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

Authors: Yuting Dong, Ji Zhao, Dana Floricioiu, Lukas Krieger, Thomas Fritz, Michael Eineder

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 Anonymous Referee #1

General comments:

I have now gone through the manuscript more than twice. Generally speaking, this is a well-written manuscript with a thorough description of methods and analysis of results. Authors have used TDM DEM and REMA DEM of the AP region and improved the quality by combining them using propagation algorithm. Authors have demonstrated the improvement by comparing using laser altimetry data captured during two campaigns. Authors have demonstrated the improvement in terms of RMSE and clearly showed the improvement in iterative 3-steps of correction.

Response: We thank the anonymous reviewer for the very constructive and helpful comments. We carefully evaluated all comments and suggestions and point-to-point responses are given in the following. For better clarification, we add Figs. R1-R4 in this response letters and all the figures and the corresponding clarification will be added to the revised manuscript or the revised supplementary material.

My major criticisms are; (1) Authors have not explained the effect of using multi-temporal datasets captured during two different periods and later comparing them with laser altimetry campaign datasets captured in other periods. There is a significant temporal constraint in merging these datasets- I suggest authors describing the effect of using such data and how much error it will introduce in their analysis.

Response: In our work, we want to detect and correct the residual systematic elevation errors in TDM DEM which are mainly introduced by the phase unwrapping (PU) errors. REMA mosaic is used as the reference DEM for the proposed algorithm. The temporal difference between the acquisition time of the REMA mosaic (acquired between 2011 and 2017) and the TDM DEM (acquired between 2013 and 2014) covering AP has negligible impact on the proposed algorithm to detect and correct the residual PU errors in TDM DEM. The reasons can be explained from two aspects. First, the 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 boundaries while the temporal changes in elevation 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.

For validation with the laser altimetry points, the acquisition time difference of the DEM datasets and laser altimetry points will be considered in the revised manuscript. Thanks for inspiring us to consider the impacts of temporal changes between different datasets. The second reviewer also points out this issue and he suggest us to incorporate the surface elevation change rate (SECR) product from Smith et al. (2020) which was calculated from ICESat/ICESat-2 surface elevation change (SEC) between 2003 and 2019. The timespan of this SEC product covers the acquisition time of TDM DEM, REMA mosaic and laser altimetry points used in this manuscript. Therefore, we plan to interpolate the SECR based on the acquisition time difference between the DEMs and the laser altimetry data to compensate for the temporal difference before calculating the statistical evaluation results.

(2) Authors generally consider REMA as a ground reference DEM and improve the TDM DEM based on the values of REMA DEM. REMA is about 8m and then they used 100m coarse values where they have voids in the REMA DEM. Propagation algorithm works on two DEMs of slightly different spatial resolution; authors should explain the effect of different spatial resolutions of datasets on the algorithm. Put other words, could you resample your two DEMs on the same resolution and then run the algorithm to find out the performance?

Response: When filling the data voids of the 8-m REMA mosaic, the 100-m REMA mosaic was resampled into the same grid size of 8-m. The proposed path propagation algorithm works on the elevation difference map between the TDM DEM and REMA mosaic. To generate the elevation difference map, the voids-filled REMA mosaic has been resampled into the same spatial resolution with the TDM DEM. The clarification about spatial resolution adjustment will be added in the revised manuscript.

From result tables, I can see improvements varying in different steps of corrections and also for different elevation settings which are expected. However, the significance of final improvement has not been justified by authors. How authors can claim this improvement and not random noise? This is mainly because I can see instances in the result tables where improvement is around 2m.

Response: The TDM DEM elevation bias correction results can be evaluated both qualitatively and quantitatively. For the residual PU errors in TDM DEM, there exist abrupt elevation jumps at the boundaries of the erroneous regions, which have been eliminated after the correction process and validated by visual inspection.

