Interactive comment on "High-resolution topography of the Antarctic Peninsula combining TanDEM-X DEM and REMA mosaic"

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The Cryosphere Discuss., https://tc.copernicus.org/preprints/tc-2020-323/

Referee comments are shown in *black*, our response in blue. Line numbers refer to the manuscript version (pdf) of 4 December 2020.

Authors' response to Dr. Romain Hugonnet

1 General comments

The paper is well-prepared and the authors make great effort to present their study rigorously. The text is generally well-written and the quality of Figures is good. The introduction accurately paints the context and limitations for Digital Elevation Models and related studies of the Antarctic Peninsula. The methodology presented for height correction is, to my knowledge, novel and its implementation is sound. The validation effort of the results with high-precision data is valuable. Finally, the resulting impacts are significant and clearly highlighted in the conclusions.

However, I have several major concerns. In decreasing order of importance, those are:

1. the general logic when combining the TDM and REMA DEMs,

2. the relation to existing methodologies,

3. the limits of the validation with IceBridge and ICESat-2,

4. the statistical estimators used in the study.

Those are detailed below.

Response: Firstly, we want to thank Dr. Romain Hugonnet for the time and effort put in this detailed and thorough review. We carefully evaluated all comments and suggestions, which are extremely valuable in improving the paper. As for the four major concerns raised by his review, point-to-point responses are given in the following. For better clarification, we add figs. R1-R4 in this response letter, and all the figures as well as the corresponding clarification will be added into the revised manuscript or the revised supplementary material.

2 Specific comments

2.1 Combining TDM and REMA DEMs

With 2 DEMs covering approximately all the AP, one can ask himself: what is the best reference DEM to use? What I draw from the authors presentation is that they decided to correct TDM DEM with REMA DEM due to:

A) the short timespans of acquisitons of TanDEM-X (2013-2014) while REMA is based on WorldView acquisitions spanning a longer period of 2009-2017. This shorter timespan of TDM leads to less issues with glacier elevation change over time on the entire AP.

B) less data gaps in TanDEM-X compared to REMA.

These factors that motivated their choice are somewhat "implicit" along the flow of paper, except in the abstract. I think the authors should clearly state all their arguments at once at *some point of the main text to make the entire reasoning behind their choice understandable (at the end of introduction? Or the start of methods?)*

Response: Thanks for the comments. We will make improvement to the manuscript from the two aspects: 1) add a comparison in terms of absolute vertical accuracy, data voids, temporal consistency and random errors (or relative vertical accuracy) between TDM DEM and REMA mosaic at AP in the discussion section to better support the logic to generate a corrected TDM DEM for glaciology applications; 2) add more clarification in the introduction about the logic based on the comparison between the two DEM products.

Additionally, I think that this choice is still subject to some discussion. And this for several reasons:

• firstly, I do not find the argument "less data gap in TDM DEM" completely valid.

As the authors show, TDM DEM contains many height errors, or artefacts, that require correction. Those could be interpreted as data gaps as well. It is not clear how much surface area is affected, but the authors should have quantified this after application of their methodology. Many of REMA data gaps likely originate from photogrammetric blunders, very much like TDM height errors originate from interferometric ones. This would partly invalidate argument B) for selecting TDM.

Response: The statistics of data voids in TDM DEM and REMA mosaic at AP between 63°S and 70°S are about 0.85% and 8%, respectively, within the ADD coastline based on our counts. The data voids are counted from the null value defined in the original data products, which are shown as white regions in Fig. R1. The elevation errors in TDM DEM to be corrected in our study are mainly caused by phase unwrapping errors which belong to systematic errors. Regions with phase unwrapping errors have abrupt elevation offsets to their neighboring areas due to the incorrect determination of height ambiguities of the wrapped phase. These regions cannot be viewed as blunders because the elevation information is effective as long as the offsets are compensated. Taking the REMA mosaic with high absolute vertical accuracy as ground reference, regions with elevation discrepancies are identified and corrected with the proposed algorithm. In the revised manuscript, regions being corrected or kept unchanged in TDM DEM will be quantified.

