjusted the Pacific Cool Temperate Forest to a darker shade of green and removed the Eastern Cool Temperate from the legend (as it is not present on the map).

Write out abbreviations for provinces, territories and states

Abbreviations have been added to the caption. "*Abbreviations for states, provinces and territories are as follows; AB: Alberta, AK: Alaska, BC: British Columbia, ID: Idaho, MT: Montana, NWT: Northwest Territories, WA: Washington, YT: Yukon.*"

Helpful to include an approximate scale bar for A.

Scale bar for A added below the legend.

Figure 4:

This is an important figure, yet confusing. Where do I start and finish looking?

The complexity of this figure is reflective of the complexity and non-linearity of the data processing workflow! To improve the readability of the flow diagram, we re-arranged the inputs so that there are no arrows crossing over one another. Furthermore, we added large boxes corresponding to the Inputs, Preprocessing, Processing, and Outputs stages.

It would be helpful to define all terms in the caption, even if already in Table 1. Note, "Sbet" is not defined in Fig 4 or Table 1.

sbet is now defined in Table 1 and in the caption of Figure 4. The following text was added to the caption, "*Abbreviations used in this figure; DSM: Digital Surface Model, DTM: Digital Terrain Model, GPS: Global Positioning Systems, INS: Inertial Navigational System, NRCAN: Natural Resources Canada, PPP: Precise Point Positioning, sbet: smoothed best estimate of trajectory."*

Figure 6:

Row B: The colorscale shows low, middle, high, but otherwise is hard to align with the image. Could you instead show on a log scale?

We tried setting the colorscale to be logarithmic as opposed to continuous, however, we felt that doing so lost some of the detailed differences between the ULS and SfM data. We have opted to keep the colorscale the same as it was to allow for better comparison between these datasets. There was some time spent trying different ranges to tweak out the best ranges for these comparisons!

Row C: I am surprised that the hillshades do not look better. Is the elevation hiding details in the hillshade? Light from 030 would better show the NNE facing scarp.

Upon checking the submitted PDF, which had to be compressed to meet the upload limit, we think the issue is that the image lost significant quality during the compression. More care will be taken on the revised upload, and the DTM should look better. Furthermore, we tried changing the lighting to be from 030 and unfortunately that did not highlight the NNE scarp (the feature is quite subtle, so the shadow may be more effective). The hillshade has been kept as is.

Figure 8:

This is a nice figure highlighting the differences between the ALS and ULS data.

Thanks!

Line 340: I mostly agree that the 28 cm error is reasonably small. Is this largely from the ULS and the ALS data? Are there any reported errors for the ALS data? Could these be used to hypothesize a likely ULS error?

This is a good question. However, we do not know what control was used for the ALS dataset, so it would be difficult to determine which component of the difference (in registration) that each dataset is responsible for. It is likely that the ALS dataset has a larger proportion of error as the ground control points used to register the dataset may have been from further afield (several kilometers) from the Elk Lake site.

On the note of reported ALS and hypothesized ULS error, we did some reported errors in the metadata summary from LidarBC. We have added the following text to the paragraph, Line 365 "*These non-zero values reflect a combination of factors, including residual misalignment of the point clouds (even after ICP co-registration) and internal vertical scatter, estimated from hard, flat, non-vegetated surfaces (e.g. roads, parking lots) at +/-6.7 cm in the ALS point cloud and +/-7.5 cm in our ULS point cloud. However, careful analysis of the DoD and M3C2 maps also supports a third cause of vertical differences.*"

Further on the note about reported errors for the ALS data, the following text was added to Line 502 referring to the LidarBC dataset for the SRMT case study, "*The sparse metadata owe to the fact that these surveys were flown by a third party and later acquired for LidarBC, without the control needed for them to verify accuracies*."

Line 412: this 1.62 m difference is quite significant. It would be very useful to calculate the height difference between the two geoids.

We agree, and while trying to figure out what is causing this difference, we realized that this difference was not because of a difference between geoids. Rather, we had made a mistake while processing the SJF drone lidar. Specifically, we did not use the PPP corrected GCP points when georeferencing the point cloud. After reprocessing the data with the PPP corrected GCP points, the translation vector is much smaller (between 0.07 and 0.32 m) and a similar value to the other datasets. Thank you for pointing this difference, we are glad to have had the opportunity to rectify our mistake.