In terms of quantitative validation with laser altimetry points, the statistical results are influenced by whether the laser points are located at the regions with elevation biases or not. Therefore, in the revised manuscript, in order to better validate the proposed correction algorithm, we will calculate the statistics of elevation differences between the DEMs and laser altimetry data at the corrected and non-corrected regions separately. Discussions about the validation results will be improved based on the revised experiments.

(3) My concern is why glaciologists would use the newly constructed improved TDM with accuracies still less than original REMA? REMA accuracies were reported less than 1m and TDM accuracies are reported around 10m. The only advantage I can see in merging is to fill data voids or gaps of REMA. From table 3, it is well demonstrated that there is no significant improvement (w.r.t (with respect to) REMA) in RMSE even after improving the TDM. The achievement of this study is to fill the data gaps in REMA using TDM. Put in other words, why reader can't call it as an improved REMA DEM or gapless REMA DEM as the basic foundation of the algorithm is the REMA and not the TDM?
Authors must understand the data circularity created by the methodology and see that REMA was used as a reference to correct TDM values and then it is compared against the TDM and original REMA.
In general, glaciologists will use this improved DEM if they find it more accurate than the REMA but this is not demonstrated. How if we simply patch up missing elevation values from REMA by TDM and smooth those gap areas? I suggest authors to suggesting future use of corrected TDM in glaciological applications. I encourage authors to describe this in the discussion section.

Response: Here we want to compare TDM DEM and REMA mosaic from the perspectives of absolute vertical accuracy, temporal consistency, data voids and random elevation errors (or relative vertical accuracy).

1. Although absolute accuracies of REMA mosaic and TDM DEM were reported as less than 1 m and around 10 m, respectively, the method to estimate the statistical accuracy is different and the statistics are estimated at a global level for TDM DEM and circum-Antarctic level for REMA mosaic (Rizzoli et al., 2017;Howat et al., 2019). Therefore, it is not meaningful to compare the two reported accuracies directly over a certain region. As mentioned by Howat et al. (2019), the AP area is a long coastal area with mountainous topography and is challenging for DEM generation. According to our validation results in the submitted manuscript, the corrected TDM DEM has achieved comparable absolute vertical accuracy with the REMA mosaic at AP area. For a better absolute accuracy comparison, we will calculate statistics for the corrected and non-corrected regions in TDM DEM and compare them to those of REMA mosaic separately in the revised manuscript.
2. The TDM DEM covering AP was acquired during austral winter of 2013 and 2014, while REMA mosaic covering AP was acquired between 2011 and 2017. The specific acquisition time of REMA mosaic covering AP is shown in Fig. R1a and Fig R1b in year and month, respectively. The short acquisition time of TDM DEM benefits from the high data acquisition efficiency of the TanDEM-X mission and minimizes the influence of temporal surface change which guarantees a good temporal consistency of the TDM DEM.