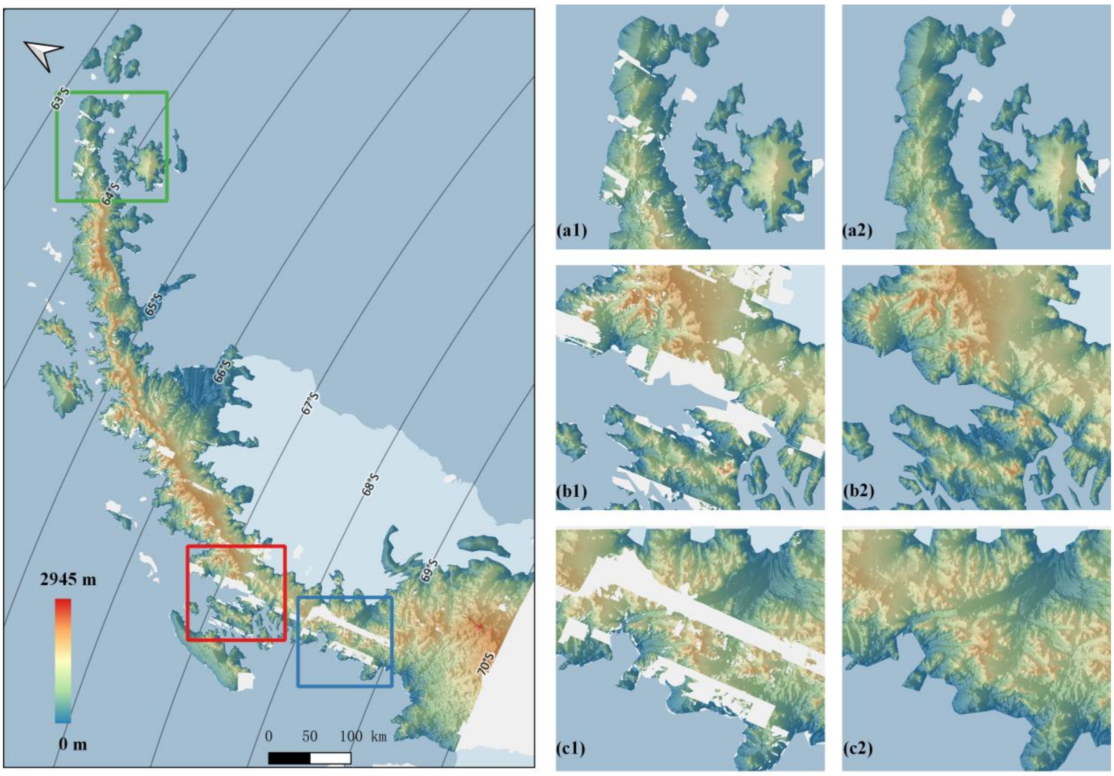

Fig. R1 REMA mosaic covering AP and the location of three sample areas. Right panel: detailed comparison of the REMA (left column) and TDM (right column) DEMs in the sample areas.

• *secondly, the REMA DEM is a mosaic based on WorldView 2 m and 8 m strips, freely available through the Polar Geospatial Center. I have not checked, but it is possible that most of the AP is covered by WorldView acquisition within a 2/3- year timespan of each other instead of suffering from the full 2009-2017 deviation. This would partly invalidate argument A) for selecting TDM.*

Response: In our study we are using the REMA mosaic tiles which are generated by the quality-controlled REMA strip DEMs. The specific acquisition time of REMA mosaic covering AP is shown in Fig. R2a and Fig R2b in year and month, respectively. So it is definitely longer than 2/3 years.

In the revised manuscript, we will mention more precisely the time span to generate REMA mosaic at AP as 2011-2017 instead of 2009-2017 and we will add Fig. R2 to the supplementary material.

