

Response to Reviewer #2 for the article, 'Assessing the application of a laser rangefinder for determining snow depth in inaccessible alpine terrain'.

P418, L8; P419, L22: data is a plural word, so use "were" instead of "was" and "have" instead of "has"

This has been corrected in the text (P2, L7 and P3, L29 in the revised manuscript).

P419, L12-15: provide references for the "extensive resources"

A reference has been inserted (P3, L21).

P419, L22: How are the data sets differenced? This is important.

The data sets are differenced by subtracting the 'snow-free' interpolated raster image from the 'snow' interpolated raster image. Both interpolated datasets are the same resolution. This is now noted in the text (P8, L24-27).

P420, L2: what resolution?

The resolution of the TLS point cloud as suggested by Prokop, 2008 and Prokop et. al. (2008) is 3-6 cm horizontal distance between measurements. This information and reference has been added to the text (P5, L6).

P420, L5: is 10 cm enough? Vertical and/or horizontal?

Whether or not accuracy in snow depth of 10 cm is sufficient depends on the study. The work of Prokop (2008) and Prokop et al. (2008) was focused on using TLS within the framework of avalanche research and prediction. In which case, 10 cm vertical (snow depth) accuracy is arguably insufficient as it is in the same order of magnitude of the snow events which provide the loading trigger. However, for the purpose of determining snow water equivalence in a rugged alpine basin, we feel that 10 cm accuracy is more than adequate. At a horizontal resolution of 3-6 cm, as in the above mentioned study, a snow depth accuracy of 10 cm far exceeds that of any manual snow surveys.

P420, L8: "rely on manual point data retrieval instead of scanning" define or describe the difference

The difference between manual point retrieval and scanning has been expanded upon within the text (P4, L6-11).

P420, L19: how much is a modest price? A tripod/terrain lidar unit is between \$100,000 and \$250, 000.

The laser rangefinder used in this study was purchased for \$6000. A comparison between the two systems has been inserted into the introduction (P4, L21).

P420, L25-26: show the 58% of inaccessible terrain on the map

The inaccessible terrain has been added to Fig. 1.

P421, L18: how are the data interpolated? Deems et al. (2006) used a different technique than Trujillo et al. (2007)

The data are interpolated using a polynomial interpolator. This is an inexact interpolator which results in smoothing of the data. This technique was chosen over an exact interpolator (such as kriging) because the vertical

accuracy of the laser points was insufficient. This discussion has been added to the text (P8, L21-27). In addition, a figure has been added (new Fig. 2) to illustrate the effect of using an inexact interpolator.

P421, L20: “excellent signal return” – mention albedo and surface influences

The text has been changed to include reference to surface influences (P5, L18-22).

P421, L24: “4.3 m at a shooting range of 500 m” – discuss the error, which is a function of the resolution and the tangent of the apparent slope. – see Deems et al (2008 J. Hydromet.) Among others.

The stated accuracy of 4.3 m was the uncertainty in the position of the target using a bearing accuracy of +/- 0.5 degree, according to the manufacturer specifications (this is clarified on P5, L23-25). This is likely an oversimplification of the accuracy of each point measurement; therefore, more discussion addressing the different sources of uncertainty has been added (impact of incidence angles P8, L14-18; interpolation P8, L21-27). Information on the incidence angles has been added to Table 2 and a discussion of the influence of incidence angle has been added to the text.

P422, L17-18: what is the basis for this uncertainty?

We acknowledge that we had limited basis for establishing satisfactory results as 10-15%, and this has been removed. However, accurate measurement of snow depth in rugged alpine watersheds remains a difficult and elusive task and therefore we feel that the level of accuracy obtained in this work still remains useful to hydrological process and modeling research. The laser method gives a reasonably good and unbiased estimate of snow depth which is useful to hydrological process and modeling research. In this watershed, and others, there is no other readily available way of obtaining snow depth, and therefore we feel the level of accuracy achieved with this method is better than having no data at all. Additionally, the accuracy is on par, or greater than the predictive capacity achieved with advanced interpolation of intensive snow survey data (Balk and Elder, 2000; Anderton et al., 2004; Lopez-Moreno and Nogues-Bravo, 2006; Erxleben et al., 2002; Molotch et al., 2005).

P423, L2: what is the basis for the basin average SWE of 575 – 700 mm?

The basin average SWE is assessed from a 1200 point snow survey conducted annually in mid-April at peak accumulation. This has been clarified in the text (P6, L28-29).

P423, L7: define “spindrift”

This colloquial term has been removed.

P424, L7: is there settling of the tripod/laser during the survey, as “the laser is set up at the snow surface”?

The area was compacted on foot prior to setting up the laser. The height from the laser to the ground surface was measured (using a snow depth probe) prior to the start of the survey and upon completion to ensure that the equipment did not settle into the snow. These points have been clarified in the text (P8, L2-5).

