Reply to Reviewers – Smith, Rheinwalt, and Bookhagen

Reviewer #1 (Remarks to the Author):

The manuscript by Smith et al. deals with the identification of the optimal grid resolution for slope and aspect derivation from LiDAR dataset. The topic is relevant and of utmost importance in the quantitative geomorphology and hydrology fields since aspect and, especially, slope are fundamental parameters for different analyses commonly carried out such as synthetic channel network derivation, feature extraction and modeling. The paper presents the theoretical steps and a real-world application of a quality metric for slope and aspect calculations developed to determine the optimal resolution minimizing truncation error and the propagated elevation uncertainty. In my opinion, the work is very well structured and the method is robust and clearly outlined in the manuscript. This innovative approach is highly promising and will be most likely of great interest for the geomorphometric community thanks also to the fact that made available the developed code in the GitHub repository. My only minor concern about this high quality work is related to the assumption that the optimal grid resolution of a Digital Elevation Model (DEM) is the one minimizing the total error. This is certainly true in most cases but for several applications, the choice of the DEM resolution is mainly controlled by the dimension of the feature investigated that is some cases may be quite small (e.g. ephemeral gully, colluvial channels) and, thus, a fine resolution may be the best choice. Typically, this is addressed by choosing a high resolution and then computing geomorphometric parameters using large moving window to filter out the noise. Apart from the sentence at lines 1-2, page 18, this issue is not mentioned in the manuscript. I suggest adding some text on this to better clarify your assumption on the "optimal" grid size.

Thank you for your comments on our paper. The issue of scale is difficult – there are many studies which use one-meter or sub-meter gridding of airborne lidar (such as we use in this study) to study small-scale features. Our analysis shows that the uncertainties for these very high resolution datasets become large; in many cases the uncertainties can grow larger than the scale of the fine-scale topography that is studied. While such high-resolution analysis should not be ruled out, it is important to be aware of the uncertainties involved, and whether or not the dataset is precise enough to support the analysis of very small landscape features – with or without using larger window sizes as an approach to smooth out noise. We have added an additional comment in the paper (page 18) to further clarify this.

Specific Comments:

L. 22, p. 1 (and throughout the text): lidar-> LiDAR

In our paper we use the lower-case 'lidar', similar to how radar is used as an abbreviation of RAdio Detection And Ranging. While LiDAR is being used in some literature, the National Academy of Sciences and other national institutions in the UK rely on lidar (https://essp.nasa.gov/essp/files/2018/02/2017-Earth-Science-Decadal-Survey.pdf; http://lidarmag.com/wp-content/uploads/PDF/LiDARNewsMagazine_DeeringStoker-CasingOfLiDAR_Vol4No6.pdf). In the literature, lidar shows the most common usage (http://lidarmag.com/wp-content/uploads/PDF/LiDARNewsMagazine_DeeringStoker-CasingOfLiDAR_Vol4No6.pdf).

L. 24-25, p.1: please consider providing a range of resolutions for "high" and "low" resolution in place of e.g 1 and 30 meters

This has been changed in-text.

L. 3-10, p. 2: I suggest mentioning also stream power studies that are quite relevant in hydrology and soil science.

We have added some relevant citations here.

L. 7, p. 8: differently->different?

This has been corrected.

Figure 13 caption: sq km->km^2

This has been changed.

L. 7, p. 21: also averaging values could be tested as resampling method, maybe the results are different with respect to those obtained using bilinear resampling. In general, I know it is out of the scope of the paper but it would be interesting to compare different resampling techniques in order to suggest the best method to resample resolution

We have added an additional panel to Figure 15 (also below as Figure 1 of this Reply) which shows the results of nearest-neighbor resampling. The four- and five-meter resampled distributions are significantly worse with nearest-neighbor, but the one- and two-meter resampled distributions match the optimal three-meter distribution quite closely. We attribute this to the methodology by which we created the lidar DEMs – the one-meter data is derived from same set of neighborhoods which are aggregated into the three-meter data. The three-meter data is thus quite similar to a nearest-neighbor resampling of the underlying one-meter DEM. We have added an additional comment on this in the paper.