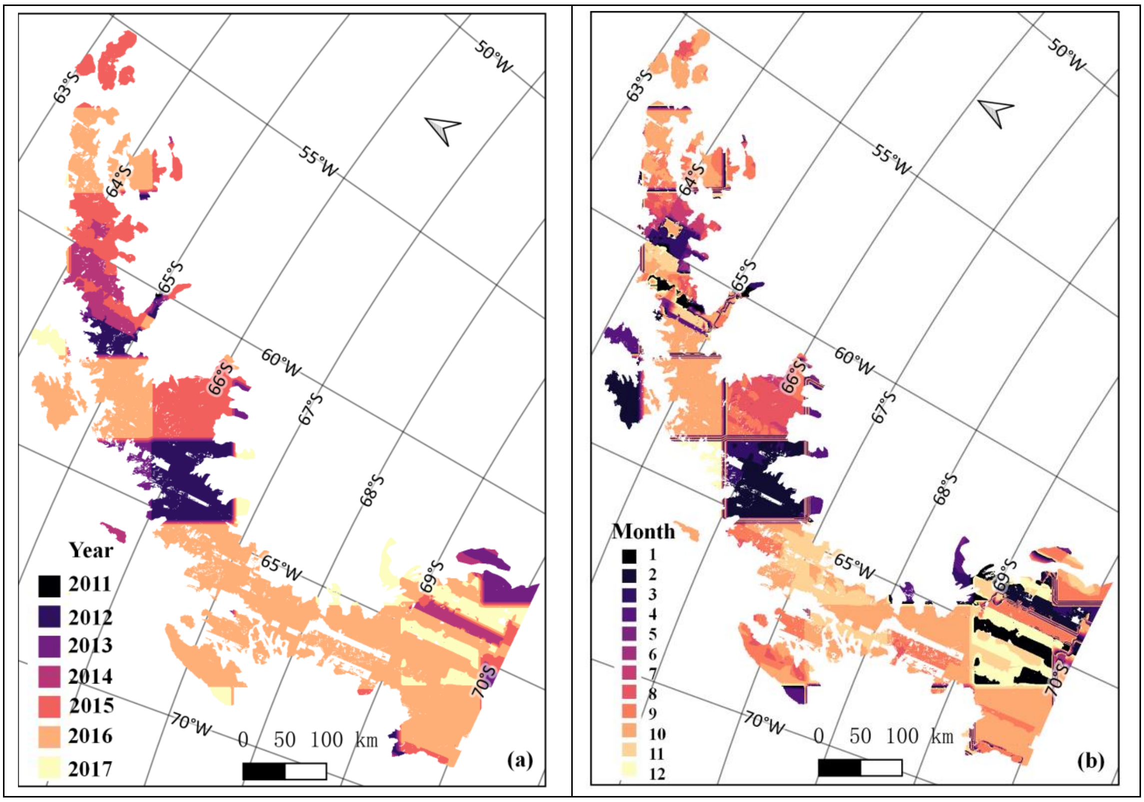

Fig. R2 Acquisition time of REMA DEM mosaic covering AP.

• *finally, the validation effort shows REMA DEM to consistently have higher vertical precision than the TDM DEM (Table 1, 2, 3: value of 90% quantile for REMA vs TDM). As a potential user, I would highly prefer to have a "consistent "AP DEM with most of its coverage based on the dataset with the highest vertical precision, which here is REMA.*

Response: Based on the validation result in Table 1-3, we would like to say that the TDM DEM has comparable absolute vertical accuracy with the REMA mosaic. Because the REMA mosaic has more data voids than TDM DEM, the number of points used for validation of TDM DEM is much larger than of REMA mosaic. For example, there are 31,764,790 and 33,246,648 points from LVIS 2015 datasets used for validating the accuracy of REMA mosaic and TDM DEM, respectively. The discrepancies in the numbers of verification points partly account for the differences in the statistics. Therefore, we will extract the intersection of the points from REMA mosaic and TDM DEM for validation in the revised manuscript. We will improve the method and the statistical estimators in the revised manuscript. Discussion of validation results in the revised manuscript will be improved based on the new results.

In the revised manuscript, we will add a discussion section about comparison between REMA mosaic and TDM DEM in terms of absolute vertical accuracy, data voids, temporal consistency and random elevation errors. The former three points have been explained in the submitted manuscript and will be clarified and improved in the revised manuscript. The fourth point (about random elevation errors) will be added to the revised manuscript. Based on the elevation errors maps accompanying the DEM products, we found that TDM DEM has smaller random errors and better theoretical relative height accuracy than REMA mosaic. In the elevation error map of REMA DEM in Fig. R3a, the error value at each pixel is the standard error from the residuals of the registration to altimetry data (Howat et al., 2019). Since each tile used for REMA mosaic generation has removed outliers and systematic errors with the preprocessing, the error value at each pixel provides an estimate of the DEM's random elevation errors. The Height Error Map (HEM) values of TDM DEM in Fig. R3b represent the corresponding height error in form of the standard deviation for each DEM pixel (Wessel, 2016). The TDM error estimates are exact and reproducible derived from rigorous mathematically correct steps (Wessel, 2016) verified in several papers (Rizzoli et al., 2012;Rizzoli et al., 2017). Fig. R4 shows the histograms of the random elevation errors of the REMA mosaic and TDM DEM covering AP. Comparing Fig. R3a and R4a to Fig. R3b and R4b, it can be seen that the TDM DEM covering AP has random elevation errors at lower level and thus better theoretical relative elevation accuracy than the REMA mosaic.