P424, L25: what is the precedent for using a “local polynomial interpolator”? What is the difference between the interpolation resolution and the measurement resolution?

To our knowledge, there is no precedent for using a local polynomial interpolator. However, we determined that the vertical uncertainty in the laser data necessitated that an inexact interpolator be applied because it results in a smoothing of the data. This is necessary because the distribution of points is different between the snow and

snow-free surveys. Trials with an exact interpolator (kriging), resulted in an irregular surface that could not be adequately differenced. Discussion has been added to the text (P8, L21-27) and a figure (new Fig. 2) has been added to illustrate the importance of using an inexact interpolator.

P425, L1: is it verification or validation?

I have used the term validation as defined in Grayson and Bloschl (2000) (Spatial Patterns in Catchment Hydrology: Observations and Modelling) in which the terms are defined as:

“verification”: strict tests such as of model code where analytical and numerical simulations are compared

“validation”: observations and simulations are compared using data that was not part of the calibration

In this context, I would consider testing laser specifications to be “verification”, and comparing measured with “laser” observations to be “validation”.

P424, L8: how were the points “differentially post-corrected”?

The X,Y,Z coordinates were collected with a Trimble GeoXH handheld GPS. The spatial accuracy of these data can be improved by differentially correcting them to a base station. The data were differentially corrected relative to a base station operated by Cansel in Calgary (160 km east of the site). Differential corrections were conducted within Trimble GPS Pathfinder software. This has been clarified in the text (P9, L3-4).

P425, L9: how was the “positional error” measured/recorded?

Values for positional error (both horizontal and vertical estimates) are output with the spatial coordinates when the GPS data are differentially corrected.

P425, L10: how was the nearest corresponding pixel to the manual measurement determined?

The data were imported to ArcGIS 9.2. A spatial geoprocessing tool was executed whereby the value of the raster layer (“calculated” snow depth) corresponding to the point layer (“measured” snow depth) was extracted (P9, L6-7; P9, L16-17).

P426, L2-3: what is the basis for the “spatial pattern:?”

The data are presented as extracted, wherein the data points begin at the upper left of the survey area and sequentially increase from the top to bottom, and left to right. We note that this does not necessarily constitute a “spatial pattern” and so this phrase has been replaced with “trends in high and low snow depths” (P9, L23).

P426, L9-11: maybe measure more points, and consider the error of the handheld GPS unit.

The GPS that was used was a differential GPS with horizontal accuracy of <1 m. We have now noted this in the text (P9, L30-31) as a possible source of uncertainty. It is agreed that measuring more snow depths at each manual measurement location may have reduced the uncertainty further.

P428, L9-12: “The spatial resolution of the laser rangefinder...” How do you know this? Is this your work? If not, then provide a citation.

A reference has been provided and the sentence has been revised (P12, L4-6).

P428, L17-19: “onset of snow melt earlier...” this is not a conclusion. Bring this up in the discussion, but not here.

This has been removed from the conclusions.

P428, L23: should be “inwatersheds do not yet exist”

This has been changed (P12, L13).

P429, L27: provide a more complete reference for “lasercraft”.

A more complete reference has been provided (P14, L8).

Table 1. state vertical and horizontal resolution range

The vertical and horizontal resolution range of the data obtained with the laser rangefinder is a function of the density of the manual data collection. Additional data on the average spacing between points (horizontal resolution) has been added to the table.

Table 2: state which is “snow on” and which is “no snow”. How do you know that the setup is at the same location? Is the point density interpolated or raw?

Table 2. has been revised to indicate which surveys were on ‘snow’ and which were ‘snow-free’. The location of the set-up was recorded with a differential GPS and the location was marked with a steel pin (snow was excavated post-survey). For all surveys, the marker was used to relocate the laser. For 2009 surveys, the re-position of the laser was also validated with a GPS with real-time correction. These details have been added to the text (P7, L32-33).

The point density in the original table is raw. However, at the request of Reviewer #1, this has been changed to ‘average distance between points’.

Figure 1. A slope map would be useful

A slope map has been included as part of Fig. 1.

Figure 3. what is the basis for the error bars? How do you know you are at the same point?

The error bars represent the range of depths obtained from the four manual measurements, with the ‘measured’ point representing the average of these depth measurements. This has been clarified in the figure caption.

Figure 4: what happened to the depths less than 1.2m? There are 28 points here, where are the other 16 from previous? You could combine Figures 3 and 4. Why are there 4 measured points with $ds > 2m$ that are outliers here? What about the other two from Figure 3?

Thank you for catching this plotting error, and we apologize for the oversight. The plots have been revised to contain the full set of data.

Figure 6 and 7: be consistent with the snow depth range so we can visually compare differences.

Depth ranges are now consistent.

Figure 7. what is the basis for these lines?

The lines represent a 'cross-section' of snow depth on the slope. The lines were extracted within ArcGIS, with each line showing a cross-section of snow depth at a different location along the slope. The snow depths at each elevation were then averaged.

References

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