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The Cryosphere Discussions

Interactive comment on "Snow depth mapping from stereo satellite imagery in mountainous terrain: evaluation using airborne lidar data" *by* César Deschamps-Berger et al.

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Review of Deschamps-Berger et al. "Snow Depth Mapping from stereo satellite imagery in mountainous terrain- evaluation using airborne lidar data

This work provides a deeper evaluation of the snow depth mapping from stereo satellite imagery approach proposed by Marti et al (2016). The advancement of this work is to consider some of the various/emerging DSM processing options and a more thorough error analysis with basin scale airborne lidar data from ASO versus manual discrete manual probe observations in locations not fully representing the variability present in the landscape. The prospect of obtaining high resolution (3m scale here) snow

depth with errors reported here to be less than 0.8m from a space borne platform is tremendously exciting and the benefits of such a capability are clearly articulated herein better than I can summarise in this space.

Much of this article is clear and well written but there are a couple aspects which would benefit from some clarification and/or clearer justifications. I will begin with some main comments and then provide a list of more technical comments/edits/suggestions. Overall I think this work is well suited to The Cryosphere. The previous review of Buhler makes many important observations which I fully agree with. I would highly recommend the authors make those edits in addition to some more articulated here.

Main Comments:

1) Error model: there is a lot of discussion of methodology and results of the scaling of the random error with length scale. I have a couple concerns on this. First we are looking at the random error metric, articulated later on as the standard deviation of the snow depth residual error. This is only one part of the error, as in overall error is comprised of random components (captured here) as well as biases (not a part of this model). Correct me if I am wrong but my read is that increasing length scales will lead to decreases in random error and will therefore not comment on the bias error? Or, this model shows that increasing the length scale will increase precision but does not say anything about the accuracy? We could have really large biases in the dDEM but these will not be reflected in the model? A quick read from the abstract doesn't articulate this nuance that I am perceiving. Without lidar or ground observations to correct for the bias this suggests there will be operational challenges to implement this method in data sparse regions. Would co-registration on common snow-free stable areas be a reasonable approach to provide these relative differences? Would you have any other suggestions to improve applicability in data sparse areas? Second, there is an assumption that stable terrain residual random errors apply to snow surfaces. Is this a valid assumption? In most topography the snow surface will reflect the underlying ground surface. In complex alpine topography the range in surface elevations can be

orders of magnitude greater than the hs corresponding to the dDEMs and therefore this is a reasonable assumption. But in many areas prone to wind redistribution parts of the landscape can be smoothed out, for example, wind blown snow fills up gullies. Therefore, I would expect the random components of the error to vary between snow and snow-free area. While the ability to predict error of a snow depth product is of interest I worry that this is perhaps a little too simplistic and detracts from the main point of the paper which is a detailed evaluation of satellite stereo imagery snow depth measurement and its comparison to airborne lidar data. The comments from Buhler about partitioning the error the errors of the snow-free and snow covered surfaces would be very valuable and provide a clearer interpretation of what the HS error is derived from.

2) Structure: There is a lot of detailed technical discussions but many sections of this paper would benefit from stepping back for am moment and explaining the justification for what is occurring and how it fits in to the overall story. As it is there are some disjointed sections. (2 examples: line 125-126 – this sentence requires context, line 240 onwards – why do we care about developing an error model?)

Specific comments:

Line 21 “A recent new method” -> “Recently, a method”

Line 32: “up to” -> “down to”? I don’t see anywhere else in the paper where it is mentioned that there is a factor of two decrease in random error going from 3m to 20m (short of a reader interpretation of Figure 10). Also as a sample size increases the standard deviation (aka random error here) will always decrease – can you articulate the nuance that the modelling modifies this relationship by accounting for spatial correlation?

Line 35-37: A great conclusion!

Line 44: Nolan et al. 2015 is not a UAV reference, they use SfM from a manned

airplane. Other early reference options would be Buhler et al. 2016, Harder et al. 2016 or De Michele et al. 2016 for starters.

Line53-55: One criticism from abstract was that the Marti paper only considered limited numbers of observations and terrain representation with manual insitu probe depths while here there is acknowledgment that there was also validation versus UAV data? Clarify this contradiction?

Line 72: Harder et al. 2016 also showed that SGM improved performance over low texture snow in the UAV-SfM snow depth mapping context.