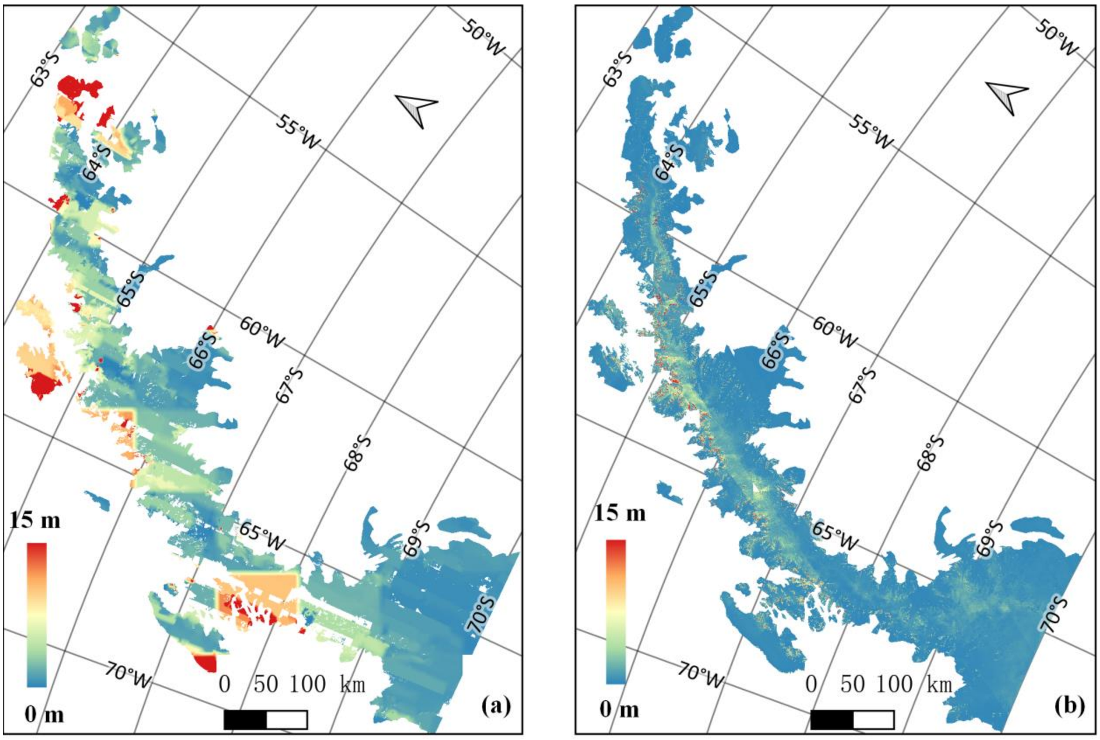

Fig. R3 Random elevation errors of (a) REMA mosaic and (b) TDM DEM covering AP.