This section (Line 435) now reads, "*The ICP rigid body transformations that best aligned the ALS and ULS point clouds involved rotations of <0.001~radians and translation vectors of 0.07-0.32 m. Post alignment, the average M3C2 distances were 0.22 m for SJF East and 0.13 m for SJF West, with standard deviations of 0.42 m and 0.31 m, respectively, while the equivalent DoDs have mean elevation discrepancies of 0.21 m and 0.15 m with standard deviations of 0.62 m and 0.53 m, respectively (Fig 9 and Table 3). These results indicate internal consistency of the two datasets to within a few decimeters.*"

<u>**Reviewer B:**</u>

In this study, Salomon et al. present a new system for UAV lidar scanning (ULS) of active fault zones with four case studies in different survey and vegetation settings along faults in the Canadian Cordillera. The paper is a joy to read. It is well-written and well-illustrated, makes a compelling case for the utility and superior performance of the ULS system compared to traditional lidar (airborne or terrestrial) and SfM, and will make a detailed reference for research groups who want to implement similar systems and workflows.

Detailed, line-by-line comments are in the attached PDF (created with an Adobe product). These are mostly minor and will be easy to address. I don't have any concerns with this study. A few more general comments:

Thank you for these kind and helpful comments; we think that they will improve the manuscript. The comments in the PDF have also been addressed and are provided line-by-line at the bottom of this document.

Although the flight lines are discussed in each section, it would be great to show them in a figure for each survey because the choice of how many and where to put flight lines is one of the operational decisions that has a huge effect on the resulting dataset.

We agree that showing the flightlines would highlight some of the considerations and planning that had to be made, thank you for the suggestion. We were concerned that adding to the existing figures would obscure some details and opted instead to produce new figures which have been added the supplemental material. The DTM for each site acquisition is shown, with the flight lines overlain. The transit lines have been removed, but stars on the figures show the locations for takeoff areas used for that collection.

For all figures that show M3C2 and DoD differences, please state in the caption if positive values are ULS higher or vice versa.

Thank you for this suggestion. It will make it a lot easier to understand the figures and comparison by having this information in the caption. All the captions for figures that contain DoDs or M3C2 distances have been updated to include the following sentence: *"Positive values indicate where the ULS dataset was higher than the comparison dataset.*"

While the text is detailed in the fieldwork portion of each survey, it lacks details in the specific processing parameters for each study, which is arguably just as important. For example, are the point cloud processing parameters in LASTools the same for all surveys? If so, please state it in Section 2.4 Data Processing, and

this comment may be obsolete. Did it take experimentation to get optimal parameter values since these algorithms were developed for ALS data?

Yes, the point cloud processing parameters (in LAStools) were the same for all surveys, except for the cell size of the raster products. This has now been stated in Section 2.4, Line 260 "*The same LAStools parameters were used to process each dataset, with the only differences being the cell size for the resultant raster products, listed in Table 3."*

The parameters were the result of some experimentation; however, this experimentation was not exhaustive and was principally a visual assessment. There may be some improvements to be made with parameter optimization, however, we were quite happy with the quality and detail that our DTMs were able to provide.

All links in the Data Availability section work. For the "pointcloud_processing.sh" script in the Zenodo archive, please add the software dependencies to the code.

Software dependencies have been added to the shell scripts, and we have also added URLs in the script to the webpages of the required software, which all have guides for installation.

<u>**Line by line changes from the PDF comments:**</u>

Line 15: replaced "*which*" with "*that*"

Line 24: Changed sentence, added words are in bold. It now reads: "*It is useful for mapping the ground surface where obscured by forest, because* ***laser pulses that avoid foliage and branches will sample the ground surface while those that don't,*** *can be digitally removed****, unlike in photogrammetry*****.**"

Line 52: Added suggested reference (Nelson et al., 2017).

Line 88: We would like to keep the word "putative" before "active faults" as many of these structures are still the subject of ongoing research and have not been confirmed as active in peer-reviewed literature.

Line 107: Added comma after "*coverage*".

Figure 1: Added "*including rotor blades*" to the caption.

Line 124: changed "*pedestrians*" to "*people*".

Figure 2: removed errant A box and added a background the label for B extent. Also shifted the location of this label to improve visibility.

Line 205: added the following text to the end of the sentence, "*to ensure that its location is well constrained, as is recommended by both Riegl and Applanix documentation*".