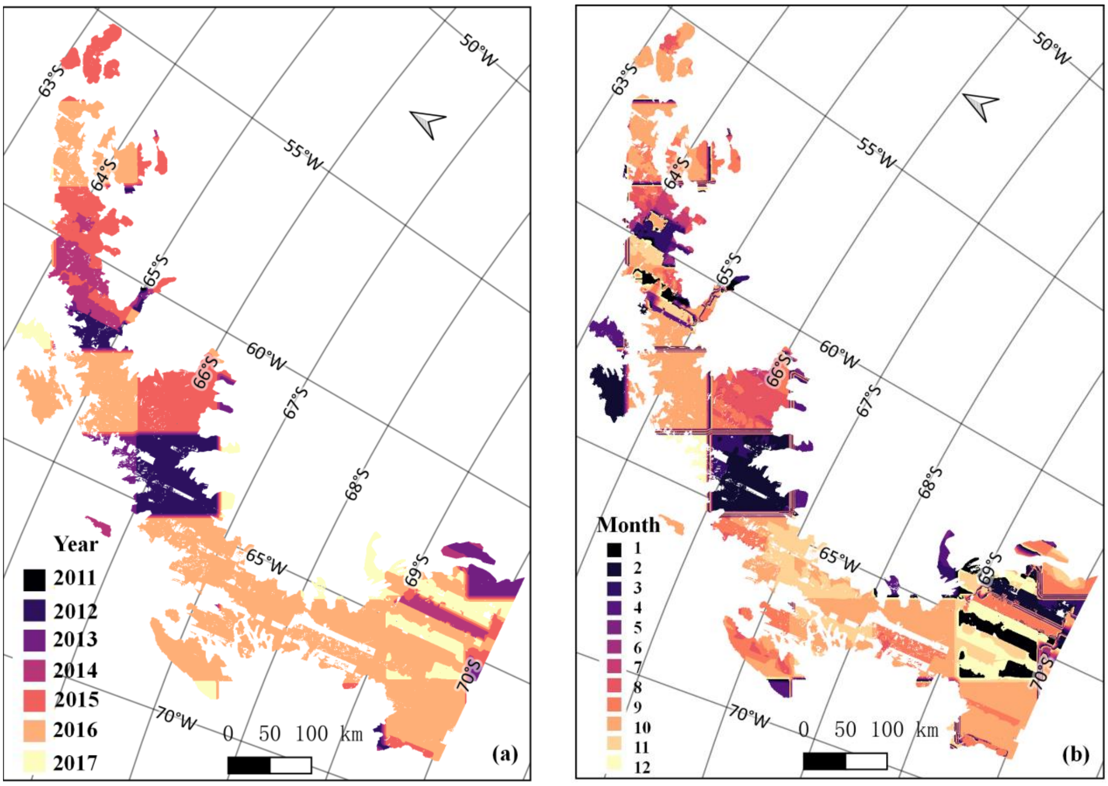

Figure R1 Acquisition time of REMA mosaic covering AP.

3. The TDM DEM has fewer data gaps than the REMA mosaic covering AP as shown in Fig. R2. The data voids in REMA mosaic in Fig. R2 are counted as about 8%, while about 0.85% for TDM DEM. For the 0.85% data voids existing in TDM DEM, we will reprocess some of the TanDEM-X bistatic data of austral winter of 2013 and 2014 to fill in these data voids in the revised manuscript.