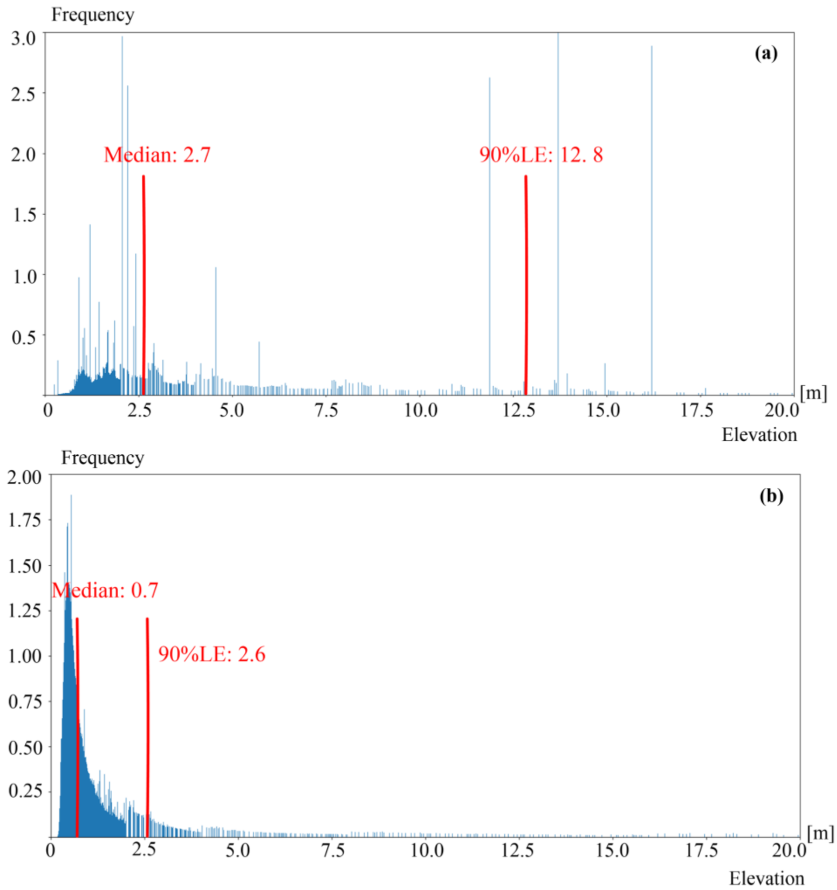

Fig. R4 Histograms of random elevation errors of (a) REMA mosaic and (b) TDM DEM covering AP. Median value and 90% quantile of the errors (90%LE) are marked in red in the histograms.

I understand that this choice is complex and that the methodology developed by the authors is already dependent on the type of blunders present in TDM DEM which might not be reapplicable to REMA with its own blunders and larger-scale data gaps. Therefore, although this choice is directionally important for the study, it certainly remains fully with the authors. A correction based on TDM DEM is undeniably valuable. In any case, the authors should provide:

• a Figure (maybe in the Supplementary) showing the surface area coverage over time of available REMA DEM strips for the AP. If many strips are closely available in time with good coverage of the AP (>80%), this really poses the question of correcting TDM blunders instead of correcting/gap-filling REMA.

Response: Fig. R1 and R2 will be added into the revised manuscript or supplementary material.

• a Table with coverage statistics + mean vertical correction for identified blunders at each multi-scale step of the methodology somewhere in the main manuscript.

Response: A table with coverage statistics and mean vertical correction at each multi-scale step will be added in the revised manuscript.

• a discussion on the influence of the 8% data gaps in REMA on the correction of TDM DEM should be provided. I acknowledge that this effect is unavoidable, yet adding a paragraph quantifying the possibly omitted TDM blunders in these 8% REMA data gaps would be useful (maybe based on the average surface area of blunders found on the rest of the AP?). Providing a map of the areas possibly affected (where there is no REMA coverage, and possibly high slopes/larger errors in the TDM Height Error Map?) would also be valuable for future users.

Response: In addition to the 8 m tiles, the REMA mosaic provides reduced-resolution resampled version at 100 m resolution. The reduced-resolution dataset has an alternate filled version in which the data voids in REMA mosaic are filled with 100-m ASTER GDEM (Howat et al., 2019;Cook et al., 2012). In our study, we resampled the 100-m filled REMA mosaic to fill in the data voids of the 8-m REMA mosaic.

The proposed algorithm runs on the elevation difference map generated from TDM DEM minus REMA mosaic. In our experiments, the gapless 8-m REMA mosaic with data voids filled with 100-m REMA mosaic has negligible effect on the proposed elevation biases detection and correction algorithm through visual inspection. The examples shown in Fig. 6 and Fig. 7 of the submitted manuscript illustrate that there are data voids in REMA mosaic (marked in white) which do not affect the correction process. The reason is that REMA mosaic was not used to correct the TDM elevation point by point, but to provide a reference elevation to correct the TDM elevation biases region by region, which is determined by the characteristics of the phase unwrapping errors.

Ideally the reference DEM should have comparable spatial resolution with the DEM to be corrected like the 12-m TDM DEM and 8-m REMA mosaic. The influence of the spatial resolution differences between different datasets depends on the spatial size of the regions affected by elevation biases and whether these regions cover areas with complex topography. In a word, as long as the biases can be deduced from the elevation difference map with distinguishable boundaries, they can be detected and corrected by the proposed algorithms. In the revised manuscript, analysis about the effects of spatial resolution difference between DEM datasets will be added.

Optionally, the authors should consider using individual strips instead of the REMA mosaic product for height error correction. This additional effort could significantly reduce temporal biases related to glacier elevation change by selecting strips closest to 2013-2014 when available (e.g. biases shown on Figure 7f). The authors would however need to co-register those strips individually to TanDEM-X before using them for corrections.