Line 136-137: this is not a method to do forest snow depth mapping so is it important to include forest lidar data processing steps?

Line 162: if including coordinate system information should also put in the projection.

Line 175: What was the extent of the Pleiades HS values that was outside these thresholds?

Line 188: Is “eroded” the proper term to describe this? I feel this may be confusing for those with geomorphology mindsets.

Figure 2: Line passes through the “co-registration” step. Does this need a box or to be offset like other processing step descriptions?

Line 240 -255: empty super and sub script boxes appear in many of the equation/symbol text. Add space between equations and the equation numbers as well?

Section 5.1. Can you clarify the results and discussion around the comparison of pairs versus triplets? In parts (like the last sentence of this section you say the triplet is the best) while in others (line 360) it is justified that a pair of images is just fine. Line 382-384 says tri-stereo is best to provide the best coverage and reduce distortion. Can this be clarified to allow for more consistency throughout?

Line 320-325: the low frequency undulation in HS residuals. Where is this coming

from? How pervasive is this error with satellite stereoscopy or is it specific to this site/processing options? For this approach to be of value what techniques can be employed to address this error (while low amplitude could be important) where there is no ASO like lidar data for validation?

Line 330-334: are you applying the error model to the undulation removed HS residual or the raw HS residual? Can you clarify that? If you consider a semivariogram that extends out to the amplitude of the undulation does the undulation length scale appear in the semirvariogram (extending figure 9)

Line 367-387: there is a justification being made here to bi-stereo imagery versus tri-stereo. Can you also articulate/quantify what the differences there may be in terms of cost differences (financial and computing). Will help to justify from a resource perspective why we should consider doing this all with pairs of images if it can articulated that there are significant savings terms of money and computing time/power requirements.

Line 410: can you clarify “decimetric accuracy”?

Line 421-424: merge with following paragraph?

Line 430+: is this supposed to be a new paragraph?

Line 436: “squares of length 210m”. squares themselves don’t have a length – can this be expressed differently?

Line 438: ”unvalidated” -> “invalidated”?

Line 455: “probably the vast majority of mountain regions with seasonal snow cover” -> “the vast majority of mountain regions with snow cover”

Line 458-459: “high competitions especially” -> “high tasking competition”

Line 459-260: can you identify specific satellite platforms that we should keep a look out for?

Line 471: this is an important point to make that needs more than 1 sentence at the end of the discussion. Can you emphasise the implications of this on where snow-depth mapping with this technique is valid and possible steps that may be available to address this limitation?

Line 474-475: “satellite very high resolution stereo images” -> “high resolution stereo satellite images”

Figures: Information in the figures is good but the layout of the figure themselves need a fair bit of formatting work.

Figure 3, 5, 6, 7, 8, 9 , 10: Can you pull out the text/lines from inside the plotting areas in to legends (based on color) outside .

Figure 4: all of the lettering (referencing inset maps etc.) is a little confusing in the legend. Perhaps add a upper-lower case distinction?

Figure 3, 7: Put x-axis descriptions outside of the plotting areas

Figure 7: slope residual plot quantiles exceed the plot area.

Figure 8: could the a? panel have coordinates (UTM?) to provide scale and could then remove the scale bar. Also remove “Map” title and on b remove the titles and add x-axis label and units.

Figure 9: “distance” -> “Distance”

Figure 10: can you provide an explanation for “raw and “corrected” in the figure caption?

References:

Bühler, Y., Adams, M. S., Bösch, R., Sto, A., Buhler, Y., Adams, M. S., Bosch, R. and Stoffel, A.: Mapping snow depth in alpine terrain with unmanned aerial systems (UASs): Potential and limitations, Cryosphere, 10, 1075–1088, doi:10.5194/tc-

10-1075-2016, 2016.

Harder, P., Schirmer, M., Pomeroy, J. W. and Helgason, W. D.: Accuracy of snow depth estimation in mountain and prairie environments by an unmanned aerial vehicle, Cryosph., 10, 2559–2571, doi:10.5194/tc-10-2559-2016, 2016.

De Michele, C., Avanzi, F., Passoni, D., Barzaghi, R., Pinto, L., Dosso, P., Ghezzi, A., Gianatti, R. and Vedova, G. Della: Using a fixed-wing UAS to map snow depth distribution: An evaluation at peak accumulation, Cryosphere, 10(2), 511–522, doi:10.5194/tc-10-511-2016, 2016.

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