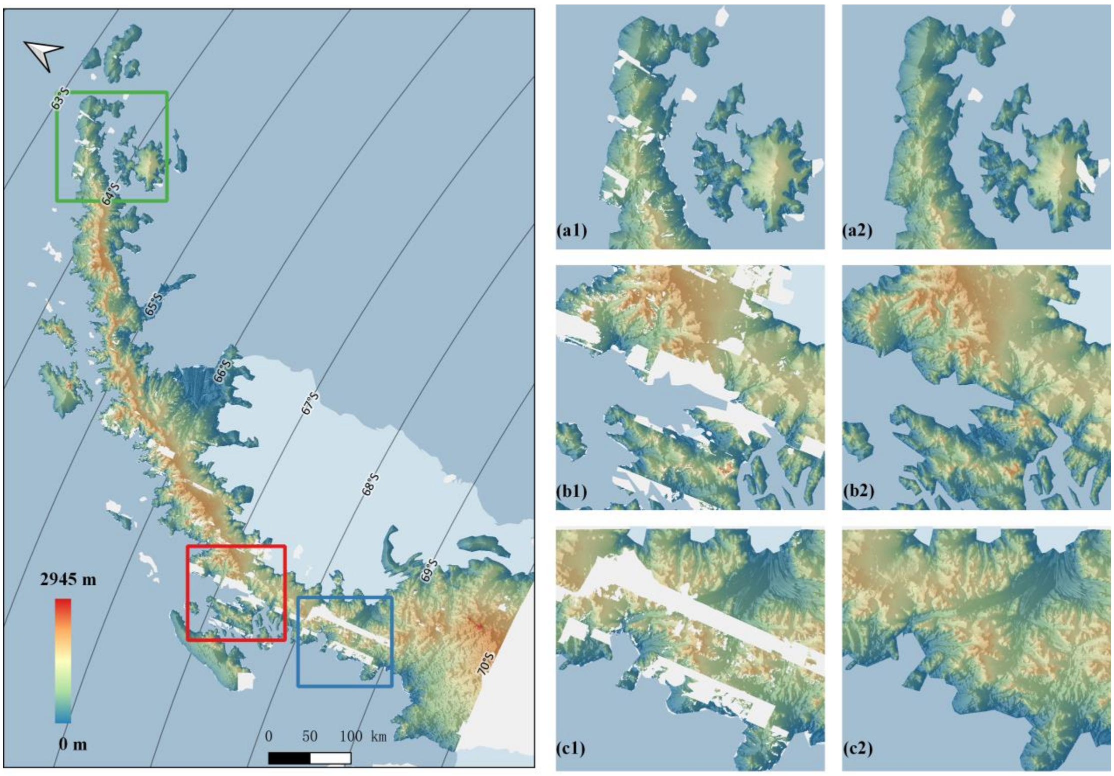

Figure R2 REMA mosaic covering AP and the location of three sample areas. Right panel: detailed comparison of the REMA (left column) and TDM (right column) DEMs in the sample areas.

4. Based on the elevation errors maps accompanying the DEM products, we can find that TDM DEM has smaller random errors and thus better theoretical relative vertical accuracy than REMA mosaic. In the elevation error map of REMA mosaic 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 for each DEM pixel the corresponding elevation error in form of the standard deviation (Wessel, 2016). The TDM error estimates are exact and reproducible derived from rigorous mathematically correct steps (Wessel, 2016) and are verified in several papers (Rizzoli et al., 2012;Rizzoli et al., 2017). Fig. R4 show the histograms of the random elevation errors of the REMA mosaic and TDM DEM covering AP. Comparing Figs. R3a and R4a to Figs. 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 vertical accuracy than the REMA mosaic.