Response: Thanks for the very constructive advice. Theoretically it is a good idea for correcting the residual elevation errors in TDM DEM with REMA tiles closest to 2013-2014, which will minimize the temporal changes between TDM DEM and REMA DEM. However, it will be much more work to do to select the right REMA tiles with high data quality and calibrate these tiles to TDM DEM or altimetry data. The REMA mosaic DEM tiles have already went through the quality-control process through visual inspection and manual correction to remove erroneous regions, as well as accurately calibrated to the laser or radar altimetry data (Howat et al., 2019). Thus we believe that REMA mosaic has high absolute vertical accuracy and is suitable as ground reference. Furthermore, the proposed correction algorithm has taken the elevation differences between REMA mosaic and TDM DEM caused by temporal surface changes into consideration from the following two aspects. First, the phase unwrapping (PU) errors have distinguishable characteristics from the temporal elevation change. Specifically speaking, the elevation errors in TDM DEM caused by the PU errors are characterized by local elevation discrepancies with abrupt elevation jumps at the boundary, while the temporal changes in elevation or penetration depth are transitional changes with a certain trend. Hence, the proposed path propagation algorithm is based on the characteristic of the PU errors to automatically detect the elevation jumps at the boundaries of the erroneous regions. Secondly, to eliminate the influence of the possible temporal elevation changes between the TDM DEM and REMA mosaic, we do not simply correct the TDM DEM to the reference elevation surface of REMA mosaic directly. Instead, we create a buffer zone around each region which has to be corrected. Stable points whose elevation differences with REMA mosaic are less than a given threshold value are extracted from the buffer zone. The average surface elevation fitted from these selected stable points is used as a reference surface for the elevation offset correction as in Fig. 5 in the submitted manuscript.

2.2 Relation to existing methodologies

The paper surprisingly lacks references to previous DEM correction/fusion methodologies. This is true both for the introduction (supposed to explain the context of existing methods and why a new one is necessary), for the methods (supposed to reference/compare to existing methods, if applicable) and discussion (based on the results, what are the benefits of using this specific method compared to others? Qualitatively at least. quantitatively would be even better e.g. by comparing with other methods locally).

Many studies have looked at merging DEMs, removing data gaps and improving general DEM quality, for example: Reuter et al. (2007), Papasaika et al. (2009) (full thesis here: https://ethz.ch/content/dam/ethz/special-interest/baug/igp/igp-dam/documents/PhD_Theses/109.pdf), Yamazaki et al. (2017), etc.

The authors should:

- *provide a scientific context referencing existing methods and justifying a new* methodology,
- *identify and cite possible similar existing methodologies, if applicable.*

Response: Thanks for the comments and suggestions. In our work, an automatic algorithm to detect and correct the residual elevation biases exiting in the non-edited TDM DEM was proposed. Different from the general DEM fusion methods to incorporate the elevation information from different DEMs equally or by weights (Papasaika et al., 2009), the proposed algorithm can effectively correct the residual systematic errors in TDM DEM. REMA mosaic is used not to correct the TDM elevation point by point, but to provide reference elevations to correct the TDM elevation biases region by region, which are determined by the characteristics of the phase unwrapping errors. Therefore this proposed method maintains the characteristics of an InSAR generated DEM and is minimally influenced by temporal or penetration differences between TDM DEM and REMA mosaic.

The references and comparisons to the existing relevant algorithms will be summarized in the introduction section and discussed specifically in the discussion section in the revised manuscript. The recommended literature will be cited.

2.3 Validation with ICESat-2 and IceBridge

Seasonal and temporal biases of validation exist but are omitted in the validation methods and its discussion. Those should be quantified and discussed.

For temporal biases, the authors could use low-resolution, large-scale elevation change maps (Smith et al. (2020)) to partition their validation data over the AP. Binning the validation points by category of expected elevation change during the period (e.g., near stable; <0.2 m yr-1, small elevation change >0.2 and <0.5, strong elevation change >0.5) could provide improved statistics to evaluate the results through the validation effort. The impact of seasonal biases in elevation changes between the two validation datasets should also be discussed using known estimates of seasonal cycle in the AP.

Response: Thanks for the very helpful suggestion to incorporating the low-resolution, large-scale elevation change maps (Smith et al., 2020) for temporal biases analysis. To show the vertical accuracy of different elevation intervals, we will partition the laser points based on the elevation ranges in the revised manuscript. The annual surface elevation change will be converted to elevation change by multiplying by the acquisition timespan between the DEMs and laser altimetry points. Then the temporal elevation change will be compensated from the elevation difference between the DEMs and laser points before calculating the statistics.