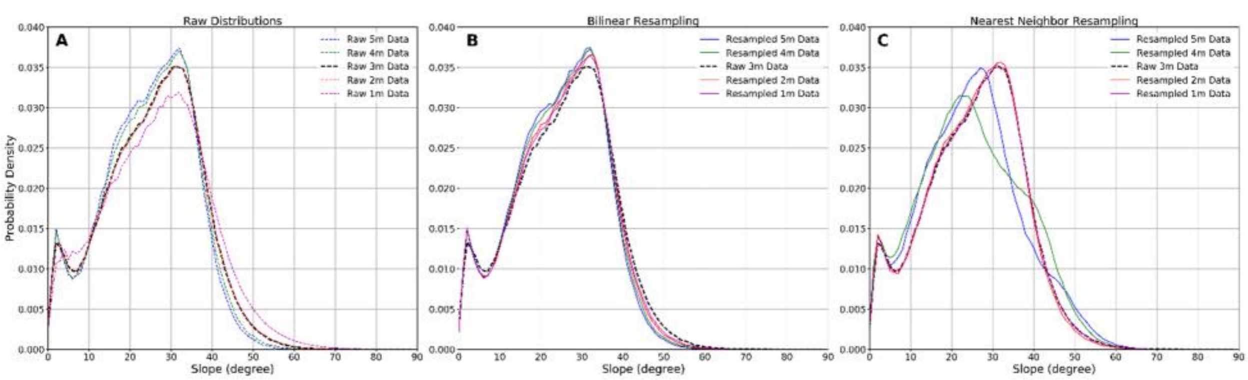

Figure 1 – Impact of two different resampling mechanisms on slope distributions.

Reviewer #2 (Remarks to the Author):

The manuscript "Determining the optimal grid resolution..." presents an analysis of two types of errors that affect DEMS and offers a method for finding the DEM resolution that will minimize these errors for real data. I think that this is a very nice study. The analysis is thorough (23 supplemental figures!), and the combination of theoretical derivations, synthetic data, and application to a real dataset makes for a convincing combination. It is definitely something that will be of interest to people working with airborne lidar data, and since you offer a readily applicable method, I think that people will find this quite useful. I find the paper just about ready to publish, so I have only a few minor comments.

I am curious about the impact of irregular topography on the choice of resolution – if you have a stepped landscape (such as terraced hillslopes), would that change the consideration of the optimal resolution?

Irregular topography will likely result in two distinct optimal resolutions – in your example the flat and steep parts of the terrain likely have different error distributions, and do not see the same impacts from TE and PEU. If the landscape is analyzed together, the calculated optimal grid resolution might not be applicable to all parts of the landscape, as we found in our analysis of individual watersheds on SCI (MS Figure 13). Depending on the analysis approach, the landscape could be broken into two segments and analyzed separately.

You show at the end that resampling gridded data to the optimal resolution is not sufficient to achieve the same quality as creating the DEM at that resolution, but it does seem to improve the slope distributions for the 1m data (it is interesting that resampling the 2 m data appears to move the distribution away from the ideal distribution). Assuming that you have the standard deviations and could calculate the optimal resolution, it seems that resampling could still be helpful if you don't have access to the ungridded point data?

We have added an additional panel to this figure (Figure 15 in the MS, Figure 1 of this Reply), which covers nearest neighbor resampling. Interestingly, the one-meter distribution is almost identical to the three-meter when nearest neighbor resampling is used. We attribute this to the lidar gridding approach we used – the three-meter neighborhood is essentially the same as the nine one-meter neighborhoods which then form the basis for the nearest neighbor resampling. In that specific case, the resampling might improve the error distribution. However, in general, the slope distributions of resampled data will not match the distribution of the target resolution. Any resampling will also introduce new biases into the data which are hard to account for.

Specific Comments:

Fig. 7: It's interesting that the optimal aspect spacing for the two highest noise levels is the same. Does this mean that the optimal spacing maxes out at this point?

This is due to the limits on grid spacing from our theoretical data – the smallest useful Gaussian Hill we can model is on an 11x11 grid. In theory, the very high noise level case should also have an optimal grid resolution – we just aren't able to model it because the data cannot be gridded any more coarsely. Note that the grid spacing values here are an expression of the width-to-height ratio of the surface, and thus aren't a 'hard' limit on grid spacing, but more related to the dimensions of the grid used to model the Gaussian Hill.

Fig. 11: I find it hard to see much of anything with the color scale in panel C. Maybe one with more contrast would be better?

This has been updated.

Watch your use of grid spacing vs. grid resolution - because higher resolution= smaller grid spacing, it can be a little confusing if you suddenly switch between them, as you do in the caption to Fig. 13.

Thank you for catching this inconsistency. This has been updated.

It would also be nice to keep the figures consistent with slope and aspect shown in the same order (ie. slope always on the left/top and aspect on the right/below) - i.e. in fig. 5 it is reversed from fig. 3.

This has been updated throughout.

pg. 22 line 16: I guess you mean <3 meters

This has been fixed.