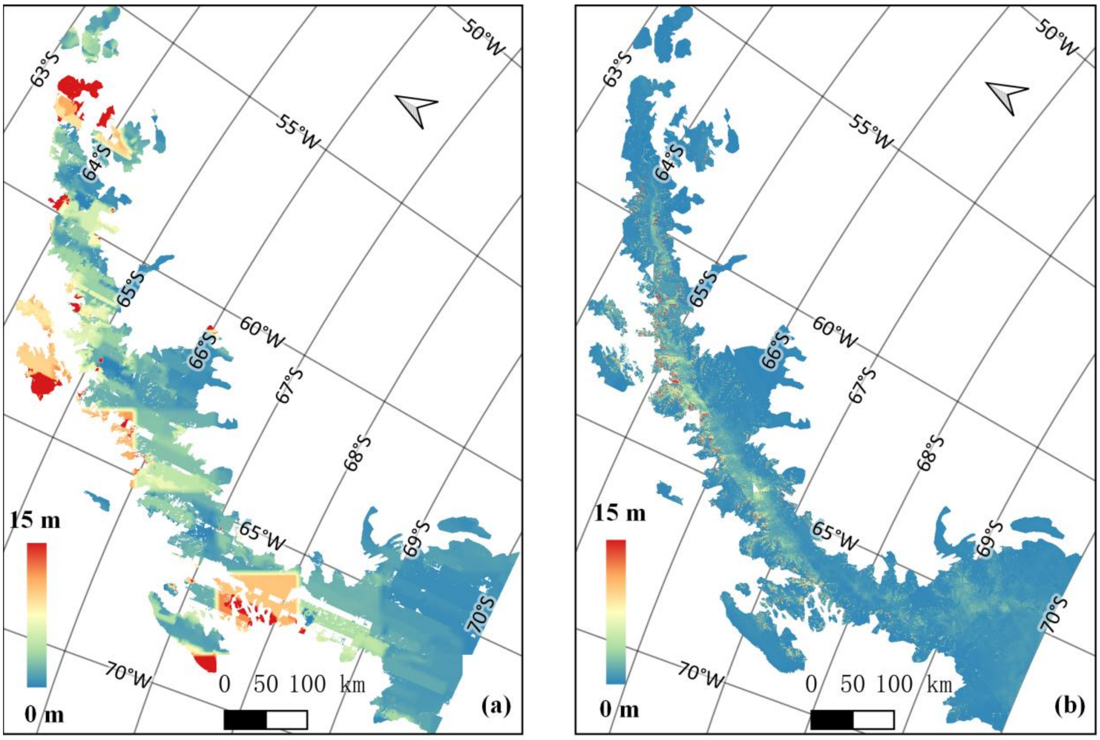

Figure R3 Random elevation errors of (a) REMA mosaic and (b) TDM DEM covering AP.

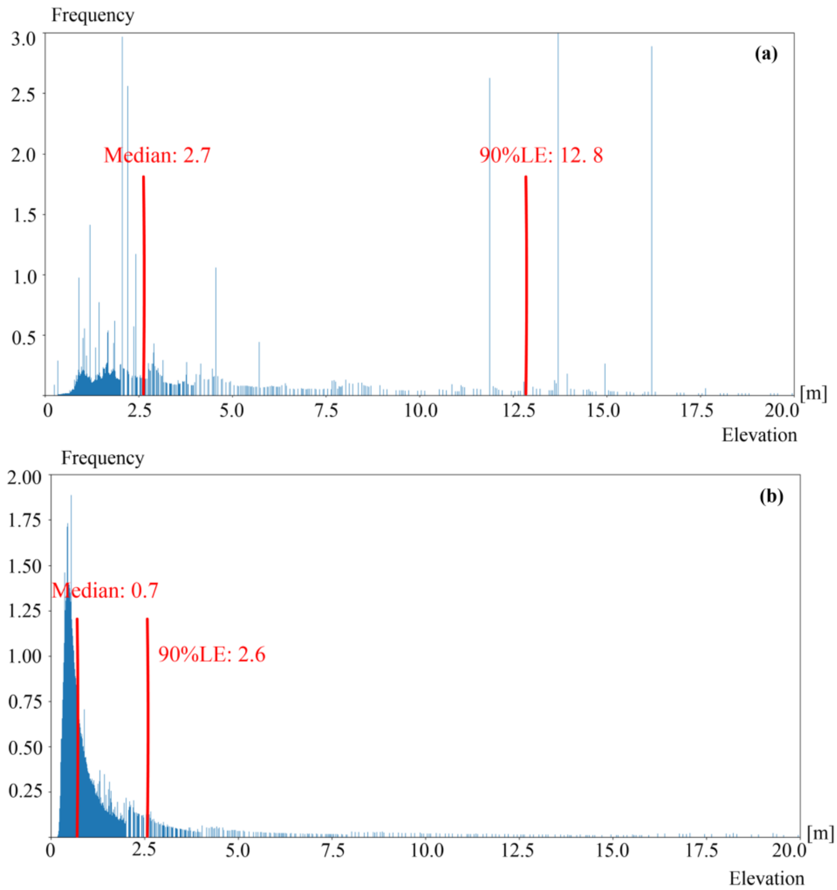

Figure R4 Histograms of random elevation errors of (a) REMA mosaic and (b) TDM DEM covering AP. Median value and 90% quantile of the errors (90%LE) are marked in red in the histograms.