As for the seasonal biases, unfortunately we have not found available seasonal changes products to compensate the seasonal changes of surface elevation. Furthermore, for REMA DEM validation in (Howat et al., 2019), laser altimetry data collected within 18 months of the REMA strip acquisition date or mosaic date stamp were selected. For TDM DEM validation in (Rizzoli et al., 2017), ICESat points were selected. In a word, the seasonal elevation changes were not taken into consideration for neither REMA DEM nor TDM DEM vertical accuracy validation with altimetry data (Rizzoli et al., 2017;Howat et al., 2019). Therefore, we ignore the seasonal biases in our validation with laser altimetry data.

2.4 Statistical estimators

Along the study, the authors provide Tables of the same format to quantify the improvement brought out by their methodology (Table 1, 2, 3 S2, S3). They use the mean of elevation difference to the validation data, the root mean square of differences and the 90% quantile of the distribution of elevation differences.

Currently, the mean does not bring much information and is hard to interpret due to temporal biases (preceding comments), but also because this statistical estimator is not very robust to outliers. I suggest using the median, as well as binning by category of expected elevation change during the period (preceding comments). Possibly, a Table showing median residuals normalized by the time difference between the validation dataset and the TanDEM-X date (1-2 years for LVIS 2015, 5-6 years for ATL06 2019) would allow for a better comparison between the biases identified in the two datasets.

Response: Thanks for the advice. In replacement of mean value, the median of the elevation difference will be added in the revised manuscript.

The RMSE is generally a good metric, it is however overly sensitive to outliers which is exactly what the TDM DEM is here suffering from. Using this estimator might "oversell" the improvement in the results, especially to the reader unfamiliar with these effects.
Consider:
• splitting your statistics by category of initial height differences, or showing the statistics independently for the corrected regions (before and after) and the untouched ones (once). I feel the second choice would be preferable.

Response: In the revised manuscript, the statistics of the corrected regions (before and after) and uncorrected ones (once) will be calculated.

• using the Mean Average Error (MAE), less sensitive to outliers.

Response: Mean Average Error (MAE) will be adopted as one of the statistical estimators in the revised manuscript.

For the 90% quantile: I see this is currently the raw quantile of the distribution (Table 1, line 3, the value is negative). I imagine that the authors want to show a measure of distribution spread (estimate of elevation precision). For this, consider either:
• taking the 90% quantile of the absolute value of the elevation difference.
• calculating the half-width between the 5% and 95% quantiles of the distribution.

Response: We will calculate the 90% quantile of the absolute value of the elevation difference in the revised manuscript.

3 Technical corrections
General on the text:
Unless the authors can justify a specific reason, I advocate for the two following changes along the manuscript:
1. Pick "elevation" or "height", don't use both interchangeably. Example in the caption of Table 2: Height differences calculated as DEM elevation minus laser height. This is confusing. I suggest using "elevation" everywhere, as it is the term most commonly used (Digital Elevation Model, Reference Elevation Model of Antarctica, etc).

Response: In the revised manuscript, the "height" will be changed into "elevation" for unification.

2. The use of "height error" seems questionable to me. "Error" by itself is not precise enough as it can refer to random errors, (i.e. uncertainties) or refer to systematic errors (i.e. biases). Here, the artefacts in the TDM DEM and the related correction methods developed by the authors fit clearly in the box of systematic errors.

Thus, it seems to me that it would be clearer to use "elevation bias" instead of "height error" along the text.

Response: "Height error" will be specified as random errors, (i.e. uncertainties) or systematic errors (i.e. biases) in the revised manuscript.

Text line by line:

75-96: Mention % value of data gaps in TDX

Response: corrected.

81: high-precision

Response: corrected.

88: stereophotogrammetry

Response: corrected.

89: such as the Advanced Spaceborne...

Response: corrected.

98-112: Please specify the REMA release used (is it r1 or r1.1?)

Response: It is the REMA mosaic DEM r1.1 used which will be specified in the revised manuscript.

114-123: Mention exact acquisition date for the LVIS data (season)

Response: The acquisition data of the LVIS data were during September and October of 2015, which will be added to the revised manuscript.

136: "the" buffer zone: This is the first mention of such a zone. Change to "a buffer zone" and refer to the related section.

Response: corrected.

140-178: All this information is not really specific to the paper Methods: shorten +optionally, move to "Data"?