Comment "Do you ever download data between flights in case of a crash landing or other equipment malfunction?"

We generally do not do this, as it would significantly increase the time needed between flights, and we choose to prioritize trying to fly as much as possible in a day. Stopping to copy data would potentially add five to ten minutes for each flight (in addition to 10 mins of static calibration), which add up when trying to do ten or more flights in a day. If there are some issues with a flight (either error messages or something visibly wrong with the platform), we may check the files to see if the data is being recorded correctly.

Line 210: added a comma between Figure 4 and "*which*".

Figure 3 Caption: Removed company name for GCP targets, defined SRMT as Southern Rocky Mountain Trench.

Line 306: The drumlinoid ridge *is* the Pleistocene glacial landform, but we can see how the commas were confusing. We have changed wording to the following: *"…surface of a Pleistocene glacial landform – a large, N-S drumlinoid ridge – between…*"

Line 314: Added a space between "*as*" and "*scattered*".

Line 317: Specified what the additional permissions were related to: "*to conduct research and operate a drone within the park,*"

Figure 5 Caption: Added "*White triangles indicate the location of the fault scarp*".

Line 342: Changed "*canopy*" to "*vegetation*".

Line 371: Changed "*little*" to "*few*".

Line 371: We did not change the wording here as we were specifically referring to the lowest points (elevation not density) within the ALS point cloud.

Figure 6:

- Added label to panel A and edited the caption text to clarify that the points shown are all ground points (not unclassified).
- The following text was added to the caption "The DTMs were constructed with an interpolation of 5 pixels in order to minimize holes."
- The following text was added to the final paragraph of ULS data acquisition and result, Line 335; "*The cross-hatched point density pattern (Fig.6B, middle column) results from the perpendicular orientations of the survey flight lines.*"
- Added a label for the location of the lake.

Table 3: Added a column for the DTM pixel size as suggested.

Figure 7:
- Added "*Positive values indicate where the ULS dataset was higher than the comparison dataset*" to the caption.
  - Added labels for the black berry bushes and footpath.
  - Changed the color scale on M3C2 histograms to match the corresponding raster.
  - Cropped raster differences to only cover land; there appeared to be some interpolation on the edges of the differenced files over the lake. Some high values do remain along the lake shore, although these are likely due to some dense vegetation and reeds present.

Line 434: removed repetitive sentence.

Figure 8 Caption: Added what the white triangles indicate on panel A. Moved illumination azimuth to refer to the DTM and not the satellite image.

Figure 9 Comment: **In the panel B, the aspect-dependent signal and channels, roads, and topographic features visible in the DoD (especially for the West site) may indicate some horizontal mis-alignment that might be able to be corrected.**

We think that there is only a minor misalignment present in panel B, similar to many other raster differencing products within the literature. As such we did not think it was necessary to attempt to correct it. The large differences are present in steep terrain, within densely vegetated gullies, which is what we were hoping to highlight (that the drone lidar did a better job of imaging the ground surface in these areas).

Figure 9 Caption: Added "*Positive values indicate where the ULS dataset was higher than the ALS dataset*".

Line 441: Fixed typo and removed "*at its*".

Line 463: changed "*trench*" to "*valley*".

Line 477: Added "*extra research and drone use permissions*".

Line 481: Removed "*skeleton*".

Line 485: replaced "*which*" with "*that*".

Figure 10 caption: added "*White triangles indicate the approximate location of the SRMTF*".

Figure 11 caption: added "*White triangles indicate the approximate location of the EDF*". Adjusted panel labels as suggested. Updated references in the text to align with the new panel labels.

Line 574: removed surplus round bracket.

Line 585: removed comma in date.

Line 613: removed “*somewhat*”.

Line 614: removed “*far*”.

Line 616: added comma between “*drone*” and “*which*”.

Line 641: added “*a ground point density of*”.

Line 657: changed “*in*” to “*on*”.

Line 668: removed “*being*”.

Line 674: changed “*or*” to “*of*”.

Line 689: changed subsection title to “*Limitations and future prospects of drone lidar*”.

Line 700: changed “*off-fault*” to “*distributed*”.

Line 718: added “*100 m x 180 m”.*

Thank you again for all the comments and suggestions; they helped improve our manuscript substantially.

Sincerely,
Guy Salomon et al.

P.S. I have also uploaded a potential cover image of the drone in action after surveying a portion of the Eastern Denali Fault in the Yukon.