Based on the above analysis, it can be found that TDM DEM has comparable absolute vertical accuracy, completeness and better temporal consistency and relative vertical accuracy compared with the REMA mosaic. In this manuscript, we developed algorithm to automatically correct the residual systematic errors in TDM DEM, which is minimally influenced by temporal or penetration differences between TDM DEM and REMA mosaic. The characteristics of an InSAR generated DEM are maintained. Therefore, we can conclude that the corrected TDM DEM is more consistent than a gap-filled REMA mosaic in perspectives of data acquisition time and vertical accuracy.
Several examples are given in the following and more potential applications can be left for the readers to explore.

- Assisting in the generation of TanDEM-X raw DEMs (Rott et al., 2018;Abdel Jaber et al., 2019) and TanDEM-X change DEM (Lachaise et al., 2019) by removing the reference topographic phase, correcting the phase unwrapping errors and calibrating the absolute phase. The corrected TDM DEM is the best choice considering the same TanDEM-X bistatic interferometric data source to generate the DEM products. From a long-term perspective, the TDM DEM acquired between 2013 and 2014 can be combined with other DEM products with a specific time stamp (such as the TDM DEM change DEM generated from data acquired between 2017 and 2019) for surface elevation change analysis over a large spatial coverage. For a voids-filled REMA mosaic with acquisition times between 2011 and 2017 this particular application is not readily possible.
- Since the REMA mosaic is obtained from optical data, the photogrammetric data acquisition is much influenced by the sunlight illumination and therefore data covering different parts of AP were acquired by different years and seasons as in Fig. R1. For applications with an interest in the seasonal elevation changes at AP, TDX DEM acquired in the austral winters of 2013 and 2014 is better suited.
- Before the release of the corrected TDM DEM covering AP with this manuscript, the gapless reference DEMs covering AP are the edited ASTER GDEM with spatial resolution of 100 m (Cook et al., 2012) and the 100-m REMA mosaic whose voids are filled with 100-m ASTER GDEM (Howat et al., 2019). Hence the corrected 12-m TDM DEM can be used for glaciological application at AP with much higher spatial resolution, like calculating the glaciological characteristics for glacier morphological analyses or filling data voids in 8-m REMA mosaic.

In the revised manuscript, we will improve the introduction to better clarify our reasons to choose the corrected TDM DEM in potential glaciological application. The comparison between TDM DEM and REMA mosaic in terms of absolute vertical accuracy, temporal consistency, data voids and relative vertical accuracy will also be added to the discussion section in the revised manuscript. Figs. R1-R4 will be added to the supplementary material of the revised manuscript. Potential applications of the corrected TDM DEM will also be added to the revised manuscript.

(4) Authors have not demonstrated the viability of their methods w.r.t published methods of merging DEMs. This should be discussed in the discussion section.

Response: Thanks for your comments. In our work, an automatic algorithm to detect and correct the residual elevation biases existing 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 not used 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. Relevant literatures will be cited.

Section-wise comments are appended as follows:

*Abstract: I have carefully read the abstract. It is generally well written, but it is somehow not attractive in the reader's perspective. Authors have failed to mention RMSE in absolute numbers rather they refer percentage. Between line 15-20, I encountered a very long statement which can be shortened. *To generate a consistent, gapless and high-resolution (12 m) topography product of the AP, we combine the TDM DEM and REMA mosaic by detecting and correcting the height errors in TDM DEM through a novel path propagation algorithm and multi-scale height error correction method based on the accurately calibrated REMA mosaic data. *. I would suggest authors to improve the abstract to make it more readable to readers and also boost it with quantitative results at the end.*

Response: Thank you for the suggestions. The abstract will be improved in the revised manuscript.

Introduction: Simplify this: 2020). AP is a complex mountainous coastal glacier system and the mass balance of the outlet glaciers is affected by climate and oceanographic forcing and also by the subglacial and surrounding topography (Cook et al., 2012). Good to see available DEMs of AP, mostly are Antarctic-wide. Table S1 provides a good overview but unfortunately, authors have missed a few regional attempts of making DEMs e.g. Fieber et al, 2018: https://doi.org/10.1016/j.rse.2017.10.042. Line 35-45, I would suggest authors revisit regional attempts of constructing DEMs of AP region.