Response: I believe the reviewer mentions the TDM DEM errors analysis section 3.1. Section 3.1 explains that the remaining elevation errors in TDM DEM causing large inconsistencies are mainly introduced by the systematic elevation errors especially the phase unwrapping errors. The proposed method is adapted to the characteristics of the residual systematic errors in TDM DEM. Therefore, it is preferable for us to maintain section 3.1 in the revised manuscript.

204: To my knowledge, "path propagation algorithm" is not a nomenclature commonly used *for this kind of method. This type of "flood-fill" method (https://en.wikipedia.org/wiki/Flood_fill) for region extraction is generally called "region extraction", "blob extraction" or most generally connected-component labeling (CCL) (https://en.wikipedia.org/wiki/Connected-component_labeling). Please adapt the nomenclature, and cite a reference for the algorithm used if applicable, and also possibly its relation to an existing computing package/parallel implementation.*

Response: Thanks for your valuable comment. Indeed, as you said, the nomenclature "path propagation" used in the paper is very similar to the generally connected-component labeling, which is used to detect erroneous areas based on the elevation difference. As we all know, connected-component labeling is generally used to detect connected regions in binary digital images (Shapiro, 1996) (https://en.wikipedia.org/wiki/Connected-component_labeling). However, our input data for the detection algorithm in the paper is elevation difference image, whose value is from negative several thousand to positive several thousand instead of 0 and 1. For the "flood-fill" method, it is also called seed fill to determine and alter the area connected to a given node (called seed) in a multi-dimensional array with some matching attribute (https://en.wikipedia.org/wiki/Flood_fill). However, the algorithm used in the paper does not need seed points to detect erroneous areas. Although these commonly used region extraction algorithms are very similar in general, they often have some subtle differences and have different application scenarios. To avoid confusion, we use the nomenclature "path propagation" in the manuscript based on the characteristics of the algorithm. In fact, the connected-component labeling algorithm and the flood-fill algorithm implemented on the famous computer vision library (such as scikit-image library and OpenCV library) cannot be directly used for our task. In order to effectively process high-resolution DEM data in the AP area (about 19G), we implemented the detection algorithm based on C/C++ language. The erroneous areas detection algorithm takes elevation difference as input, and draws on the idea of the merge strategy in the split and merge segmentation algorithm. It merges spatially adjacent target pixels with similar local elevation offsets into common regions, and each merged regions will be labeled for subsequent corrections. For each correction area, each adjacent target point with similar local elevation offsets will be gradually merged along the searched path starting from any one of the target points. This process is like propagating a certain label along the path to form a correction area, so we use the nomenclature "path propagation". In the revised paper, the difference between the used detection algorithm and the connected component labeling algorithm implemented in existing computing package will be explained and the corresponding reference cited. The nomenclature "path propagation" will be still used in the revised paper, considering the subtle difference of these region extraction methods. If you think it would be better to use another nomenclature (such as connected component labeling), we can revise the nomenclature in the revised paper.

252: increases

Response: corrected.

253: increases

Response: corrected.

254: high-precision
Response: corrected.

255: multi-scale (for consistency)
Response: corrected.

258: "Their spatial extent increased from: : : to: : :"
Response: corrected.

264: Figure 6b
Response: corrected.

271: Why use the "geographically closest point" in the DEM instead of a bilinear interpolation to the center of the LVIS/ATL06 point? With the TDM DEM at a posting of 12 m, the potential 6 m horizontal bias using a "nearest neighbour" approach from the center of the point can lead to a 3 m vertical error on a 25◦ slope (50% slope), and higher for larger slopes. This procedure might be deteriorating the quality of the validation effort, consider switching to bilinear interpolation of the raster data.

Response: In the revised manuscript, the bilinear interpolation to the center of the laser altimetry point will be adopted as replacement of the searching for the "geographically closest point".

321: ATL06
Response: corrected.

333: elimination of the residual height errors
Response: corrected.

341: Refer to Figure 10 before mentioning profiles L3/L4
Response: corrected.

371: The vertical scales should be specified sooner, in the Methods section maybe?

Response: The vertical scales will be specified sooner in the methods section in the revised manuscript.

On the Figures and Tables:
Fig. 2: Axis labels of histogram are too small in I. Text of schematics is squeezed vertically in III.
Response: Fig. 2 will be improved in the revised manuscript and all the mentioned issues will be improved.

Fig. 5: Specify if this is a schematic was created for demonstration purposes, or from real AP data at a specific transect.

Response: Fig. 5 is a schematic created for demonstration purposes, which will be specified in the revised manuscript.

Fig. 6, 7: Add glacier outlines.
Response: corrected.

4 References for the review

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