Response: Thank you for the additional reference. The regional attempts of constructing DEMs of AP will be referred in the revised manuscript.

Line 45: By analysing all these available DEMs, it can be noted that the DEMs of AP have always suffered from large elevation uncertainty, coarse resolution, wide data voids or incomplete data coverage, which are caused by the complex mountainous terrain and cloudy weather of AP. I think this a very generic statement which is applicable for most of the regions of the continent and restricted to only AP.

Response: Thanks. The phrasing of this sentence will be improved.

I see authors are using the term posting, are you referring to the spatial resolution? Line 56: To obtain a consistent, gapless and precise DEM product at the high spatial resolution of AP, we intend to create a high-resolution DEM of AP by combining the TDM DEM and REMA mosaic, the two up-to-date DEMs with similar posting. Authors should use comparable posting rather than a similar posting.

Response: Yes, the term posting is referred to spatial resolution in the submitted manuscript. In the revised version, all the "posting" is replaced with "spatial resolution" for consistency. "Similar posting" has been changed into "comparable spatial resolution".

In general, the introduction section is not fully developed. It gives a feeling of missing information. For instance, authors should mention about the necessity of accurate and high-resolution DEM in the region and previous literature or applications of DEM used in the AP for various glaciological studies. This would provide a robust background on how accurate DEM can improve these existing studies. Authors mentioned about Cook et al. (2021) attempt of improving DEM but they ignore other efforts of combining multiple datasets to generate improved DEMs in Antarctica. To my knowledge, there are established attempts of developing DEMs in the Antarctic by combining two or more datasets- Authors should review those efforts in and then place their study at the end and explain how their effort is different than others.

Response: Thanks. The introduction will be improved in the revised manuscript based on your comments.

Experimental area and data: Fig. 1: Authors should mention elevation on the colour scale. And may consider naming a few landmark points in the figure to make it more readable. Somehow one yellow box is hidden behind the green coastline. You may consider changing the draping and make the yellow box above the green coastline layer so it is visible. Is the background RAMPv2 DEM or imagery? And you may also consider showing the high-resolution window showing sampling locations. Experimental data: This section is very well written, well done! Minor comment: use the term elevation and height consistently throughout the manuscript.

Response: Thanks for your comments. Fig. 1 will be improved with a few landmark points added. To increase the contrast between the DEM and footprints of the laser altimetry points, the elevation values are shown in grey scale. Moreover, in Fig. 8, the DEM elevation values are shown in the colour scale. For the yellow box in the Fig. 1, actually the yellow box is on the top of all the layers. We select a small sample area to present the details of the experimental results marked by the small yellow box. In the revised manuscript, we will add zoom-in windows of the sample areas. In addition, the term "height" has been changed into "elevation" in the revised manuscript.

Methodology: Line 130-135: use the term ground reference and not the ground truth.

Response: The term "ground truth" has been changed into "ground reference" in the revised manuscript.

Fig. 2: In the first section box, I cannot see x and y-axis numbers (Height difference against frequency graph). In section II, what are different shades of blue showing height error regions? Are you missing a colours scale here? I cannot see the text in blue in the Fitted reference surface model of section III. What is this blue line?. Authors should improve the caption of this figure describing the flow process briefly.

Response: Thanks for your comments. In the revised manuscript, x and y-axis numbers will be enlarged to be readable. The different shades of blue represent the detected erroneous regions with elevation biases. Each region corresponds to a similar elevation bias value. A color scale will be added in section II of Fig. 2. The small figure of section will be improved to make every line and text readable. The blue line represents the corrected TDM DEM elevation surface and more details can also be found in Fig. 5 of section 3.1. Fig. 2 is a framework of the proposed algorithm in four different modules and every module corresponds to a sub-section in methodology 3.1-3.4. For some key process like the elevation bias correction procedure, detailed and enlarged figure will be illustrated in each sub-section. Fig. 2 will be improved in the revised manuscript with all the details clarified and the caption will be extended.

Fig. 3: You may consider showing REMA DEM of the same region shown in (a) Authors have mentioned of using empirical threshold but did not mention much about the process of defining the empirical threshold to execute propagation algorithm. I understood the method of correcting TDM DEM against REMA using propagation algorithm, but I am also concerned about pixel resolution difference between two datasets and then impact of this varying resolution on the algorithm. It is more evident when authors are using 100-m sampled data where REMA has data voids.

Response: Thanks for your comments. Fig. 3 will be improved in the revised manuscript with REMA DEM of the same region added. More explanation about the process of defining the empirical threshold to execute the path propagation algorithm will be added in the revised manuscript.

The proposed algorithm operates on the elevation difference map generated from TDM DEM minus REMA mosaic. Before the generation of the elevation map, the 8-m REMA mosaic has been resampled to the same spatial resolution of the TDM DEM of 12 m. The data voids of 8-m REMA mosaic are filled by the 100-m REMA mosaic whose voids have been filled by the 100-m edited ASTER GDEM (Howat et al., 2019). The clarification about spatial resolution adjustment of DEM datasets will be added in the revised manuscript.

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. The examples shown in Fig. 6 and Fig. 7 of the submitted manuscript illustrate that there are data voids in REMA DEM (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.

References

Abdel Jaber, W., Rott, H., Floricioiu, D., Wuite, J., and Miranda, N.: Heterogeneous spatial and temporal pattern of surface elevation change and mass balance of the Patagonian ice fields between 2000 and 2016, The Cryosphere, 13, 2511-2535, 2019.

Cook, A. J., Murray, T., Luckman, A., Vaughan, D. G., and Barrand, N. E.: A new 100-m Digital Elevation Model of the Antarctic Peninsula derived from ASTER Global DEM: methods and accuracy assessment, Earth system science data., 4, 129-142, 2012.

Howat, I. M., Porter, C., Smith, B. E., Noh, M.-J., and Morin, P.: The reference elevation model of Antarctica, The Cryosphere, 13, 665-674, 2019.

Lachaise, M., Bachmann, M., Fritz, T., Huber, M., Schweißhelm, B., and Wessel, B.: Generation Of the Tandem-X Change Dem From the New Global Acquisitions (2017-2019), IGARSS 2019-2019 IEEE International Geoscience and Remote Sensing Symposium, 2019, 4480-4483,

Papasaika, H., Poli, D., and Baltsavias, E.: Fusion of Digital Elevation Models from Various Data Sources, 2009 International Conference on Advanced Geographic Information Systems & Web Services, 2009, 117-122,

Rizzoli, P., Martone, M., Gonzalez, C., Wecklich, C., Tridon, D. B., Bräutigam, B., Bachmann, M., Schulze, D., Fritz, T., and Huber, M.: Generation and performance assessment of the global TanDEM-X digital elevation model, ISPRS J. Photogramm. Remote Sens., 132, 119-139, 2017.

Rott, H., Abdel Jaber, W., Wuite, J., Scheiblauer, S., Floricioiu, D., Van Wessem, J. M., Nagler, T., Miranda, N., and Van Den Broeke, M. R.: Changing pattern of ice flow and mass balance for glaciers discharging into the Larsen A and B embayments, Antarctic Peninsula, 2011 to 2016, Cryosphere, 12, 1273-1291, 2018.

Smith, B., Fricker, H. A., Gardner, A. S., Medley, B., Nilsson, J., Paolo, F. S., Holschuh, N., Adusumilli, S., Brunt, K., and Csatho, B.: Pervasive ice sheet mass loss reflects competing ocean and atmosphere processes, Science, 2020.